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# Improving the Assessment of Noise Exposure and Warning Signal Audibility on Construction Sites

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## Abstract

Fifty-one percent of construction workers are exposed to hazardous noise that can cause permanent noise-induced hearing loss (NIHL), and 52% do not wear a hearing protection device (HPD). Hearing loss could be reduced more effectively with more accurate measurements of noise exposure. The common occupational noise exposure measurement devices are single-channel noise dosimeters worn on a worker's shoulder, which are not advanced enough to capture and analyze complex sounds that pose threats to workers' hearing. This research proposes a more accurate noise exposure and audibility assessment by using binaural (two-ear) measurements, paving the way for more effective noise characterization and hearing loss prevention in loud workplaces, as well as helping workers identify the source of warning signals. The difference between these two measures would significantly affect interpretations of hearing loss risk (dose) calculations. This project's results showed clinically significant differences (>3 dB) between the auditory risk assessment using current state-of-the art and proposed binaural measurements. A preliminary acoustic perception study was conducted in a laboratory setting using human participants and binaural measurements of the warning signal and noise of the construction equipment. It was found that localization of the audible warning signals could not be identified. The findings from this project are crucial for highlighting the importance of binaural measurements and, more generally, of accurate assessment of noise exposure and auditory warning signal perception of the workers on a construction site.

## Key Findings

- The study, by testing binaural (two-ear measurements), exposed drawbacks of the standard monaural noise exposure measurement and analysis method of single-channel dosimeter and sound level meter.
- The study quantified sound impulsiveness/hazardousness with a binaural loudness metric, which is similar to human hearing, a measurement that is not possible with traditional sound pressure level (SPL) metrics. (Results, Part I)
- There were significant differences in traditional monaural and binaural assessment of noise exposure on a construction site, with the binaural measurements always higher than those from the single-channel dosimeter measurements. (Results, Part II A)
- Binaural assessment, which better reflects noise exposure on a construction site, allowed for identification of a more noise-exposed ear and quantification of asymmetry of noise exposure (i.e., as a percentage of the total number of measurements with higher SPL and/or loudness, from each ear, or a number of impulsive events and their acoustic characteristics for each ear). (Results, Part II B)
- A preliminary acoustic perception study, conducted using the recorded warning signals from the operating construction equipment (played over headphones in an acoustic perception lab with human participants), found that the localization of the audible warning signals could not be identified. (Results Part III)
- The study created a database of approximately 1500 noise events commonly encountered on a construction site from the daily noise exposure recordings and is available upon request from PIs for future noise exposure metric development and construction noise assessment research.

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## Introduction

NIOSH and the National Hearing Conservation Association identified construction workers as an ‘‘underserved’’ population, with 51% of construction workers exposed to hazardous noise (Kerns et al, 2018), and 25% of noise-exposed construction workers developing a hearing loss that negatively impacts their day-to-day activities and communication (Masterson et al, 2015). Hearing loss is correlated with higher risk of depression, social isolation, cognitive decline, and poor educational outcomes (Lawrence et al., 2020). Accordingly, it is crucial to accurately measure and analyze the noise exposure at construction sites.

Several previous studies have revealed common types of noise monitoring on construction sites (Seixas et al, 2012; Fernández et al, 2009; Suter, 2002; Seixas et al, 2001; Mahdi et al, 2020; Fedorko et al, 2019; Hong et al, 2015). Another set of studies analyzed construction workers’ on-site noise exposure using personal noise dosimeters and sound level meters (traditional noise exposure measurement devices) through different methodologies:

(i) Task-Based Measurement (TBM), a method in which construction tasks are measured (e.g. excavation, demolition, construction framing, earthwork) (Reeb-Whitaker et al, 2004);

(ii) Job Based Measurement (JBM), a method in which complicated work patterns are split into task categories (Legris and Poulin, 1998; Li et al, 2016; Fernández et al, 2009; and

(iii) Full-shift Measurement (FSM), a method in which continuous sound pressure level is measured over a working day (Arezes et al, 2012; Dabirian et al, 2020).

These studies documented the daily construction worker noise exposure, or a particular hazardously noisy task as is recommended by OSHA (29 CFR 1910.95).

