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Measuring Impact Noise with Smartphone Apps

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MEASURING IMPACT NOISE WITH SMARTPHONE APPS

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ABSTRACT

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The ability of smartphone apps to measure impact noise has not been evaluated. This study was designed to explore the feasibility of using smartphone apps as a means to evaluate impact noise levels in industrial settings. Impact noise was generated by dropping a 4 Kg shotput onto a .5” thick steel plate at heights ranging from 6.5 to 102 cm. Two iPhones and two Android phones were tested with three apps each using both the phone’s built-in microphone and an external microphone. Sound level measurements of each drop were simultaneously recorded by a calibrated smartphone and a gold standard system capable of accurately measuring high intensity impact noise. These experimentally grouped datapoints (phone/app) were analyzed to determine if any smartphone/app/microphone could measure impact noise to within ±2dB SPL of the gold standard system. The results of this study showed that none of the three Android apps tested could measure impact noise with any meaningful degree of accuracy. The absolute mean differences for measurements recorded with Android devices ranged from 29.5 to 53.4 dB SPL. Measurements recorded with iPhones were closer than Android devices to gold standard measurements, with absolute mean differences ranging from 0.3 to 43.1 dB using the internal mic and 0.5 to 44.8 dB with the external mic. Measurements from the SoundMeter iOS app were closest to the gold standard, with absolute mean differences of from 0.5 to 4.8 dB.

The data recorded using Android phones to measure impact noise in this study indicated that even with an external microphone and proper calibration, Android smartphones and apps are unable to measure impact noise with any degree of accuracy and should not be relied upon to make any decisions regarding occupational impact noise exposure. iOS phones more closely approximated the performance of the gold standard measurements. The SoundMeter app with the iMM-6 external microphone coupled to either the iPhone 6 or iPhone Se approximated the performance of a calibrated Type II sound level meter and would be the preferred instrument combination for impact noise field measurement up to 142 dB peak SPL.

ACKNOWLEDGEMENTS

To my family

To my friends

To my research committee,

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ABBREVIATIONS

ABR	acoustic brainstem response
BPS	beats per second
CSL	Computerized Speech Lab
dB	decibel(s)
Lavg	average level
Leq	level equivalent
MEMS	microelectromechanical systems
MSHA	Mine Safety and Health Administration
NIHL	noise induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PEL	permissible noise exposure level
PPE	personal protective equipment
PTS	permanent threshold shift
SPL	sound pressure level
SLM	sound level meter
TTS	temporary threshold shift
TWA	time weighted average
VA	Veterans Administration

CHAPTER I

STATEMENT OF THE PROBLEM

An estimated 22 million civilian workers are exposed to hazardous levels of noise (Roberts, Kardous, Neitzel, 2016). Government agencies such as the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH) have been created to help ensure the safety of workers by establishing guidelines for and enforcing safe exposures to workplace hazards. These agencies regulate or recommend exposure limits for a number of different occupational hazards including noise.

Impact noise can be defined as the sound produced by the collision of masses, followed by the vibration of those masses (Flamme & Murphy, in press). Measuring impulse and impact noise is difficult and requires specialized equipment because of the high amplitude and short duration of the signal (Rasmussen, Flamme, Stewart, Meinke, & Lankford, 2009). Impact noise can have peak sound pressure levels in excess of 140 dB SPL and last only milliseconds, depending on the physical properties and force involved in the collision.

Impact noise affects the inner ear differently than continuous noise, often causing mechanical damage to tissue (Fu, 2011). In addition to amplitude, impact noise repetition rate is an important mechanism in contributing to cochlear damage. Even at relatively low amplitude levels (107 dB SPL), repetition rates faster than .5 per second cause significantly more temporary threshold shifts.

Workers in the United States are subject to environmental noise monitoring in an effort to minimize risk of occupational noise-induced hearing loss. Limits set for time weighted average and maximum noise dose percentage inaccurately incorporate impact noise; however both the OSHA and the NIOSH require or suggest that impact/impulse noise be integrated into noise exposure measurements of workers (Kardous, Willson, & Murphy, 2005).

Many workers are exposed to high-level impact noise. Workers in the manufacturing sector work in close proximity to machines that stamp, hammer, and shape metal parts. Other machines drop metal parts into metal bins or create impact noise during normal operation. All these sources combined to cause nearly 18,000 workplace hearing injuries in 2010 (National Institute for Occupational Safety and Health [NIOSH], 2010). Workers in the mining industry must work around conveyer belts, rock drills, rock smashers, and other equipment. It is not surprising that 80% of miners suffer material hearing impairment by the time they retire (NIOSH, 2015b). Construction workers are also at risk of developing noise-induced hearing loss; in a study by Kerr, McCullagh, Savik, & Dvorak (2003), 53% of the 147 construction laborers tested had hearing thresholds at 4 kHz worse than 25 dB HL.

Most sound level meters and noise dosimeters are not only expensive to purchase, but also require complex proprietary software to evaluate results. Smartphones have become extremely common in the U.S. and around the world. Many computer application developers have created “apps” for smartphones that are capable of measuring environmental noise to varying degrees of accuracy. This project aimed to determine the ability of calibrated smartphone apps to accurately measure impact noise in a laboratory setting. Outcomes from this research may inform health and safety personnel interested in utilizing lower cost and more accessible technology for noise exposure measurements in the workplaces.

The following research questions were asked:

Q1 What are the differences in peak sound pressure level for impact noise when measured with the internal microphone of a calibrated smartphone device using sound level meter apps versus a gold-standard laboratory sound measurement system?

Q2 What are the differences in peak sound pressure level for impact noise when measured with an external microphone coupled to the calibrated smartphone device using sound measurement apps and the gold-standard laboratory equipment?

Q3 What are the differences in peak sound pressure level for impact noise when measured with the internal microphone of the calibrated smartphone device as compared to an external microphone?

CHAPTER II

REVIEW OF THE LITERATURE

Noise-induced hearing loss (NIHL) is caused by exposure to hazardous noise levels. In the United States, over 22 million civilian workers are exposed to hazardous levels of noise (Roberts et al., 2016). In the military, the most common injuries to service members are caused by excessive noise exposure. In 2013, the U. S. Department of Veterans Affairs (VA) reported over 2.1 million veterans living with service-connected hearing loss and/or tinnitus and nearly 1.4 million receiving financial benefits as a result (Department of Veterans Affairs [VA], 2013). These numbers are slightly higher than 2009 when the VA recognized 1.2 million cases and paid over 1.1 billion dollars in compensation (Government Accountability Office Report to Congressional Committees, 2011). The risk of NIHL from continuous noise is increased when the worker is also exposed to high-level impact or impulse noise.

Impulse and Impact Noise

Hamernik and Hsueh (1991) defined impulse noise as “a noise transient that arises as the result of a sudden release of energy (most often electrical or chemical) into the atmosphere” (p. 189). The authors differentiate impulse noise from impact noise, noting that impact noise is caused by mechanical interactions and the waveform will be different depending on the physical characteristics of the materials, and that impact noise generally has a peak SPL under 140 dB. The National Institute for Occupational Safety and Health does not differentiate between impulse and impact noise, simply defining impulsive noise as “characterized by a sharp rise and rapid decay in sound levels and is less than 1 sec in duration” (NIOSH, 1998, p. xiii).

Noise Measurement

A sound level meter (SLM) is a device commonly used to measure sound amplitude, frequency composition, and other acoustical parameters. In order to record or measure a sound, the acoustic signal must first be changed into a signal that can be quantified and manipulated. The first piece of equipment in this step is the microphone. Inside the microphone, a diaphragm vibrates as a result of the interaction with the physical sound wave. This movement creates a tiny electrical signal analogous to the sound wave. This signal is too small to process and is boosted by a preamplifier. After this step, the now-amplified signal moves through a series of circuitry that processes the signal and converts it to a meaningful readout on the screen. The signal processing components for a SLM is illustrated below in Figure 1.

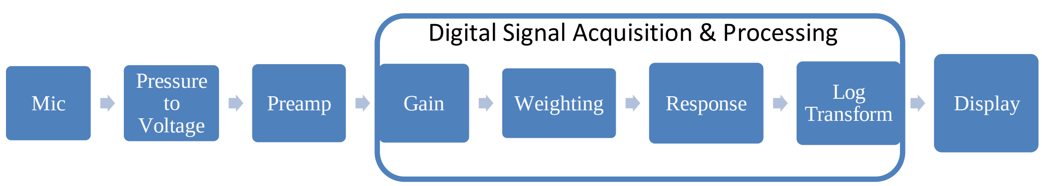

Figure 1. Sound level meter signal processing chain.

The electrical signal may be processed in several ways in order to display different information on the SLM to the operator. First, the signal may be “weighted.” Weighting is a way to filter a sound signal that places varying levels of importance on different frequencies that make up the signal. Common weighting networks include “A,” “C,” and “Z,” with “A” being the most common filter used for environmental noise monitoring. A-weighting is "said to be best for the frequency response of the human ear: when a sound dosimeter is set to A-weighting, it responds to the frequency components of sound much like your ear responds" (Occupational Safety and Health Administration [OSHA], 2013, Loudness and Weighting Networks, para. 2). With A-weighting, very low frequency components in the signal are attenuated and more emphasis is placed at frequencies where the human ear is most sensitive (around 1-4 kHz).

Another way a SLM processes sound is in terms of "response time." The SLM is programmed with a "time constant," or window in which the meter averages its readings. The time constant can be "fast," with a time constant of 125 milliseconds, or "slow," with a time constant of 1 second (OSHA 2013). Typically, for continuous noise, exposure measurements are made with the meter set to "slow" response.

This signal can be further analyzed by a process known as "integration" where the total sound exposure over a given period of time is accounted for and displayed as a sound exposure level (SEL). This SEL is used in calculations for occupational noise compliance standards discussed in detail in the section Noise Exposure Measurement in the Workplace.

Impulse and Impact Noise Measurement

Rasmussen et al. (2009) described the techniques and equipment required to accurately measure high-level impulse noise from recreational firearms. The authors reported that microphone sensitivity is an important variable when measuring impulse noise. An inverse relationship exists between sensitivity and peak signal handling capability; the less sensitive the microphone, the greater the sound pressure level it can accurately represent. Because firearm impulse noise contains very high frequency components, the transducer must be small in relation to the physical wavelength of the individual frequencies. Microphone orientation to sound source is another important variable. If the microphone is pointed directly towards the source, it will cause diffraction of the sound waves. If perpendicular, diffraction is minimized, but higher frequency measurements may be inaccurate due to interactions of physical wavelength of sound and microphone diaphragm diameter. Common microphone diameters range from 1” to 1/8,” and Rasmussen et al. chose the 1/8” size to minimize this effect and measure higher peak levels. The authors also reported that the maximum signal amplitude that can be accurately measured by a system is partially dependent on the maximum voltage the preamplifier can handle. The input voltage to the preamplifier dictates this maximum and if the voltage is too high, the system will be overloaded.

Meinke et al. (2016) compared sound pressure level readings from five commercial SLMs equipped with 1/8” microphones against readings obtained with a gold-standard laboratory test system and processed via MATLAB to determine how accurately SLMs measured impulse noise from a firearm. The SLMs were placed at different distances from the weapon that corresponded to 130, 140, 150, 160, and 170 dB peak SPL as confirmed by the laboratory apparatus. The five commercially available sound level meters were unable to accurately measure impulse noise at or above ~150 dB SPL. The error at 170 dB was ~17 dB for all five sound level meters tested, and the displayed reading often did not match the AC value output delivered by the SLM, possibly indicating errors in response time or log transfer function or circuit voltage limitations. Simply adding a “better” (1/8 inch) microphone does not necessarily increase the maximum measurement range and does not improve the accuracy of high-level impulse sound measurement for commercial sound level meters.

Laboratory Impulse Noise Source

An acoustic shock tube is a device that enables researchers to create high amplitude shockwaves in the confines of a laboratory test environment. The acoustic shock tube has a number of advantages over firearms or explosives for this purpose. The use of firearms and explosives requires a large parcel of vacant land appropriate for setting off detonations, highly trained technicians to handle the explosive, and numerous other safety precautions and bureaucratic red tape that make testing cumbersome (NIOSH, 2013). The shock tube uses a cylinder or compressed air separated from another open cylinder at atmospheric pressure by a thin polyurethane or metal membrane. When the membrane is punctured, the rapid release of the pressurized gas causes a shockwave whose amplitude can be calibrated by adjusting the thickness of the partition used.

Impact Noise and Sources

Flamme and Murphy (in press) defined impact noise as “produced by collision of masses, followed by free vibration of those masses”. The authors also noted that compared to impulse noise, impact noise generally lasts longer, has lower peak levels, and has more low-frequency energy.