Hearing loss can be reduced with accurate assessment of noise exposure. The use of the traditional devices (dosimeters and sound level meters) in the aforementioned methodologies relies on single-channel measurements. Such measurements cannot be used to assess the realistic human binaural perception of sounds, especially for asymmetrical sound exposure and localization of sounds, simply because they do not accommodate situations where sound signals differ between the two ears. Although traditional noise assessment methods make a tremendous contribution in controlling and mitigating the occupational noise risks, they fail to provide comprehensive assessment of the soundscape on a construction site. This shortcoming may potentially increase the risks of excessive noise exposure and insufficient audibility of warning signals at sites. Accurate characterization of the hazardousness of noise as well as localization of important sounds are directly linked to the binaural (two-ear) nature of human hearing. To address the aforementioned research gap, this study used binaural (two-ear) measurements with microphones at the ears’ locations for accurate evaluation of the acoustic signal perception by workers on a construction site. No published studies are available on the binaural assessment of the acoustic environment on a construction site.

The most recent studies of in-ear noise dosimetry use miniature microphones, placed deep inside the ear canal, to monitor daily noise exposure levels (Rabinowitz et al, 2013; Bonnet et al, 2020; Hugues et al, 2018). While these measurements are interesting, they are used primarily in experimental research rather than everyday worker monitoring. Additionally, there is currently no standard method to combine data from the two ears (obtained using this measurement method) that would form a single metric to indicate the worker's risk of noise-induced hearing loss (NIHL). Therefore, this project conducted data analysis of the binaural measurements based on the most recently developed loudness calculation algorithm (ISO 532-2, 2017) that can accommodate situations where the signals differ at the two ears, as is typically the case in real listening situations such as a construction site. Ultimately, and conveniently, the ISO 532-2 loudness algorithm can provide an estimate of the binaural loudness as a single value. As such, the binaural loudness metric is a potential alternative for improving the accuracy of noise exposure assessment, as proposed in this study. Loudness-based assessment of noise exposure based on binaural measurements can potentially reveal significant differences between hazardousness of sounds. A louder impulsive sound is known to be more hazardous than a steady-state sound, perceived as less loud, may both have the same measured sound pressure level (SPL) and calculated SPL-based noise dosage. Impulsiveness of the noise signals, and potentially auditory risk due to impulsiveness, can potentially be quantified by the binaural loudness calculation. This was investigated in the analysis of the binaural noise data collected from the construction sites. Therefore, the proposed noise exposure quantification method was based on advanced (binaural) measurement of complex physical acoustical stimuli, and standardized binaural psychoacoustic/loudness metric, in contrast to the traditional method based solely on sound pressure level (SPL), which may not capture any differences in hearing loss risk.

The results of the study directly support NIOSH's National Occupational Research Agenda (NORA) Construction Strategic Goal #6—to reduce occupational hearing loss in construction through a multifaceted research and outreach effort. Furthermore, this research aligns with CPWR's special emphasis area to reach high-risk sectors such as small employers, vulnerable workers, and residential and light commercial construction. The study participants were from this industry sector and the results provide awareness of the importance of hearing conservation, signal audibility, and safety in the high-risk sector workplaces.

The proposed findings of this research have several practical applications for the workers and their employers. First, the proposed technique can provide a much more reliable approach for measuring the sound exposure, which can lead to a more efficient safety strategy for mitigating risk by reducing exposure time or using more effective personal protective equipment (PPE). Second, using the proposed approach, a database of sound exposure for different construction activities can be developed to enable pairwise comparison and reassigning at-risk workers. Finally, companies that are developing construction equipment and tools can benefit from the results of the study by obtaining a more accurate estimate of sound generated from their products.

## Importance of Binaural Measurements and Accurate Acoustic Assessment

Accurate acoustic measures are important for two reasons: hearing loss and safety. This section will highlight the importance of binaural measurements and analysis, specifically from the context of accurate assessment of noise exposure and auditory warning signal perception of the workers on a construction site.

Existing acoustic evaluation methods used by OSHA (i.e., dosimeter and personal sound meters) do not accommodate situations where sound signals differ across the two ears. Speech communication in a noisy environment depends strongly on binaural processing (Genuit, 2004).

This processing supports directional hearing and binaural release from masking (Bronkhorst and Plomp, 1988; Moore, 2012). In addition, the outer ear acts as a directional filter that can change the sound pressure level at the eardrum by +15 to –30 dB, depending on the frequency and direction of sound incidence (Blauert, 1997), and this can introduce strong SPL differences between the ears.

A sound field is distorted by the presence of a listener, through sound reflection, absorption, and diffraction. The perceived sound is also a function of the shape of the human body, particularly the upper body (torso, shoulders and head). Dosimeters and sound level meters do not account for the effects of the presence of a human listener on the sound field. The microphone of the dosimeter is typically located on the shoulder and sound level meters are typically placed at a convenient location on the construction site, as close as possible to the sound receptors (construction workers). However, binaural measurements are essential for accurately characterizing the audibility and localization of warning signals and speech intelligibility on a site. Binaural measurements are particularly important because of the hazards on a construction site, warnings for which depend on the audibility and localization of warning signals and speech intelligibility. The audibility of the sounds, especially from alarm/auditory warning signals, and voice/speech signals containing critical safety/emergency or work-related information, plays a critical factor in the decision to wear hearing protection devices (HPDs) on site. Therefore, this study focused on binaural measurements to accurately evaluate the worker noise exposure and warning signal audibility on a construction site. This was performed with a binaural headset with a portable data acquisition system, allowing for mobile measurements that accurately capture sound as perceived by the construction workers throughout the day.

Improved measurement accuracy of binaural recordings offers a playback capability with a unique impression of standing in the original sound field. As such, binaural recordings are also suitable for sound simulations in a laboratory setting, hearing protection modelling and assessment, and explorative studies on the noise exposure assessment on a construction site, with listening tests and human test subjects.

The following three major characteristics of acoustic soundscape on the construction site were captured by this project's binaural measurements:

***Time-varying characteristics***

Time-varying characteristics of sound have an impact on the perception of impulsive and broadband noise, both commonly encountered on a construction site, and affecting the aforementioned parameters (audibility, localization, and hearing loss). For example, impulsive and broadband noise have different loudness characteristics (expressed in sones) even when characterized by the same SPL (expressed in dB). Traditional dosimeters and sound level meters are unable to accurately capture the effects of impulsive noise on a construction site. In order to fully evaluate the effect of impulsive noise on the auditory system, specific parameters should be considered such as peak pressure, durations, rise time, energy, spectral content, number and mixture of impulses, and time between impulses (Kardous et al, 2005). Current dosimeters do not provide any of these measurement parameters other than peak pressure – the range and accuracy of peak pressure measurements are not adequate, because of the low sampling frequency of the dosimeter. In contrast, adequately sampled binaural measurements obtain all of this information.

***Asymmetric noise exposure***

Asymmetric noise exposure is also common in construction jobs and is most often attributed to the "head shadowing" effect (Berg et al, 2014), which occurs when one ear is shielded from the noise. The result may be asymmetric hearing loss. This is a common benefit claim for noise-induced hearing loss cases and is often attributed to occupational noise exposure, even if the phenomenon is often unexplained (Dobie, 2014). Binaural measurements and analysis would contribute to the prevention of asymmetrical hearing loss by providing a more accurate acoustic assessment of the construction work environment.

***Sound (warning signal) localization***

Sound localization—in particular, of warning signals—on a construction site is another important acoustic phenomenon that requires binaural assessment. Suter (2002) indicated that both hearing protection devices (HPDs) and hearing loss degrade the ability to localize the warning and speech on a construction site.

## Objectives

The objective of this research is to develop a more accurate acoustic measurement and assessment of construction sites, with emphasis on comparing traditional methods (i.e., monaural and SPL-based assessment) to a novel method (i.e., binaural and loudness-based assessment), using the measurements of noise exposure and warning signal audibility. Specifically, the study:

- Tested the viability of using sound recording similar to human hearing on a construction site for noise exposure assessment: Binaural (two-ear) measurements
- Analyzed perception of construction noise similar to human hearing: Binaural psychoacoustic/loudness-based metric
- Exposed significant differences in traditional monaural and binaural assessment of noise exposure on a construction site
- Assessed noise exposure differences across ears on a construction site: asymmetric noise exposure
- Performed preliminary acoustic perception assessment of warning signal localization.