Akay (1978) described the five basic mechanisms that create impact sound. The first is “air ejection.” As two objects rapidly come together, the air between them is compressed and forcefully ejected. This process is reversed as the objects rebound after collision and create another pressure pulse when air rushes in to fill the vacuum created as the two objects separate. The second mechanism described by Akay is “rigid body radiation." He defined this as a "pressure disturbance generated in an acoustic medium by the acceleration of an object" (p. 978). As two objects collide, the rapid acceleration causes sound waves to radiate from them. The third mechanism is "radiation due to rapid surface deformations" (p. 979). A sound pressure peak is created when two objects collide, and one is deformed. This peak is a discrete waveform and can be distinguished from the sound waves caused by the collision of masses. The fourth mechanism is termed "pseudo-steady state radiation" (p. 979). This can be thought of as the excess energy left over after the collision between objects is converted to mechanical work. In industrial settings, this energy is absorbed by manufacturing machinery and causes it to vibrate. The fifth mechanism is "radiation from material fracture" (p. 979). This is noise caused by material fracturing, and its intensity depends on how rapidly the material fractures. It does not appear that a standardized means of creating and measuring impact noise in the laboratory has been developed or implemented to date.

Occupational Hearing Loss Prevention

Today various government agencies regulate employees' exposure to hazardous noise by monitoring employee noise exposure and hearing acuity, establishing criteria for wearing personal protective equipment (PPE), mandating hearing conservation training, and ensuring employer compliance with record-keeping regulations. One of the key roles employers play in these programs is monitoring noise levels in the workplace. Traditional SLMs and noise dosimeters are expensive, and the use of smartphone or computer tablet "apps" may be a viable way to survey the workplace or act as a stand-in for more expensive equipment, especially in developing countries (Roberts et al., 2016).

United States Occupations with High Rates of Hearing Loss

According to NIOSH, approximately 16 million Americans work in the manufacturing sector, producing everything from food and beverages to transportation equipment and chemicals (NIOSH, 2010). Hearing loss accounted for 17,700 of the 59,100 cases of workplace injuries reported to OSHA, making it the most commonly recorded work-related illness for the sector (NIOSH, 2010). Occupational hearing loss caused by exposure to manufacturing equipment is a preventable illness and could be significantly reduced if OSHA regulations, and ideally, NIOSH best-practice guidelines (NIOSH, 1998) are followed.

Hammer forging is the process of shaping metal that has been heated with blows from a hammer or die. This process is used to create a variety of manufactured goods like jewelry, knives, and firearm components. Pal Singh and Bhardwaj (2013) conducted a survey of 572 randomly selected workers in hammer forging plants in India and used both pure tone audiometry testing and environmental noise measurements to determine if worker PPE use and job type influenced audiometric findings. The authors discovered that depending on where the workers were located in the plant, noise doses ranged from 95% to over 800% using OSHA 5 dB exchange rate. The two tasks associated with the highest decibel levels, forger and furnace job taker, had A-weighted L_{eq} value of 105.1 and 103.3 dBA, respectively. Pure tone audiometry results showed that over 90% of workers had hearing thresholds worse than 25 dB hearing level (HL) in both ears at all frequencies tested (500 Hz to 8K Hz). The authors contributed the abnormally high prevalence of NIHL to the fact that 85% of employees work longer than average work weeks (50-60 hours) and the majority reported seldom or never wearing hearing protection.

Mining is another industry with a high occurrence of NIHL. Mining is such a dangerous occupation that another separate government agency, the Mine Safety and Health Administration (MSHA), was created to govern its work environment and procedures. The NIOSH reported that people employed in the mining industry suffer the highest prevalence of hazardous noise exposure of all major industry with 25% of workers having a hearing problem and 80% suffering hearing impairment by retirement age (NIOSH, 2015a). Miners are exposed to a hazardous noise from a number of different sources, including conveyer systems, roof bolting machines, and scrubber fans (NIOSH, 2015b). A report by McBride (2004) noted the estimated noise exposure of several different types of mining equipment. Average dBA levels ranged from 88 (cutting machines) to 117 (pneumatic percussion tools). He also noted that many types of equipment emitted multiple hazards; hand drills, in particular, have impact noise from the drill bit, impulse noise from the exhaust, and strong vibrations from the body of the drill. Another study by Kitcher, Ocansey, and Tumpi (2012) examined NIHL in miners in the African country of Ghana. The authors discovered that workers in the stone crushing plant and mechanic shop were exposed to the highest noise levels (99.6 and 98.6 dBA, respectively) and the prevalence of NIHL was 33.6%.

Construction industry workers are also at elevated risk for developing occupational NIHL. Because construction workers have a wide scope of jobsite responsibilities, they have the potential to be exposed to several impact noise hazards in one day, ranging from chipping concrete with a jackhammer to pneumatic nail guns.

Another variable is phase of construction. Neitzel, Seixas, Camp, & Yost (1999) discovered that while TWAs did not vary significantly by specific job title in construction workers, the phase of construction did play a significant role. Construction workers involved in the "structural stage" of a construction project exceeded the NIOSH recommended exposure level (TWA of 85 dBA) in over 90% of samples. In a study by Kerr et al. (2003), 53% of the 147 construction laborers tested had hearing thresholds at 4 kHz worse than 25 dB HL, indicating NIHL.

Hearing Loss from Impact Noise

Impact and impulse noise have long been known to have a more detrimental effect on hearing than equal levels of steady state noise (Schwetz, Hloch, & Schewczik, 1979; Hamernik, Turrentine, Roberto, Salvi, & Henderson, 1984). Henderson, Subramaniam, Gratton, & Saunders (1991) explored how impact noise effected both temporary and permanent threshold shifts in chinchillas. Thresholds were established in healthy subjects using acoustic brainstem response (ABR). After establishing this baseline, the test subjects were grouped and subjected to impact noise of 107, 113, 125, or 137 dBA. In addition to amplitude, the rate of stimulation was either 4 beats per second (BPS), 1 BPS, or ¼ BPS of electronically synthesized impact noise. Thresholds were retested again immediately after exposure and then again, every 5 days until 30 days passed in order to establish both temporary threshold shift (TTS) and permanent threshold shift (PTS) values. The authors discovered that TTSs were present at all levels and stimulation rates, but the severity of the shift varied between test groups until exposure levels reached 125 dBA and became stable across groups. Permanent threshold shift results were similar to TTS with respect to variability across groups until exposure levels reached 131 dBA. The authors also demonstrated that PTS increased as stimulation rate increased until exposure levels reached 131 dBA. Above this level, PTS values were severe and independent of rate.

In addition to temporary and permanent threshold shifts, impulse/impact noise causes mechanical damage to inner ear structures not seen in long-term continuous noise exposures. Specifically, outer hair cells may become separated from each other, fall over, or break (Fu, 2011). In addition to hair cell damage, the tectorial membrane may be torn, and structural support cells can be damaged. Imaging from a chinchilla subjected to 4 kHz tone at 110 dBA revealed that the four rows of outer hair cells on the area of maximal displacement of the cochlea had been completely destroyed. The researchers discovered that a smooth layer of scar tissue replaced the damaged area and the sensory cells required to sense sound had completely vanished (Fu, 2011).

Noise Exposure Measurement in the Workplace

Noise exposure in the workplace can be measured using noise-dosimetry, which is especially useful for mobile workers. When using noise dosimeters, the sound level in any environment must exceed the “threshold” to be averaged into any reading. The OSHA sets the threshold at 80 dBA for noise measurements used for determining the need for hearing conservation programs (OSHA, 2013). Sound exposure levels may be quantified in a few different ways that either represent exposure as a percentage dose or as an averaged level in decibels. Two common measurement parameters are time weighted average (TWA) and average level (Lavg) or level equivalent (Leq).

Time weighted average is defined as “a constant sound level lasting 8 hours that would result in the equivalent sound energy as the noise that was sampled. The TWA calculation always averages the sampled sound over an eight-hour period" (OSHA, 2013, Appendix A, Glossary). Therefore, TWA can be thought of simply as the average noise level over the course of eight hours and is represented as a decibel number. Averaging sound exposure over an eight-hour period is a useful means to monitor workers who may be exposed to varying levels of sound throughout the work day, possibly moving from one duty to another. It is also important to note that TWA measurements are all normalized to an eight-hour period. Noise exposure sampling of less than eight hours may incorrectly estimate eight-hour exposures depending on the averaging approach implemented in the noise dosimeter algorithm for accounting for the time not sampled. For longer shifts (>eight hours), the full-shift noise exposure must be normalized to an eight-hour TWA. Workers whose noise exposure exceeds 85 dBA TWA are required to be included in a hearing conservation program per OSHA (1983).

Another way to report noise exposure is Lavg. This is "the average sound level measured over the run time of the measurement" using a 5-dB exchange rate to integrate the sound levels over time (OSHA, 2013, Appendix A, Glossary). The Lavg and the TWA will be equivalent when the sample time is eight hours. In cases of shorter or longer sample times, the values will differ. When sound levels are integrated over time using the 3-dB exchange rate recommended by NIOSH, the metric is referenced as level equivalent or Leq.

Other concepts to understand when measuring sound for workplace safety are "exchange rate" and "dose." Exchange rate is defined as "the increase or decrease in decibels corresponding to twice (or half) the nose dose" (OSHA, 2013, Appendix A, Glossary). Dose is defined as "a dose reading of 100% is the maximum allowable exposure to accumulated noise" (OSHA, 2013, Appendix A, Glossary). The OSHA uses an exchange rate of 5 dB and sets the 100% dose at 90 dBA, so reducing the TWA to 85 would yield a dose of 50%, and increasing it to 95 would result in a dose of 200%. The NIOSH uses an exchange rate of 3 dB and sets the 100% dose at 85 dBA, so reducing the TWA to 82 would yield a dose of 50%, and increasing it to 88 dBA would result in a dose of 200% (NIOSH, 1998, P xiii).

As mentioned previously, one common way to measure hazardous sound exposure in the workplace is to use a device called a noise dosimeter. This device measures varying noise levels occurring over time in the environment and converts it to TWA that can be used to ensure worker exposure does not exceed OSHA/NIOSH suggested maximums. The OSHA specifies that the permissible noise exposure level (PEL) sampling should include all sounds from 90 dBA and above, and impact/impulse noise and sets a maximum ceiling limit of 115 dBA measured using a slow response with a peak sound pressure level limit of 140 dB (OSHA, 1983). The OSHA also utilizes an "action level," where if the TWA is greater than 85 dBA, employees must be a part of a hearing conservation program, undergo training, and complete annual hearing tests. The NIOSH recommends integrating all sounds from 80 to 140 dBA using a 3-dB exchange rate. The NIOSH recommended that exposure limit criterion is 85 dBA for 100% dose and did not specify a ceiling level (NIOSH, 1998).

National Institute for Occupational Safety and Health Versus Occupational Safety Health Administration

The National Institute for Occupational Safety and Health is the scientific agency responsible for developing criteria for safe occupational exposures to workplace hazards.

The NIOSH best practice guidelines recommend that employers monitor work environments where workers may be exposed to sound levels over 85 dBA (NIOSH, 1998). The NIOSH makes recommendations to employers, but does not have the authority to enforce them. Another government agency, OSHA, actually enforces laws related to workplace safety including noise exposure. The OSHA standards are slightly more liberal than NIOSH recommendations across the board. In addition to the different exchange rates discussed earlier, the two agencies set different values for permissible exposure limit (PEL). The OSHA uses a TWA of 90, and the limit for NIOSH (termed recommended exposure limit) is 85. These seeming small differences add up quickly; an 85 dBA TWA is a 100% dose for NIOSH, but only a 50% dose for OSHA; a 91 dBA TWA is a 400% dose for NIOSH, but a 115% dose for OSHA. The stricter NIOSH standards for allowable noise exposure reduce the risk of developing NHL over a 40-year working career by 50% (NIOSH, 1998) and are used by most regulatory agencies around the world. Both NIOSH and OSHA limit the maximum peak level exposure to 140 dB SPL.