## Methods

***Measurement Methods***

The Full-shift Measurement (FSM) methodology utilized over the course of several days of measurements on a construction site allows for a comprehensive acoustic assessment. The FSM relies on piecewise analysis of the recorded sound signals, where the analyzed "pieces" or selected time intervals of the recorded signals would be associated with particular tasks of jobs, per Task-Based Measurement (TBM) and Job-Based Measurement (JBM) methodologies. The analysis can also be performed over a selected time interval (every hour, every few hours or minutes). To the best of our knowledge, such measurements and the associated analyses are not available in the published literature of construction noise assessments. The FSM over the course of several days offers a comprehensive acoustic assessment. Therefore, it is the selected measurement methodology in this proposed study.

The data collection process was performed at a construction site in Detroit (**Figures 1** and **2**). Three workers/volunteers participated on each of the three days, using both traditional (dosimeter wearable on the shoulder) and binaural (two-ear headset) sound measuring devices. Three sets of dosimeters and SQobold binaural data acquisition (DAQ) system were rented from HBK and HEAD Acoustics Inc., respectively. The sound level meter (SLM) measurements were obtained at the exterior of the building, as close as possible to the building and the workers' location. Its location, however, had to be far enough to prevent any interference with the construction activities. Approximately 960 gigabytes of data from all the equipment (dosimeters, SQobold binaural headset, and the SLM) was recorded over the course of three days.

The data was then organized with a detailed file naming convention, and backed up on an external hard drive, a Lawrence Technological University (LTU) network shared drive, and a research laptop dedicated to the project. The worker activities were observed and the comments from the workers obtained at the end of each day regarding their perception of the levels and loudness of noise experienced throughout the day. **Figure 1** illustrates the location of the wearable devices, including different positions of the SQobold DAQ system carried around the waist in a pouch ("fanny pack") during the workday. The most convenient location for the pouch was determined by the worker/volunteer. The wire connecting the headset to the DAQ system was covered by the workers' clothes and not exposed to the work environment. Depending on the handedness of the worker, the dosimeter was placed on the shoulder of the side of the working hand, presumably closer to the noise sources throughout the day.

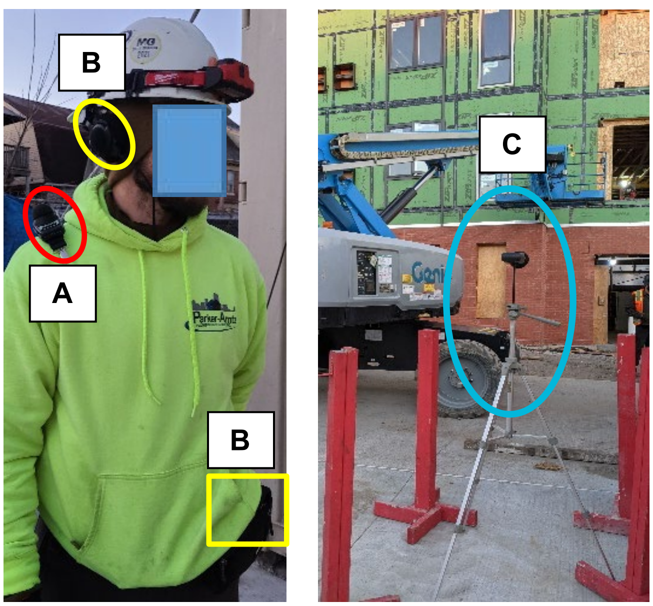


**Figure 1:** Noise exposure measurement setup, with dosimeter (A: red), SQobold binaural headset and DAQ system (B: yellow), and sound level meter (C: blue)


**Figure 2:** Audibility of warning signals, measurement setup with siren sound emission adjustment (E: bottom/green), and SQobold binaural measurement around the equipment (D: top/yellow)

Prior to the measurements, work analysis with job and task information planned throughout the day was obtained from the volunteers. On the first two measurement days, the volunteers were two carpenters and a plumber. On the third day, the volunteers were three carpenters. Next, time frames were obtained from the binaural recordings based on the types of activities throughout the day. Those time frames were later analyzed using the sound pressure level (dB and dBA) and loudness (sone) metrics, as specified in the project proposal. The warning signal measurements (**Figure 2**) were also obtained at three locations surrounding the equipment. The warning signal and operating equipment noise signals could not be separately measured, due to the nature of the equipment design (the warning signals could not be activated without the equipment operating and generating noise).