Approaches to Manage Occupational Noise Exposure

The NIOSH has established a hierarchy of controls that apply to not only noise exposure, but also to all environmental safety hazards an employee may face (NIOSH, 2015a). The hierarchy consists of five methods to minimize employee exposure to hazards including elimination, substitution, engineering controls, administrative controls, and PPE. The controls are ranked from most effective (elimination) to least effective (PPE) and are meant to be implemented in that order. An example of elimination would be to remove a piece of equipment with high sound pressure levels from a mining operation. While this would be the most effective course of action, it is often impossible for an existing operation. Substitution would entail replacing the equipment that is causing the hazard with another that does not and is also an effective option, but may be financially or logistically impossible to accomplish. An example of engineering controls would be to make modifications to an existing piece of equipment that would reduce exposure by either minimizing the level of noise created or insulating the employee from the noise. Administrative controls rely on changing how manpower is allocated to a task. These controls are commonly used when excessive exposure levels cannot be controlled by other more effective methods. An example would be to rotate crew members to different stations over the course of a shift to minimize exposure to a particularly loud task. The least effective, but most commonly used, exposure control is requiring employees to wear PPE while working. This approach is least effective because of the variability in the fit of hearing protectors, and the effectiveness of the strategy relies upon worker behavior which can be influenced by a number of factors.

Noise Dosimetry and Impact Noise

Kardous et al. (2005) examined noise dosimeter effectiveness for measuring impulse noise and found the devices are limited by several technical issues. Specifically, the microphone response above 3 kHz is poor, and the microphones are unable to measure peak sound pressure levels greater than ~146 dB. Another difficulty the authors pointed out was the conversion of impulse noise to time weighted average. The current NIOSH equation for dose is $D = [C_1/T_1+C_2/T_2+ . . . +C_N/T_N]$, where C_N is the total time of exposure at a specified level and T_N is the exposure duration that would expect to cause harm. The value for T_N is determined by measuring the sound in the "slow" response time setting, causing a significantly lower value than the actual peak sound pressure level. When the values for T_N (2.2 seconds) and C_N (456 milliseconds) are entered into the equation, the result is a contribution of only approx. 0.02-0.03%. So, because the duration of an impulse/impact sound is so short, a worker could safely be exposed to 5000 gunshots according to the NIOSH equation. For these reasons, the authors found dosimeters entirely unsuitable for measuring exposure to impulse noise. The contribution of impact noise to the overall noise exposure may also be underestimated due to the same issues related to slow response and may be limited, depending on the spectral characteristics of the impact noise source, especially if A-weighting is applied to the measurement.

Another tool commonly used to measure noise is the sound level meter. This device measures sound pressure in the atmosphere and displays sound pressure level in decibels (dB SPL), rather than TWA or dose. Sound level meters are useful for measuring individual noise sources, evaluating hearing protective devices' suitability, and aiding in the analysis of noise sources for possible noise control (OSHA, 2013). Sound level meters are broken into two basic types, depending on accuracy: Type 1 is used for precision field measurements and have an accuracy of ±1 dBA, and Type 2 is used for general measurements with a tolerance of ±2 dBA (OSHA, 2013).

Noise Measurement with Smartphones and Tablet Apps

Numerous sound level meter apps are available for download for free or for a small cost. The apps are available for different operating systems, and each is designed with different features and capabilities. Table 1 and Table 2 provide a summary of popular sound level apps for both Android and Apple OS operating systems as of November, 2016.

Table 1

iOS Apps Tested

App	Developer	Response Time	Features	Price
SPLnFFT	Fabien Lefebvre	Slow/fast	A/C weighting; external mic. calibration	$3.99
NIOSH SLM	EA Lab	Slow/fast	A/C/Z weighting; external mic. calibration	Free
SoundMeter	Faber Acoustical	Slow/fast/impulse	A/C weighting; external mic. calibration	$19.99

Table 2

Android Apps Tested

App	Developer	Response Time	Features	Price
SPL Meter	Keuwlsoft	Slow/fast	A/C weighting; external mic. Calibration	Free
decibel Pro	BSP Mobile Solutions	Unknown	A/C weighting; “automatic” calibration	$3.60
Noise Meter	JINASYS	Slow/fast/user adjustable	A/C weighting; Leq calibration	Free

Sound Level Meter App Compared to Sound Level Meter

Sound level meters and sound level apps differ in the terms of the measurement components and signal processing chain. The first step in the chain is the microphone.

Smartphone microphones are primarily intended to detect sound sources close to the mic (the user's voice) and not environmental sounds around the user. While this increases the clarity of the signal for the person on the other end of the line, it may limit the ability of an app to measure sounds accurately. Most cell phone manufacturers today use a microelectromechanical systems (MEMS) class microphone that can accurately capture sounds from 30 dB SPL to 130 dB SPL and has a flat frequency response (Kardous & Shaw, 2014). Unfortunately, there are many companies manufacturing MEMS microphones (Knowles, AAC, Goertek, and BSE, to name a few), and cell phone companies do not disclose which one or ones they use in each phone. This makes it nearly impossible to know the exact specifications for the microphone and whether recording errors are caused by the hardware or software. When the signal arrives at the microphone, a tiny electrical voltage is created. The amplitude of this signal is dependent on the amplitude of the signal and the sensitivity of the microphone. This is another possible opportunity for error to occur, and since the microphone sensitivity is unknown, it may be difficult to analyze. The voltage created by the microphone is analogous to the original signal and must be converted to a digital signal so that it can be manipulated by the app's software. The app manipulates the response time, weighting and decibel conversion using digital filters not disclosed by the software developers (Nast, Speer, & Le Prell, 2014). The proprietary processing of this digital signal is probably different for each app and is yet another opportunity for error to occur. This processed digital signal is then displayed on the screen.

Accuracy of Sound Level Meter Apps

Kardous and Shaw (2014) examined the ability of smart devices to measure continuous sound using only the built-in microphone. The authors tested a number of smartphones and tablets manufactured by Apple, Samsung, HTC, and Motorola. Inclusion criteria for the applications tested were: ability to report A-weighted and unweighted sound levels, slow or fast response time setting, and 3 or 5 dB exchange rate, and ability to display both equivalent continuous average sound level or time weighted average. The authors tested 10 Apple apps that met the criteria. None of the apps available for the Android operating system met all inclusion criteria, but the authors selected four that were closest. The authors did not go into specific about detail on how each app failed to meet inclusion criteria. Sound level measurements were taken in the sound field using pink noise starting at 65 dBA and increasing to 95 dBA in 5 dB steps. The value reported by the smart device was compared to a calibrated Type 1 SLM. The results showed that some apps were very accurate. Three of the iOS apps (SPLnFFT, NoiSee, and SoundMeter) were within ±2 dB of the reference value for A-weighted sound levels. The researchers also noted that Android apps were generally unsatisfactory for measuring sound due to the wide variance in values reported from the same app across different devices and the fact that Android devices are manufactured by many different companies and there was no consistency in the hardware components.

Roberts et al. (2016) extended the 2014 study by Kardous and Shaw (2014) and added external microphones to the experimental design. The researchers selected the three apps that gave the best performance from the 2014 Kardous and Shaw study and chose to use only Apple branded iOS products because of the more uniform hardware and tighter controls placed on the Apple operating system compared to Android devices. In addition to the iPhone 4, 4S, and 5 used in the previous study, the authors used three 5th generation iPods. Two external microphones were used, the iMM-6 manufactured by Dayton Audio (Springboro, Ohio) and the i436 manufactured by MicW (Beijing, China). The authors conducted two experiments. The first was designed to evaluate the variability of the external mic while measuring noise levels in the same type of device running the same app. Pink noise was generated in a sound-treated chamber, and measurements were taken in the same manner as the 2014 study at levels from 60 to 100 dBA in 5 dB steps. This experiment revealed that when measurements are taken by the same type of device using the same app and same microphone, the data will be similar, but not necessarily accurate in comparison to the ±2 dB required of a type II SLM. Some device/app/mic combinations were more accurate than others, and to complicate things further, the noise level sometimes influenced the accuracy of the measurement. The authors discovered that when the iMM-6 microphone was used, the mean difference between sound meter app measurements and the reference mic was 0 at all noise levels from 70-100 dBA. The SPLnFFT app was the next most accurate, with a mean difference on 1-2.1 dB over the same range. NoiSee was also accurate, with mean differences from .1 to .7 dB up to the 95 dB level, but when noise reached the 100 dBA level, mean difference rose to 4.3 dBA.

Kardous, Shaw, and Murphy (2016) noted that different generations of smartphone devices use different microphone hardware and software depending on the current operating system. The second experiment was designed to show if using an external mic would compensate for this and allow different versions of smartphones to make accurate measurements once an external mic was attached. When the internal microphone was used, sound level readings could be off by as much as 25 dBA. When the external mic was used, the differences reported were less than 1 dBA. Despite the promising improvement when using the external microphones, the authors noted that there are still hurtles to using smart devices to monitor noise levels, including the necessity to calibrate the app before accurate measurements can be made and inconsistent software and hardware updates. It is also noteworthy that these studies limited the measurements to continuous sound levels between 65 dB and 95 dB SPL and microphone performance when measuring sound levels below or above these limits is unknown.

Nast et al. (2014) tested five apps that ranged in cost from free to over $10 in an iPhone 4S using the phone's microphone compared to a calibrated Type I sound level meter. The authors placed each device in a sound isolation chamber and presented narrow-band noise in the sound field centered at frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz at intensities of 50, 70, and 85 dB HL. Following calibration with a type I SLM, sound level measurements were taken every 10 seconds with the smartphones, and the average of 10 samples were recorded for each narrow-band frequency. The researcher took measurements with the app set to both A-weighting and C-weighting. The smartphones were unable to measure low noise levels (~ 0 dB HL) due to high internal noise generated by the phone and elevated ambient noise levels in the test room. Most smartphone apps measured C-weighted sounds more accurately than A-weighted sounds, and most apps underestimated the actual sound level, especially at 85 dB HL and above. The authors do not recommend the use of SLM apps to monitor workplace noise unless correctly calibrated.

Study Rationale

While there are a number of studies in which the authors examined the accuracy of smartphone devices and apps to measure constant noise, there are none that examine the performance of smartphones using internal and external microphones to measure impact noise in a laboratory setting. In addition, no study has been performed that examined the effect of using an external microphone in an Android device. The use of an external microphone may overcome the hardware limitations mentioned by previous authors and expand the availability of reliable environmental noise monitoring equipment to a larger number of workplaces, especially those in developing countries.

CHAPTER III

METHODS

This study borrowed from previous studies with respect to experimental setup. Hardware positioning, data collection, and statistical analysis was similar to that of Nast et al. (2014), Rasmussen et al. (2009), and Roberts et al. (2016).

Experimental Setup

Instrumentation

Sound field measurements were conducted in a lab. Instrumentation used for data collection consisted of a gold standard system capable of measuring sound levels with a high degree of accuracy, and the smartphones were evaluated.

Gold standard system. The gold standard system consisted of the Computerized Speech Lab (Pentax Medical) system (CSL) employing a G.R.A.S. Sound and Vibration 1/4" type 46BD combination microphone and preamplifier. Sampling rate was set at 100,000 Hz, and16-bit quantization was used. Acoustic waveforms recorded by the CSL system were saved as individual .wav files and analyzed with a custom script written for GNU Octave 4.2.1 software. The peak SPL level was obtained from the Octave script output and served as the reference. These reference values were compared to individual measurements gathered from the smartphones for accuracy.

Smartphones, apps, and microphone. Test phones consisted of two iOS operating system phones (Apple iPhone 6S and iPhone 7) and two Android operating system phones (Samsung Galaxy Amp 2 and Sony Xperia Z3 Compact). Three applications were tested for each operating system. Two of the three apps selected for iOS performed well in previous studies (Kardous et al., 2014; Nast et al., 2014); they were SPLnFFT (Fabien Lefebvre) and SoundMeter (Faber Acoustical, LLC). The third iOS application tested was NIOSH SLM (EA Lab). Although Android devices/apps were reported to exhibit inadequate performance in the literature, three apps stood out as having more features and were selected for this study. They were SPL Meter (Keuwlsoft), decibel Pro (BSP Mobile Solutions), and Noise Meter (JINASYS). Measurements were recorded using both the phone's built-in microphone and an iMM-6 Calibrated Measurement Microphone manufactured by Dayton Audio (Springboro, Ohio).

Calibration

The CSL system was calibrated by recording a 114 dB calibration tone from a G.R.A.S. Sound and Vibration Pistonphone Type 42AA. After this tone was recorded, a 1.5 second duration section from the middle of the recording where the waveform was most stable was extracted using Audacity 2.2.2 software. This extracted waveform section was saved for use as a calibration signal applied during waveform analysis via a custom GNU Octave script (Appendix A).

Applications were calibrated by adjusting displayed readings to match a calibrated Larson Davis System 824 Type I sound level meter. The calibration signal consisted of white noise presented at 80 dB SPL generated by the Audacity software from a laptop computer connected to an Acoustic Research Powered Partner 570 speaker. Calibration was completed in a manner that would maximize accuracy of readings and attempt to mitigate measurement errors caused by app limitations. Each smartphone was placed on a microphone stand 1 meter from the speaker, and the displayed dB level was adjusted to within ± 1 dB of the Type I SLM reading inside a sound treated booth. Microphones were in a grazing orientation to the source. Each smart phone and app combination was calibrated separately for internal and external microphone test conditions prior to impact sound level measurements. Immediately following calibration, the microphone stand with the smartphone still in place was moved to the experimental setup, and data collection for that smartphone/app combination was completed. This process was identical for each combination tested, with the exception of the "SPL Meter" app for Android devices. This app had multiple calibration levels, and calibration levels of 60 and 80 dB SPL unweighted were selected to provide a range of inputs. Calibration was not attempted for this app above 80 dB SPL. All phones were calibrated and tested in either "Z" or "None" weighted conditions, with either "impulse" or "fast" time constant selected, depending on application capabilities.

Impact Noise Source

Impact noise was generated by dropping a 4 Kg cast iron shotput onto a horizontal ½" thick A-36 grade diamond plate piece of steel resting on concrete blocks. The plate was oriented with the diamond plate facing down so that the shotput impacted the smooth side of the plate. Drop height was adjusted from high to low, or low to high, depending on where the shelf was located following completion of the smartphone/app/mic prior to it.

Drop height was controlled by raising and lowering a shelf that supported the shotput. The shelf was supported by hanging brackets that moved up and down on shelf tracks secured to a piece of plywood. The shelf tracks allowed a drop height range of from 6.5 to 102 centimeters in 1.5-centimeter increments. This range was divided into 31 numbered levels to allow the shelf to be easily and consistently adjusted during data acquisition.

The release mechanism consisted of a 10” long piece of 6” dimeter PVC oriented at a shallow angle. An 1/8” diameter stick was inserted horizontally to retain the shotput approximately 2.5 cm from the lip of the pipe. To release the shotput, the stick was quickly removed. Due to the shallow slope of the ramp (~5º), the gate was completely removed before the shotput began any forward motion, eliminating the possibility of the gate interfering with the shotput on release and ensuring it fell in a consistent and repeatable manner. Figure 2 displays the experimental setup with steel plate, release mechanism, acoustic foam, and height adjustment visible.

Figure 2. Experimental setup.

Data were recorded with the shelf at six different levels, 6.5, 25.5, 51, 70, 82.5, and 102 cm. Three repetitions were completed for each phone/app/microphone combination. Peak sound levels generated ranged from 123.1 dB at 6.5 cm to 142.7 dB at 102 cm. Drop height and corresponding descriptive metrics are presented in Table 3. Hearing protection was worn by the researcher at all times during data acquisition.

Table 3

Drop Height and Decibels Produced

Drop Height (cm)	Mean (dB)	Median (dB)	SD	N
6.5	126.7	126.6	1.3	72
25.5	134.3	134.2	1.4	72
51.0	137.0	137.1	1.0	72
70.0	138.4	138.5	0.9	72
82.5	139.5	139.6	1.1	72
102.0	140.1	140.4	1.2	72

Data Collection

Peak SPL values recorded by the gold standard microphone served as the "reference value" to which sound level meter apps were compared. Each smartphone device was retained on a microphone stand 1 meter above the ground and 1 meter away from the point of impact. Smartphone devices were supported by a commercial microphone stand and held in place with Fun Tac Mounting putty manufactured by Loctite (Düsseldorf, Germany). Each smartphone was oriented horizontally as they would be held if the operator was reading the display during routine use. The active internal microphone on each smartphone was determined by rubbing each microphone until a measurement spike was observed. The microphone automatically selected by each app was not changed. The reference microphone was positioned in a grazing orientation equidistant from the sound source and 8.5 cm to the left or right of the smartphone microphone being measured, depending on whether two devices were available; otherwise, the reference mic was always to the left if a single smartphone was utilized.

When two smartphones were available for testing at the same time, they were measured simultaneously in an effort to increase efficiency of data collection.

Each smartphone was measured during three trials at each shotput drop height using each smartphone/microphone/app combination. Each of the four smartphones contributed 108 measurements for a total of 432 smartphone data points. Each of the smartphone data points had a corresponding gold standard measurement, bringing the grand total to 864 data points.

Descriptive Statistics

The mean difference between the CSL system measurements and smartphone measurements was calculated for every combination of dB level, app, and microphone. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Negative values indicated measurement was a lower intensity than the reference system. Data were summarized by device, app, and microphone used.

CHAPTER IV

RESULTS

A total of 435 data points was recorded during the data collection portion of the study. Three samples were erroneously recorded with the reference microphone out of the correct position following smartphone calibration and were immediately purged. Therefore, a total of 432 valid samples was collected and analyzed.

The mean differences between smartphone internal microphone measurements and gold standard measurements were compared to determine if smartphone measurements were within ±2 dB of gold standard values. The only phone/app combination to meet this criterion was the Apple iPhone Se using the SoundMeter app at low drop heights. Overall, measurements collected with iPhones were closer to gold standard values than measurements from Android devices, and detailed outcomes are provided below.

iPhone Internal Microphone Measurements

iPhone internal microphone measurements are presented in Table 4. Mean differences in peak SPL were generally between 1 and 40 dB, depending on application. The lowest mean difference recorded for the iPhone 6 was with the SoundMeter app at the lowest drop level (6.5 cm). iPhone 6 internal mic measurements are presented in Figure 3. Measurements from the iPhone Se had smaller differences between mean peak sound pressure levels and were ±2 dB of the gold standard for four of six drop levels with the SoundMeter app. This is significant as the standard for Type 2 sound level meters calls for accuracy within ±2 dB (American National Standards Institute, 2013). Difference in means with the SPLnFFT and NIOSH app were higher in both phones and ranged from 15.2 to 43.1 dB.

Table 4

Difference in Mean SPL iOS Phones Internal Mic and Gold Standard (dB)

		Drop Height Level (cm)					
Phone	App	6.5	25.5	51.0	70.0	82.5	102.0
iPhone 6	SPLnFFT	-32.2	-39.8	-41.5	-42.5	-43.1	-43.1
	NIOSH	-24.2	-23.6	-32.2	-29.2	-27.5	-24.5
	SoundMeter	-6.8	-15.6	-17.9	-19.0	-18.4	-19.3
iPhone Se	SPLnFFT	-17.1	-20.6	-22.7	-24.6	-25.2	-25.2
	NIOSH	-25.8	-23.9	-15.2	-15.3	-15.4	-27.9
	SoundMeter	-1.8	0.3	-1.1	-2.3	-2.6	-1.0

Figure 3 displays difference in mean sound pressure levels between gold standard system and smartphone app used with the iPhone 6 internal microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Figure 4 displays difference in mean sound pressure levels between gold standard and smartphone app with the iPhone Se internal microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

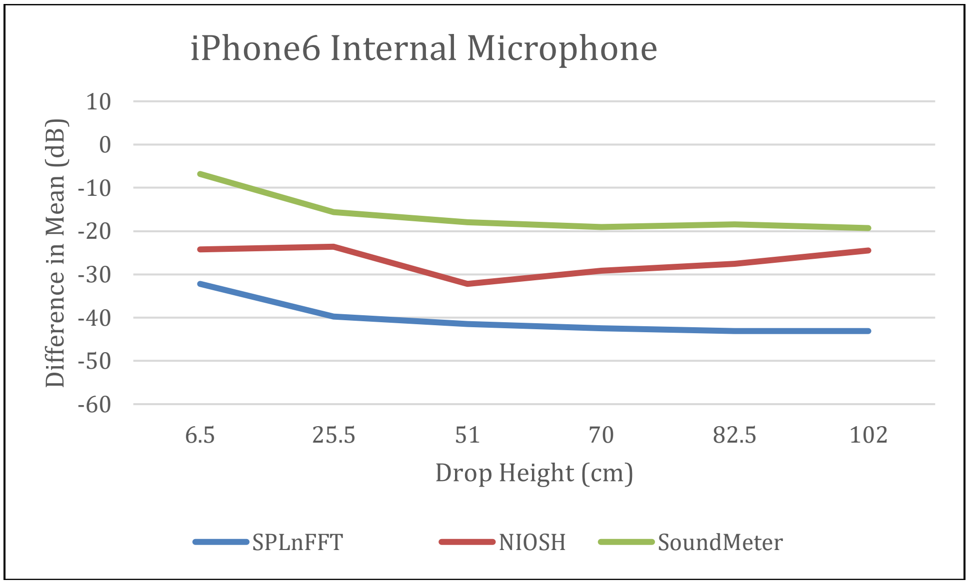

Figure 3. Difference in mean between iPhone 6 internal mic and gold standard.

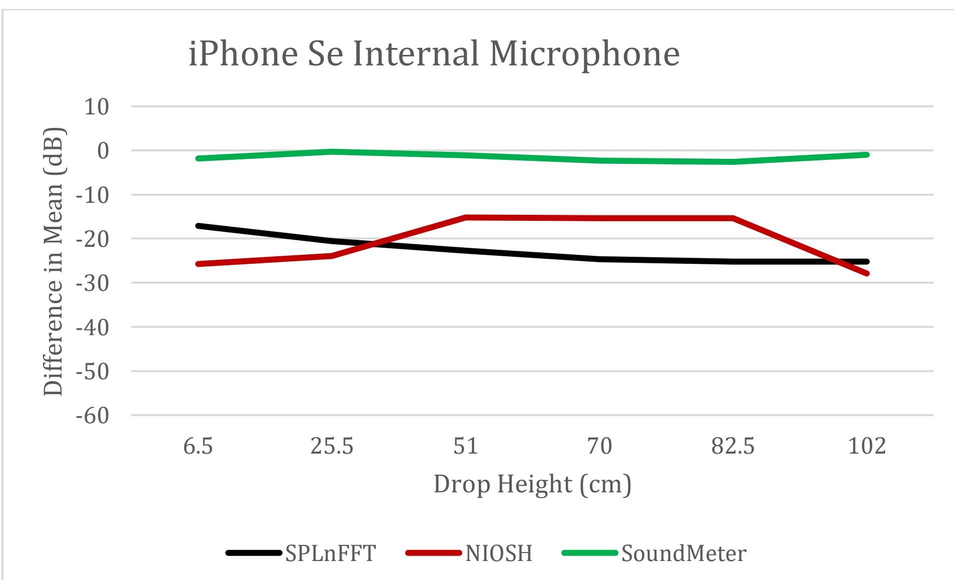

Figure 4. Difference in mean between iPhone Se internal mic and gold standard.

Android Internal Microphone Measurements

Samsung Galaxy Amp II (Amp II) mean measurement differences ranged from 30 to 58 dB with all applications tested over the range of drop heights. The highest sound pressure level value recorded with any app with the Amp II's internal mic at 98 dB SPL. Measurements from the Amp II were consistently 40 to 50 dB below gold standard measurements with all apps in all but the lowest drop height level. Sony Xperia Z3 Compact (Sony Z3) mean peak level measurement differences ranged from 30 to 51 dB with all applications tested over the range of drop heights. The highest value recorded with the Sony Z3's internal mic was 103.7 dB SPL with any app. Android internal microphone measurements are presented in Table 5.

Table 5

Difference in Mean SPL Android Phones Internal Mic and Gold Standard (dB)

		Drop Height Level (cm)					
Phone	App	6.5	25.5	51.0	70.0	82.5	102.0
Amp II	SPL Meter	-30.2	-42.2	-42.1	-42.2	-46.2	-46.7
	decibel Pro	-35.5	-39.9	-43.1	-42.8	-43.7	-44.8
	Noise Meter	-43.7	-41.5	-49.6	-53.4	-53.4	-52.7
Sony Z3	SPL Meter	-29.5	-42.5	-44.7	-42.5	-42.0	-45.7
	Decibel Pro	-40.9	-44.5	-46.9	-49.1	-48.9	-50.9
	Noise Meter	-39.3	-46.2	-46.4	-49.4	-48.3	-50.9

Figure 5 displays difference in mean sound pressure levels between gold standard system and app used in the Amp II internal microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Figure 6 displays difference in mean sound pressure levels between gold standard system and app used with the Sony Z3 internal microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

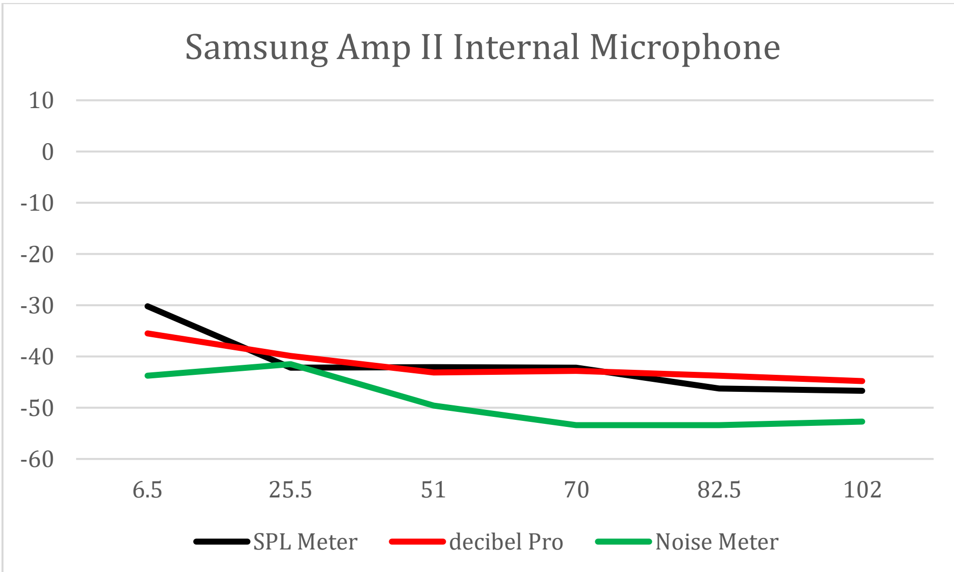

Figure 5. Difference in mean between Samsung Amp II internal mic and gold standard.