**Figure 3** illustrates a preliminary acoustic perception evaluation that was conducted at LTU Phono lab, with seven human participants, with warning signal mixed in with the noise to evaluate warning signal audibility and localization. The participants were normal-hearing individuals, at least 19 years of age, and were recruited from the general LTU population. The measurements of warning signal and running equipment (measured as presented in Figure 2) noise were played over the headphones (**Figure 3**). The participants were simply asked to verbally indicate to the research personnel: 1) whether or not they were able to hear particular sounds (warning signals and speech), and 2) whether or not they were able to determine the direction of sound (localization).

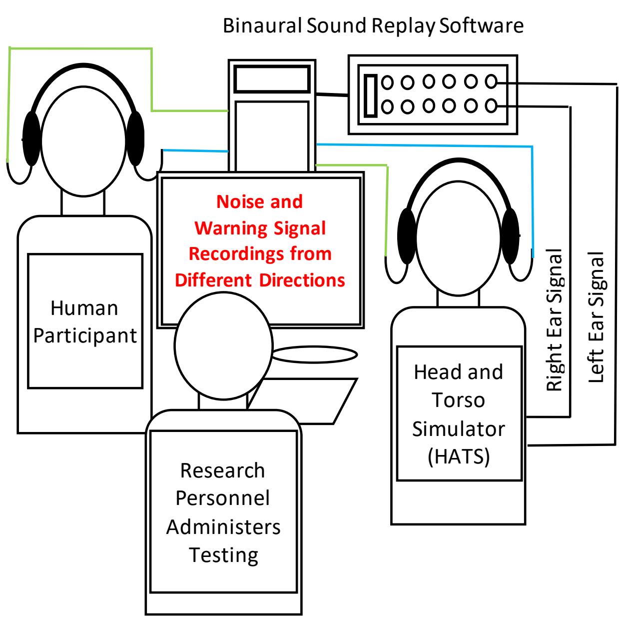


**Figure 3:** The acoustic perception evaluation of warning signal audibility and localization, conducted in the LTU Phono Lab, using the recorded noise and warning signals shown in Figure 2.

***Analysis Methods***

There were three parts to the analysis.

**Part I** – The analysis was based on evaluating whether the traditional SPL-based and loudness-based assessment can reveal differences in impulsiveness of sounds. A louder impulsive sound is known to be more dangerous than a steady-state sound, perceived as less loud, may both have the same SPL/SPL-based noise dosage.

**Part II** – This part tested a working hypothesis that binaural measurements and analysis can reveal:

A) clinically significant differences (>3 dB) between traditional SPL-based single-channel dosimeter noise exposure assessment

B) asymmetrical noise exposure (≥ 1 dB between left and right ear based on the fact that 1 dB would be a perceptible difference in sound).

**Part III** determined whether the localization of the recorded warning signal in noise is possible using acoustic perception evaluation.

### Procedure for Analysis: SPL and Loudness Calculations (Parts I and II)

An example setup for both **SPL** and **loudness analysis**, performed for each time frame, using BK Connect software, is shown in **Figure 4 (left and right, respectively)**. The SPL calculation overview is shown in **Figure 5**. The SPL calculation utilizes the root mean square (RMS) value of the sound pressure measurements ($p$), over the selected time frame, associated with a job, task, shift, or specific time duration of a noise event of interest. The reference pressure, $p_{ref}$ is 0.00002 Pa. The exposure level calculations, based on SPL assessment (**Figure 5**), utilized the methods described in ISO 9612. The binaural loudness calculations overview, based on the ISO 532-2 algorithm, is illustrated in **Figure 6**.