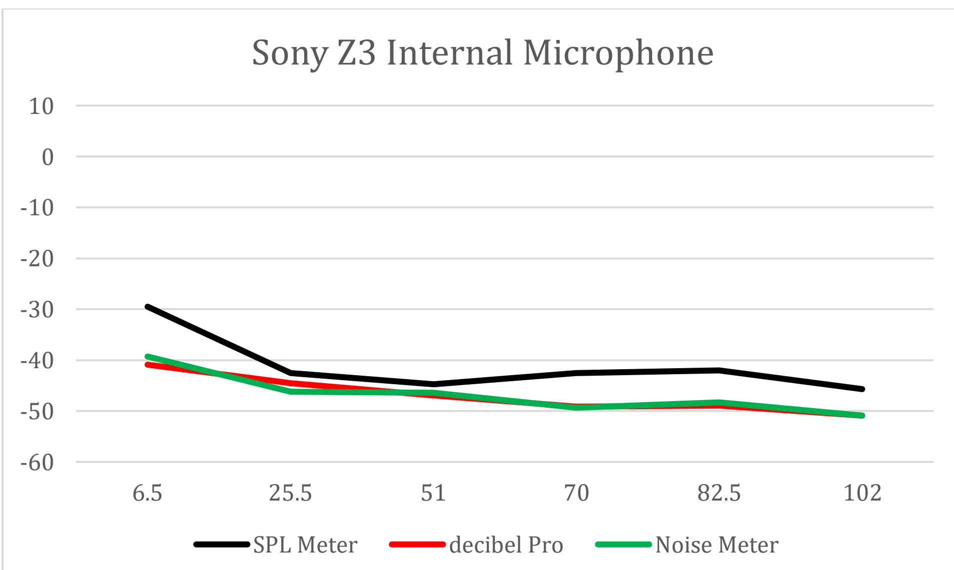

Figure 6. Difference in mean between Sony Xperia Z3 internal mic and gold standard.

External Microphone Performance

The mean sound pressure level differences between smartphone external measurements and gold standard system measurements were compared. Again, measurements collected with iPhones were closer to gold standard values than measurements from Android devices.

iPhone External Microphone Measurements

iPhone external microphone measurements are presented in Table 6. Mean sound pressure level differences ranged from 44.8 dB to less than 1 dB, depending on application and microphone used. The lowest mean sound pressure differences recorded for both the iPhone 6 and iPhone Se with the external microphone were recorded with the SoundMeter app and ranged from 0.6 to 4 dB for the former, and 0.5 to 5.5 dB for the latter. Figure 7 displays difference in mean sound pressure levels between gold standard system and app used in the iPhone 6 with the iMM-6 external microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Figure 8 displays difference in mean sound pressure levels between gold standard system and app used in the iPhone Se with the iMM-6 external microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

Table 6

Difference in Mean SPL iOS Phones External Mic and Gold Standard (dB)

		Drop Height Level (cm)					
Phone	App	6.5	25.5	51.0	70.0	82.5	102.0
iPhone 6	SPLnFFT	-16.7	-19.5	-19.6	-20.6	-21.1	-22.3
	NIOSH	-24.4	-19.0	-25.8	-25.6	-28.7	-26.7
	SoundMeter	3.9	-1.0	-0.6	-2.9	-3.9	-4.8
iPhone Se	SPLnFFT	-29.4	-40.8	-44.8	-44.4	-36.9	-37.4
	NIOSH	-23.8	-21.1	-17.4	-19.2	-25.0	-23.0
	SoundMeter	4.4	4.5	2.2	-0.5	-0.7	-0.5

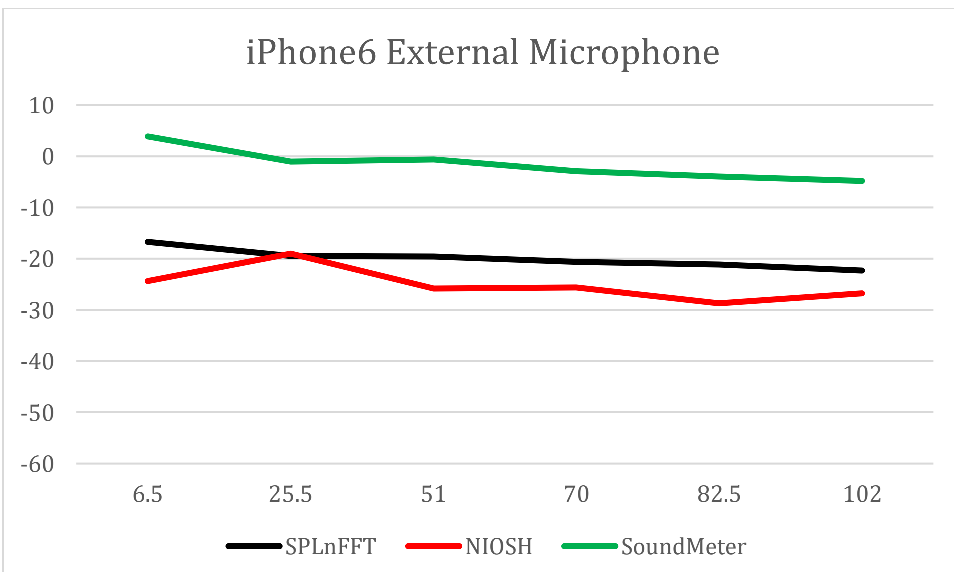

Figure 7. Difference in mean between iPhone 6 external mic and gold standard.

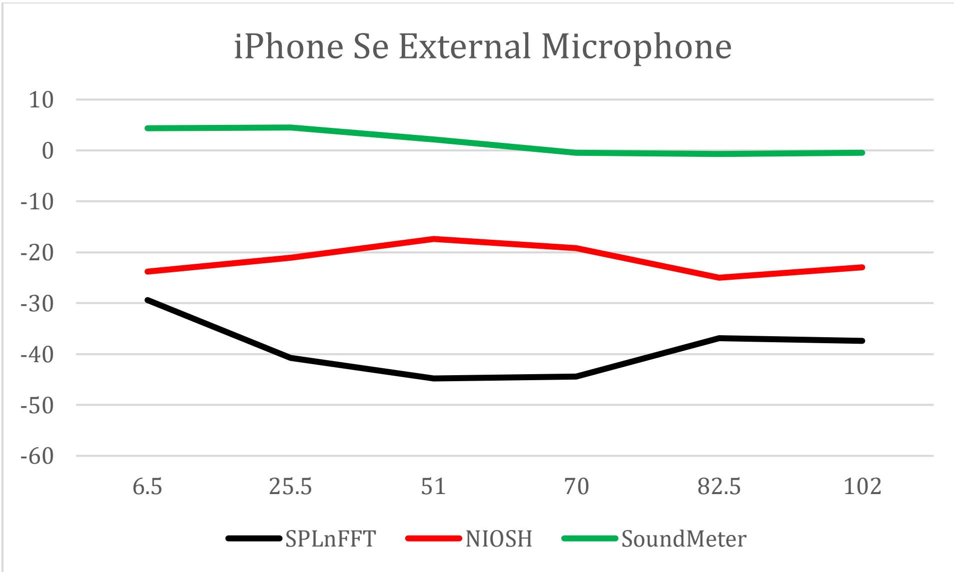

Figure 8. Difference in mean between iPhone Se external mic and gold standard.

Android External Microphone Measurements

AMP II mean peak SPL measurement differences ranged from 42.3 to 58.6 dB with all applications tested over the range of drop heights. The highest value recorded with any app with the AMP II app and the external mic was 88 dB SPL. Sound pressure levels from the AMP II were 42 to 58.6 dB below gold standard measurements with all the apps. Sony Z3 mean sound pressure level differences ranged from 31 to 45 dB for all applications tested over the full range of drop heights. The highest value recorded with the Sony Z3's external mic was 102.2 dB SPL with the SPL Meter app. Figure 9 displays difference in mean sound pressure levels between gold standard system and app used in the Amp II with the iMM-6 external microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Figure 10 displays difference in mean sound pressure levels between gold standard and app used in the Sony Z3 with iMM-6 external microphone at each drop height. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

Table 7

Difference in Mean SPL Android Phones External Mic and Gold Standard (dB)

		Drop Height Level (cm)					
Phone	App	6.5	25.5	51.0	70.0	82.5	102.0
AMP II	SPL Meter	-45.9	-52.4	-52.7	-53.5	-52.8	-52.7
	decibel Pro	-42.3	-48.6	-50.9	-51.3	-52.7	-52.4
	Noise Meter	-47.3	-53.4	-55.4	-58.6	-57.5	-58.1
Sony Z3	SPL Meter	-30.7	-39.2	-39	-46.0	-43.5	-40.9
	Decibel Pro	-34.0	-39.9	-43.4	-44.6	-44.6	-45.7
	Noise Meter	-35.4	-40.3	-43.6	-41.9	-44.6	-45.2

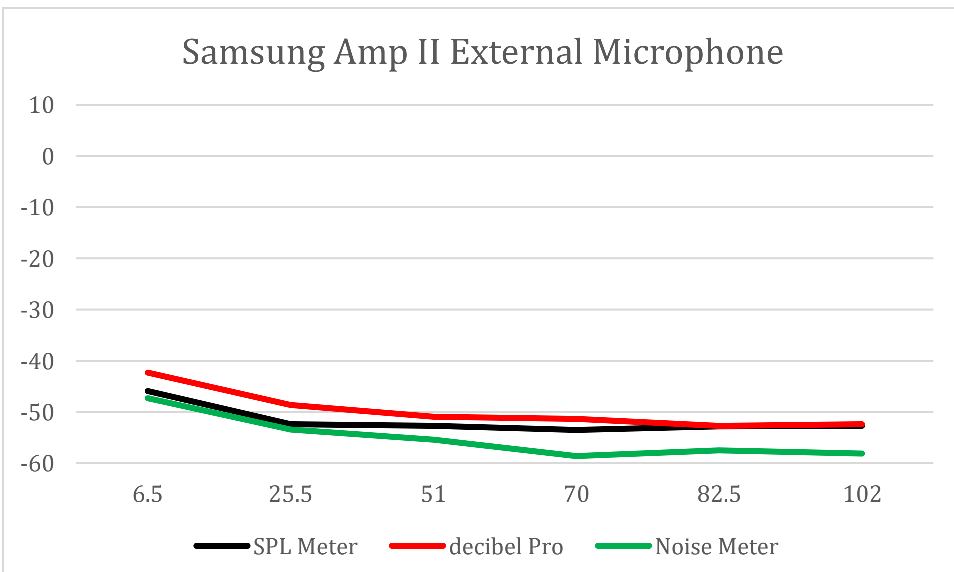

Figure 9. Difference in mean between Samsung Amp II external mic and gold standard.

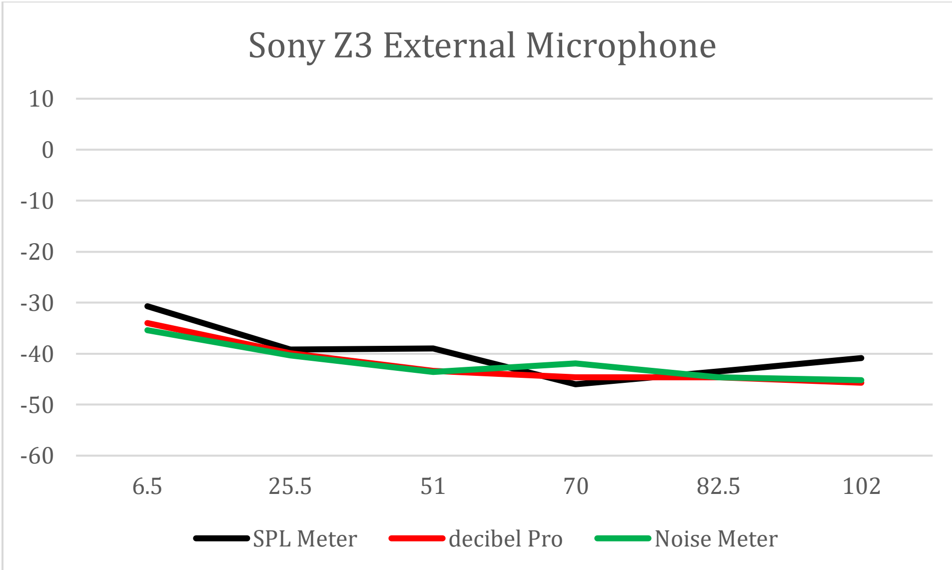

Figure 10. Difference in mean between Sony Xperia Z3 external mic and gold standard.

Internal Versus External Microphone Performance

Improvements in accuracy with the iMM-6 external microphone used with iPhones varied by app and specific phone model. While accuracy was improved using the external microphone with the SPLnFFT app in the iPhone 6, it was reduced with the same app in the iPhone Se. The highest value obtained with the SPLnFFT app was 97 dB SPL with the internal microphone and 117.5 with the external microphone. Accuracy was improved in the iPhone 6 at all levels and at higher levels (above ~138 dB SPL) in the iPhone Se with the SoundMeter app. The external mic had no noticeable effect on accuracy with the NIOSH app in either iPhone. Although mean differences were reduced slightly by the use of the external microphone with the NIOSH app, measurements were consistently 20 to 30 dB below the gold standard system with both internal and external microphones at all levels tested.

iPhone Internal Versus External Microphone

The highest value recorded by the SPLnFFT app was 97 dB SPL with the internal microphone and 117.5 dB SPL with the external mic. Mean sound pressure level differences recorded with the SPLnFFT and SoundMeter apps were generally reduced with the use of the external microphone (Figures 11 and 12). Although mean differences were reduced slightly using the external microphone with the NIOSH app, sound pressure level measurements were consistently 20 to 30 dB below the gold standard system measurements obtained with both internal and external mics at all drop levels tested. The lowest mean sound pressure level difference recorded for the iPhone 6 was with the SoundMeter app and external microphone combination. Figure 11 displays comparison of difference in mean sound pressure levels between gold standard system and application used in the iPhone 6 for internal and external microphones: (A) SPLnFFT, (B) NIOSH, and (C) SoundMeter. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement. Figure 12 displays comparison of difference in mean sound pressure levels between gold standard system and application used in the iPhone Se: (A) SPLnFFT, (B) NIOSH, (C) SoundMeter. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

Table 8

Difference in Mean Peak dB SPL iPhone 6

		Drop Height Level (cm)					
App	Microphone	6.5	25.5	51.0	70.0	82.5	102.0
SPLnFFT	Internal	-32.2	-39.8	-41.5	-42.5	-43.1	-43.1
	iMM-6	-16.7	-19.5	-19.6	-20.6	-21.1	-22.3
NIOSH	Internal	-24.2	-23.6	-32.2	-29.2	-27.5	-24.5
	iMM-6	-24.4	-19.0	-25.8	-25.6	-28.7	-26.7
SoundMeter	Internal	-6.8	-15.6	-17.9	-19.0	-18.4	-19.3
	iMM-6	-3.9	-1.0	-0.6	-2.9	-3.9	-4.8

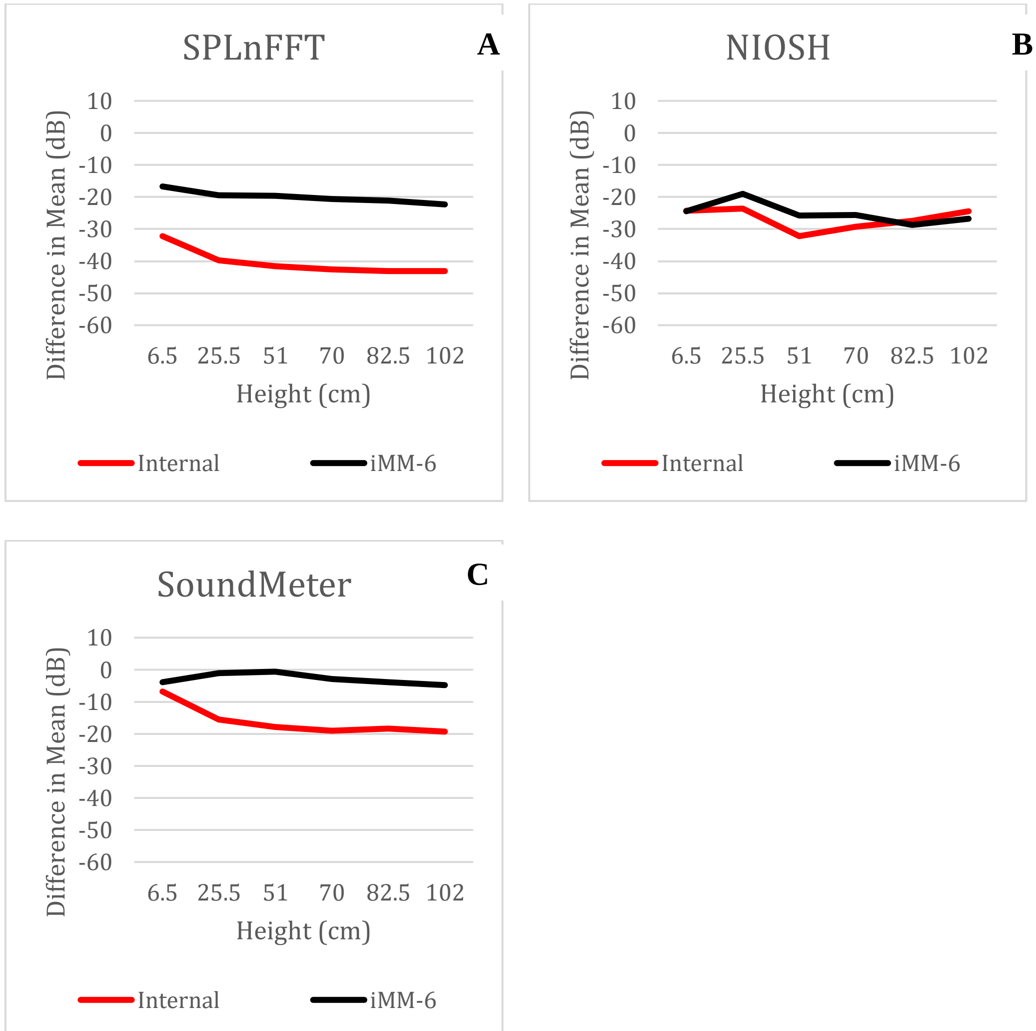

Figure 11. Comparison of internal and external mic performance iPhone 6.

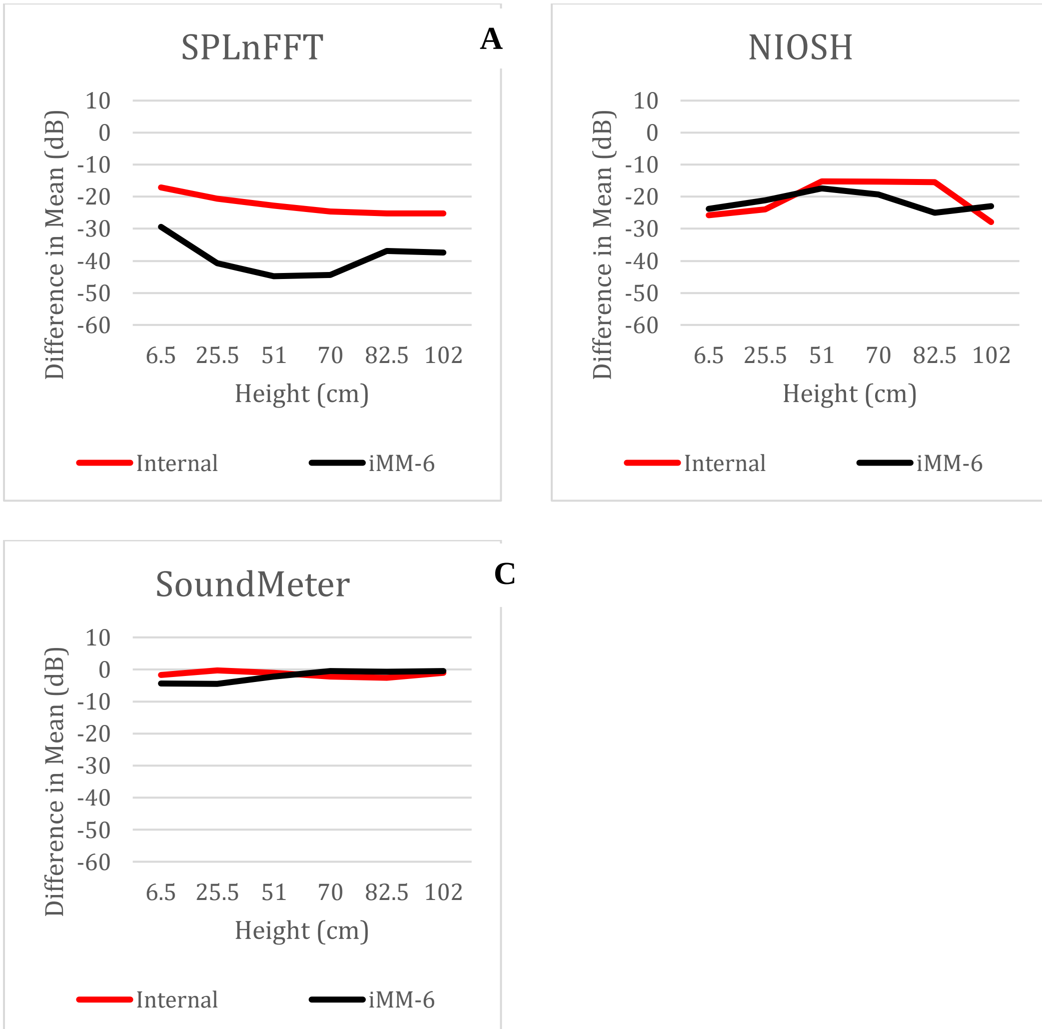

Figure 12. Comparison of internal and external mic performance iPhone Se.

iPhone Se measurements are presented in Table 9. Mean sound pressure level differences were generally 15 to 40 dB, but the iPhone Se measurements were generally more accurate than the iPhone 6 when comparing internal microphones. As previously observed in the iPhone 6, the SPLnFFT app measurements were the most inconsistent with the gold standard system measurements and had the greatest mean differences (17.1 to 44.8 dB). Measurements from the NIOSH app made with the iPhone Se were also similar to the iPhone 6. The SoundMeter app measurements were closer (0.3 to 4.5 dB) to the gold standard system than any other phone/app combination tested. Mean sound pressure level differences were within 3 dB with the internal mic and 4.5 dB with the external iMM-6 mic.

Table 9

Difference in Mean Peak dB SPL iPhone Se

		Drop Height Level (cm)					
App	Microphone	6.5	25.5	51.0	70.0	82.5	102.0
SPLnFFT	Internal	-17.1	-20.6	-22.7	-24.6	-25.2	-25.2
	iMM-6	-29.4	-40.8	-44.8	-44.4	-36.9	-37.4
NIOSH	Internal	-25.8	-23.9	-15.2	-15.3	-15.4	-27.9
	iMM-6	-23.8	-21.1	-17.4	-19.2	-25.0	-23.0
SoundMeter	Internal	-1.8	-0.3	-1.1	-2.3	-2.6	-1.0
	iMM-6	-4.4	-4.5	-2.2	-0.5	-0.7	-0.5

Android Internal Versus External Microphone

Samsung Galaxy Amp II (Amp II) mean sound pressure level measurement differences ranged from 30 to 58 dB with all application microphone combinations tested over the range of drop heights. The highest value recorded with any app with the Amp II's internal mic was 98 dB SPL and 86.9 SPL with the external mic. Mean sound pressure level differences were higher (42.3 to 53.5 dB) with the external mic for all applications and drop heights tested. Measurements from the Amp II were consistently 40 to 50 dB below gold standard sound level pressure measurements with all apps and both microphones in all but the lowest drop heights. Figure 13 displays comparison of difference in mean sound pressure levels between gold standard system and application used in the Amp II: (A) SPL Meter, (B) decibel Pro, and (C) Noise Meter. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

Table 10

Difference in Mean Peak dB SPL Samsung Amp II

App	Microphone	Drop Height Level (cm)					
		6.5	25.5	51.0	70.0	82.5	102.0
SPL Meter	Internal	-30.2	-42.2	-42.1	-42.2	-46.2	-46.7
	iMM-6	-45.9	-52.4	-52.7	-53.5	-52.8	-52.7
decibel Pro	Internal	-35.5	-39.9	-43.1	-42.8	-43.7	-44.8
	iMM-6	-42.3	-48.6	-50.9	-51.3	-52.7	-52.4
Noise Meter	Internal	-43.7	-41.5	-49.6	-53.4	-53.4	-52.7
	iMM-6	-47.3	-53.4	-55.4	-58.6	-57.5	-58.1

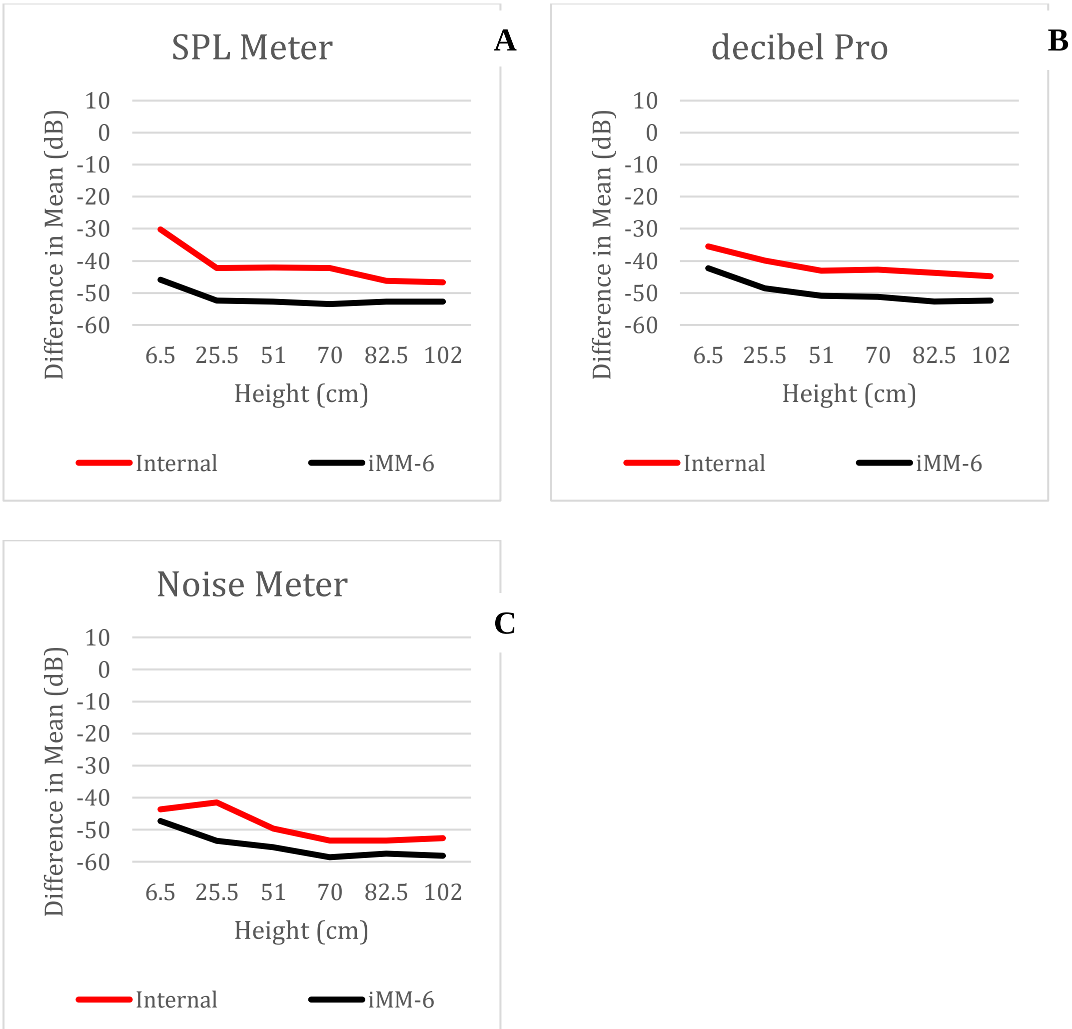

Figure 13. Comparison of internal and external mic performance Samsung Amp II.

Sony Xperia Z3 Compact (Z3) mean sound pressure level measurement differences ranged from 30 to 51 dB with all application/microphone combinations tested over the range of drop heights. The highest value recorded with the Z3's internal mic was 103.7 dB SPL with any app and 102.4 dB SPL with the external mic. Mean differences were similar between the internal and external mic for all applications and drop heights tested. Figure 14 displays comparison of difference in mean sound pressure levels between gold standard system and application used in the Sony Xperia Z3 compact: (A) SPL Meter, (B) decibel Pro, (C) Noise Meter. A mean difference of zero would indicate perfect agreement between the two, and the larger the mean difference, the poorer agreement.

Table 11

Difference in Mean Peak dB SPL Sony Xperia Z3 Compact

		Drop Height Level (cm)					
App	Microphone	6.5	25.5	51.0	70.0	82.5	102.0
SPL Meter	Internal	-29.5	-42.5	-44.7	-42.5	-42.0	-45.7
	iMM-6	-30.7	-39.2	-39.0	-46.0	-43.5	-40.9
decibel Pro	Internal	-40.9	-44.5	-46.9	-49.1	-48.9	-50.9
	iMM-6	-34.0	-39.9	-43.4	-44.6	-44.6	-45.7
Noise Meter	Internal	-39.3	-46.2	-46.4	-49.4	-48.3	-50.9
	iMM-6	-35.4	-40.3	-43.6	-41.9	-44.6	-45.2

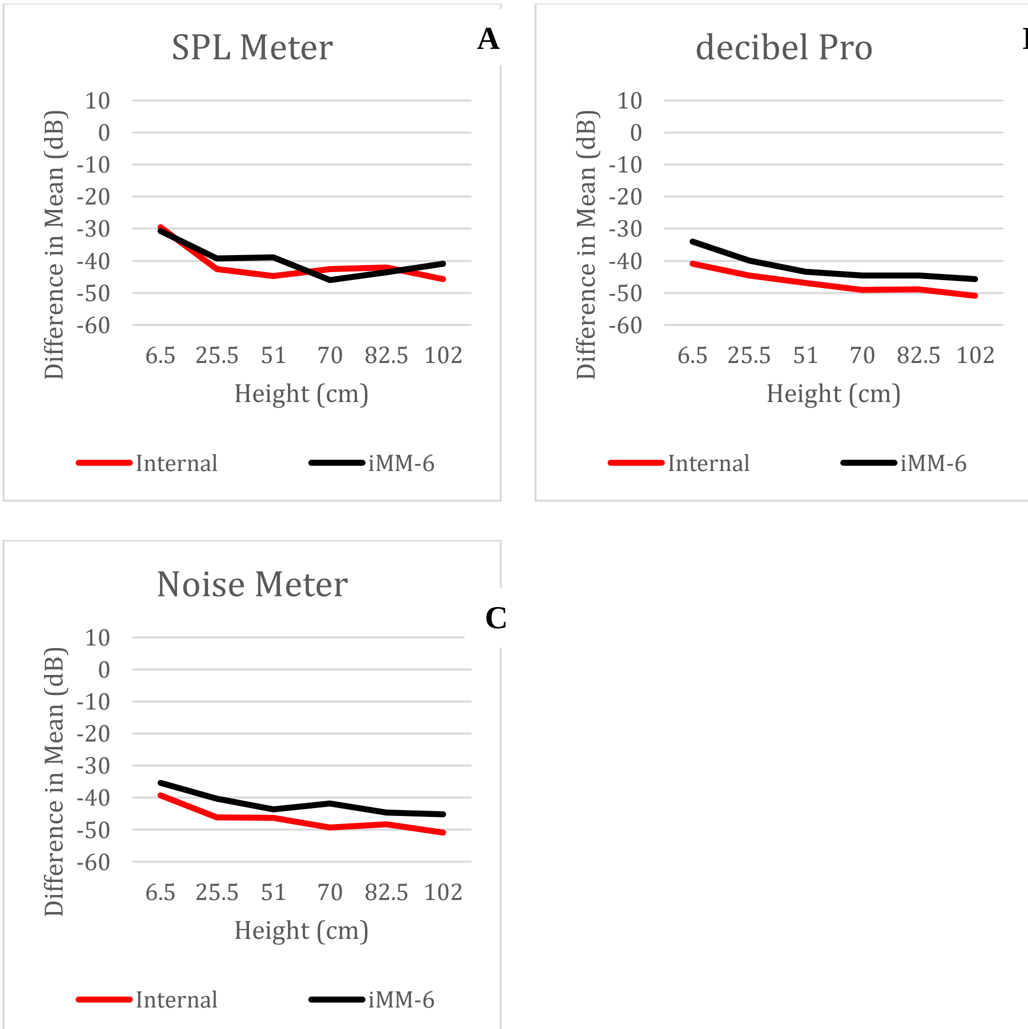

Figure 14. Comparison of internal and external mic performance Sony Xperia Z3.

Summary Observations for Internal Versus External Microphones

The effect of the external microphone with the iPhones was highly variable depending on specific phone and app. Accuracy was generally improved with the iPhone 6 using both the SPLnFFT and SoundMeter apps, but no improvement was noted with the NIOSH app. The internal mic on the iPhone Se actually outperformed the external mic with the SPLnFFT app at all drop height levels.

Simply adding the iMM-6 external microphone did not improve the performance of Android phones. While some smartphone/app combinations exhibited a slight increase in accuracy, others showed no improvement, or performed poorer.

Descriptive Statistics

Difference in Peak SPL for iOS

The differences in peak SPL between iPhones and the gold standard system are presented in Table 12. The 50th percentile values reported by the SPLnFFT app were 29.1 dB below gold standard measurements with the internal microphone and 25.4 dB below with the external microphone. Results from the NIOSH app were 23.2 and 22.8 dB below gold standard results with the internal and external microphones, respectively. The SoundMeter app measurements were 4.8 dB below with the internal microphone, but improved with the external microphone to within 1 dB of the gold standard measurement. Absolute values of mean differences for iOS smartphones are represented in Figure 15.

Table 12

Peak dB SPL Difference Between iOS Phones and Gold Standard

		dB SPL Difference				
App	Microphone	Mean	SD	5th	50th	95th
SPLnFFT	Internal	-31.5	9.6	-43.8	-29.1	-17.3
	iMM-6	-29.1	10.5	-47.6	-25.4	-16.6
NIOSH	Internal	-23.7	7.9	-34.8	-23.2	-23.7
	iMM-6	-23.3	5.0	-34.8	-22.8	-16.3
SoundMeter	Internal	-8.54	8.4	-19.6	-4.8	2.1
	iMM-6	-0.01	3.1	-4.2	-0.6	4.9

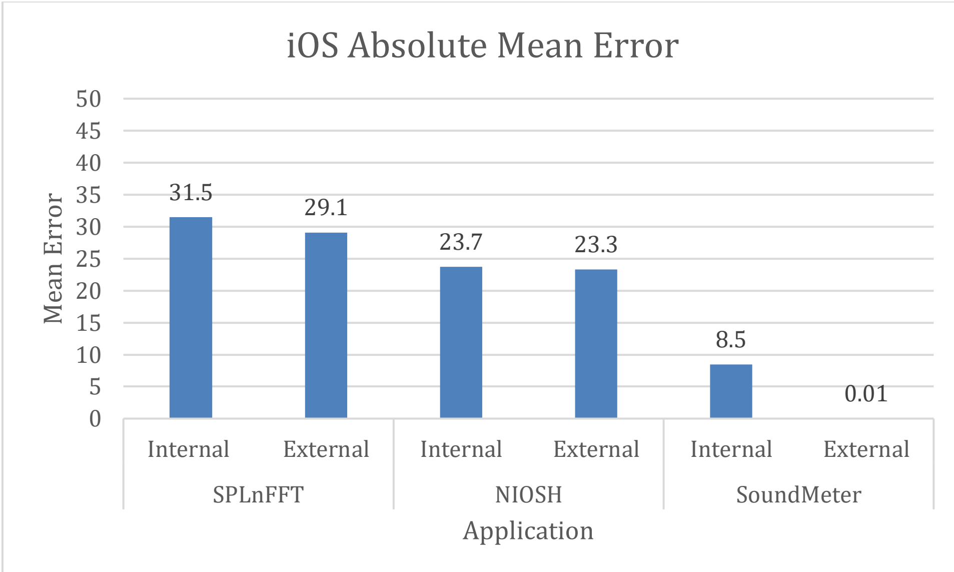

Figure 15. Mean error of iOS phones from gold standard.

Android operating system results are presented in Table 13. The 50th percentile values reported by the SPL Meter app were 42.3 dB below gold standard measurements with the internal microphone and 46.5 dB below with the external microphone. Results from the decibel Pro app were 43.8 and 45.3 dB below gold standard results with the internal and external microphones, respectively. The Noise Meter app measurements were 48.8 dB below with the internal microphone and 47.2 dB below with the external microphone. Similar to other studies (Khan, Murphy, & Zechmann, 2012; Roberts et al., 2016), measurements from the Android phones were less accurate than iOS phones. Absolute values of mean differences for Android smartphones are represented in Figure 16 below.

Table 13

Peak dB SPL Difference Between Android Phones and Gold Standard

		dB SPL Difference				
App	Microphone	Mean	SD	5th	50th	95th
SPL Meter	Internal	-41.3	6.3	-50.2	-42.3	-27.6
	iMM-6	-45.8	7.7	-54.7	-46.5	-27.6
decibel Pro	Internal	-44.2	4.3	-51.2	-43.8	-35.4
	iMM-6	-45.9	5.5	-53.1	-45.3	-34.1
Noise Meter	Internal	-47.9	5.3	-54.9	-48.8	-37.2
	iMM-6	-48.4	7.7	-59.7	-47.2	-34.2

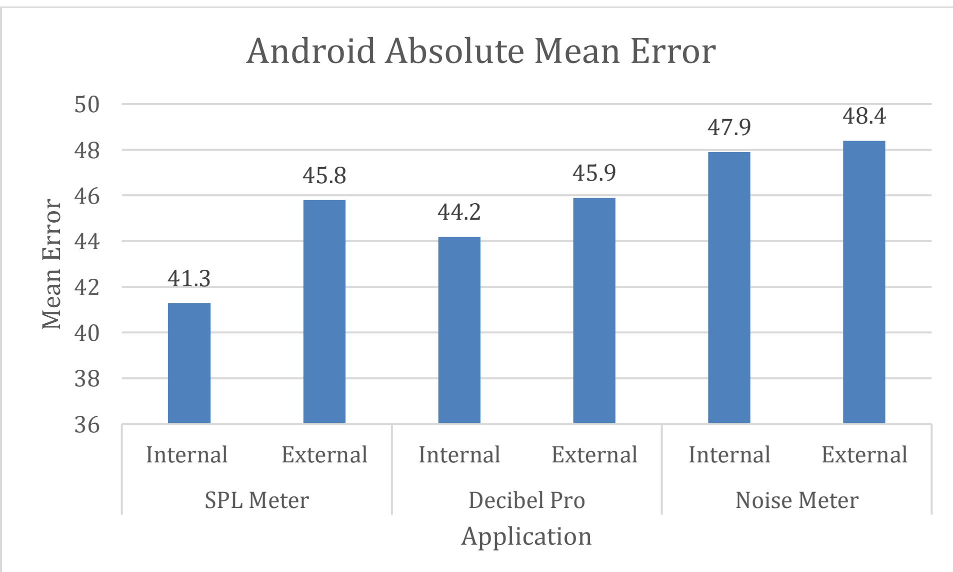

Figure 16. Absolute values of mean differences of Android measurements from gold standard system measurements.

CHAPTER V

DISCUSSION

Experimental Setup Condition Following Testing

At the conclusion of testing, there were no visible dents, scratches, or other imperfections on the steel plate caused by testing. The shotput had lost approximately 35% of the protective paint covering, but exhibited no other deformities such as flat spots, dents, or scratches. The overall system proved to be very robust, and this most likely contributed to reduced variability in recorded readings.

This setup is a valid way to create impact noise in a laboratory setting, but does have some limitations. First, the range of impact noise levels created was rather limited, ranging from 123.1 to 142.7 dB peak SPL. It may be possible to increase this range by rolling the shotput at a shallow angle to better control the impact velocity. Secondly, with the current setup, as the drop height increased, the horizontal distance the shotput travelled before striking the steel plate also increased and changed the actual distance between microphone and sound source. This could be remedied by utilizing a release mechanism that allows the shotput to fall vertically.

Implications for Field Measurements

Impact noise measurement with smartphone apps in the workplace is not widely studied, and it is unknown how common the practice is. With the widespread proliferation of smartphones into contemporary society and the cost of sound level meters, it is reasonable to assume this it is a relatively common occurrence. As demonstrated by earlier studies, certain smartphone/app combinations can be used to measure pink noise (Roberts et al., 2016) and pure tones (Nast et al., 2014) with a degree of accuracy similar to a type II sound level meter.

There are a number of possible causes for the measurement errors observed. In the case of the Android phones, the app developers are tasked with designing an app that must work across a broad range of phone manufacturers who happen to use the Android operating system. The individual smartphone models will have a variety of different hardware (microphones, preamplifiers, etc.) that may interact with the software differently. Another possible limitation for the Android operating system is the low cost of apps relative to iOS apps. Many of these apps are either free or 99 cents, whereas the top performing iOS app in this study cost $19.99.

Smartphone microphones are not necessarily designed to measure high-level impact noise. The specifications and physical properties of a microphone purpose build to measure speech signals in close proximity to the microphone may make it difficult or impossible to accurately measure high-amplitude impact or impulse noise.

Limitations

The sample size of one device per manufacturer model, one external microphone, and six evaluated apps is small. While this study was designed to draw from a broad range of popular smartphones, there is the possibility that one of the devices selected exhibited performance outside of norms for that manufacturer or model.

This study was designed to emulate how an untrained individual may use a smartphone to take readings in field conditions. The values displayed on the screen do not necessarily demonstrate the app's capability to measure impact noise. This point can be best illustrated by the NIOSH app, which has a two-part instantaneous level readout. The main readout is a numerical value, and below it is a digital bar that represents changes in sound amplitude, but does not have a corresponding numerical value associated with it. During some recordings, this bar would rapidly increase to a high level, but the numerical value displayed would be significantly smaller. This may indicate that the app was measuring the impact more accurately than the displayed numerical value. Perhaps the numerical display was using a longer time constant, fast, while the bar used the selected, shorter time constant, impulse.

Future Study

A larger sample size of smartphones, apps, and microphones would be beneficial. A four-way interaction could be used to evaluate the effect of amplitude, smartphone, app, and microphone to determine if measurement errors are the result of amplitude clipping, peak limiting, or some other means.

The experimental design could be further analyzed to determine if the impact noise created in this study is analogous to real-world impact noise in industries such as hammer forging, metal parts stamping, mining, etc. If so, this setup could serve as a small, convenient, repeatable source of impact noise for the study of hearing protective devices or noise mitigation in a laboratory setting.

Summary

This study demonstrated that those wishing to use a smartphone to measure impact noise should consider using only iOS phones, preferably with an external microphone. The only app that approximated the performance of a type II SLM was the

SoundMeter app combined with the iMM-6 external microphone. Even if the user employs this combination, they must be aware that measurements could be wildly inaccurate without proper calibration. Using either iOS smartphone with the SoundMeter app, accurately measuring impact noise up 142 dB SPL is possible if the smartphone is properly calibrated.

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APPENDIX A

OCTAVE SCRIPT CREATED BY DR. DONALD FINAN

Octave Script

Created by Dr. Donald Finan

```
clear all

% Calibration: Initial Calibration File
%--------------------------------------------------------------------------
[filecal inpath] = uigetfile('*.wav','Select INITIAL Calibration File');
cd(inpath);
[yA, fs] = audioread(filecal);
yD = yA-mean(yA); % Demean calibration data file

% Barometric correction factor
dBin = inputdlg('Input dB Correction factor');
dBcf = str2num(dBin{1,1});
dBcf = 114 + dBcf;
dBcfPa = 0.00002*(10^(dBcf/20)); % Correction factor for actual cal value (114dB
nominal) in Pa

% RMS of INITIAL calibration signal
yRMS = sqrt(meansq(yD)); % RMS value of uncalibrated (quantization units) y data

% Calibration check: Initial calibration file
m = dBcfPa/yRMS;  % Slope for calibration regression formula below
yDc = m*yD; % Calibrated data (Pa) = m*y + b, where b = 0 (data has been demeaned)
dBCal = 20 * log10(sqrt(meansq(yDc))/0.00002); % This should equal the inputted dB
Correction Factor in dB

disp('')
disp(['INITIAL Calibration File ' filecal ' : Calibration Factor = ' num2str(dBCal)])
disp('')

hc1 = figure;
plot(yDc);
ylabel('Amplitude Pa');
title(['INITIAL Calibration Signal, Barometric Correction Factor = ' dBin ' dB']);

hc1a = figure;
plot(yDc(1:5000));
title(['INITIAL Calibration Signal - closeup, Barometric Correction Factor = ' dBin '
dB']);

%--------------------------------------------------------------------------
% Calibration: FINAL Calibration File
```

```
%---------------------------------------------------------------------------
[filecal2 inpath2] = uigetfile('*.wav','Select FINAL Calibration File');
cd(inpath2);
[yA2, fs2] = audioread(filecal2);
yD2 = yA2-mean(yA2); % Demean calibration data file

% RMS of FINAL calibration signal
yRMS2 = sqrt(meansq(yD2)); % RMS value of uncalibrated (quantization units) y data

% Calibration check: FINAL calibration file
m2 = dBcfPa/yRMS2;  % Slope for calibration regression formula below
yDc2 = m*yD2; % Calibrated data (Pa) = m*y + b, where b = 0 (data has been
demeaned)
dBCal2 = 20 * log10(sqrt(meansq(yDc2))/0.00002);  % This should equal the inputted
dB Correction Factor in dB

disp(['FINAL Calibration File ' filecal2 ' : Calibration Factor = ' num2str(dBCal2)])

hc2 = figure;
plot(yDc2);
ylabel('Amplitude Pa');
title(['FINAL Calibration Signal, Barometric Correction Factor = ' dBin ' dB']);

hc2a = figure;
plot(yDc2(1:5000));
title(['FINAL Calibration Signal - closeup, Barometric Correction Factor = ' dBin ' dB']);

%---------------------------------------------------------------------------

goagain = 1;
count = 1;
while goagain == 1
  % Open data file
  disp('')
  filein = uigetfile('*.wav','Select Data File for analysis');
  [y, fs] = audioread(filein);
  dwell = 1/fs;
  x = [0:(size(y)-1)]*dwell;
  y = y-mean(y); % Demean data file
  yC = m*y;  % Calibrate data file

  PeakdB(count) = 20 * log10(max(abs(yC))/0.00002);  % Peak dB of calibrated data

  disp('')
  disp(['File: ' filein]);
  disp(['Peak dB SPL: ' num2str(PeakdB(count))]);
```

```
  OutName(count) = {filein};
  %OutData.Data(count) = PeakdB;

  whpeak = find(abs(yC)==max(abs(yC)));
  xs = x-(x(whpeak(1)));
  xlo = whpeak(1)-20000; % Range for x-axis for plot
  if (length(y) > (whpeak(1)+150000))
    xhi = whpeak(1)+150000;
  else
    xhi = length(y)
  endif

  h1 = figure;
  plot(xs(xlo:xhi),yC(xlo:xhi))
  xlabel('Sec');
  ylabel('Amplitude Pa')
  title(['Peak Amplitude: ' num2str(PeakdB(count)) ' dB at time zero']);
  axis([xs(xlo),xs(xhi)])

  h2 = figure;
  xlo2 = whpeak(1)-10000; % Range for x-axis for plot
  xhi2 = whpeak(1)+10000;
  plot(xs(xlo2:xhi2),abs(yC(xlo2:xhi2)))
  xlabel('Sec');
  ylabel('Amplitude Pa')
  title(['Peak Amplitude: ' num2str(PeakdB(count)) ' dB at time zero']);
  axis([xs(xlo2),xs(xhi2),0,max(abs(yC)+0.1*max(abs(yC)))])

  count = count + 1;

  but1 = questdlg('Open another data file in set (same calibration file)','Go
Again','Yes','No','Yes');
  if (strcmp(but1,'No'))
    goagain = 0;
  endif
  close(h1)
  close(h2)
endwhile

%but2 = questdlg('Save data to Text file?','Save?','Yes','No','Yes');
%if (strcmp(but2,'Yes'))
%  save_precision(6);
%  fileout = [filecal(1:(length(filecal)-4)) '.txt'];
%  save('-ascii', [fileout], 'PeakdB')
%endif
```