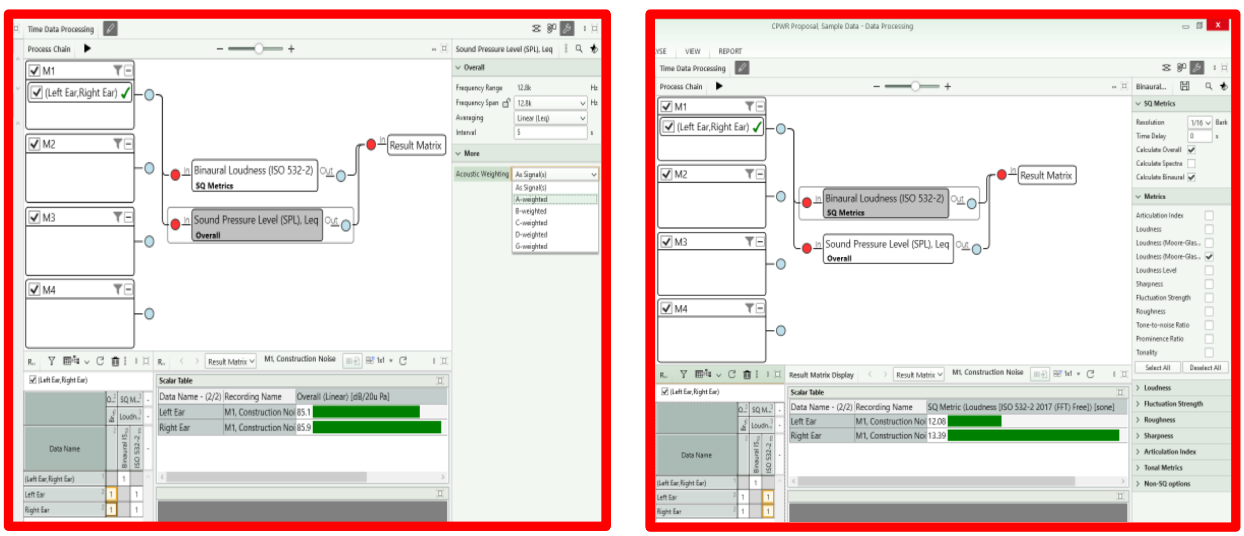


**Figure 4:** BK Connect software analysis interface showing example SPL (left) and binaural loudness (right) analysis, data processing parameters and the results, as explained in Figure 5 and Figure 6, respectively.

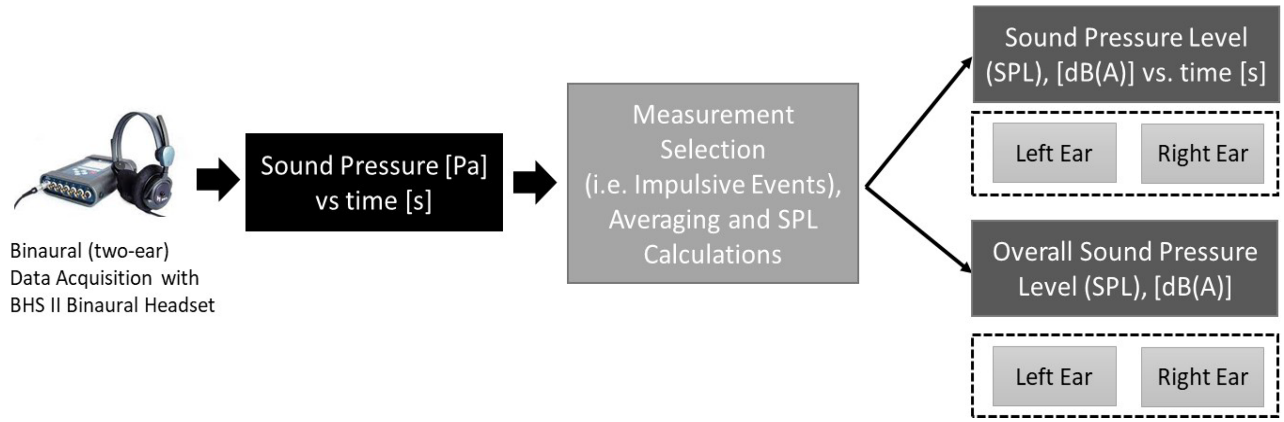


**Figure 5:** SPL analysis overview for each selected measurement time frame (as a function of time, and overall). See Figure 4 (left) for BK Connect software setup for this calculation.

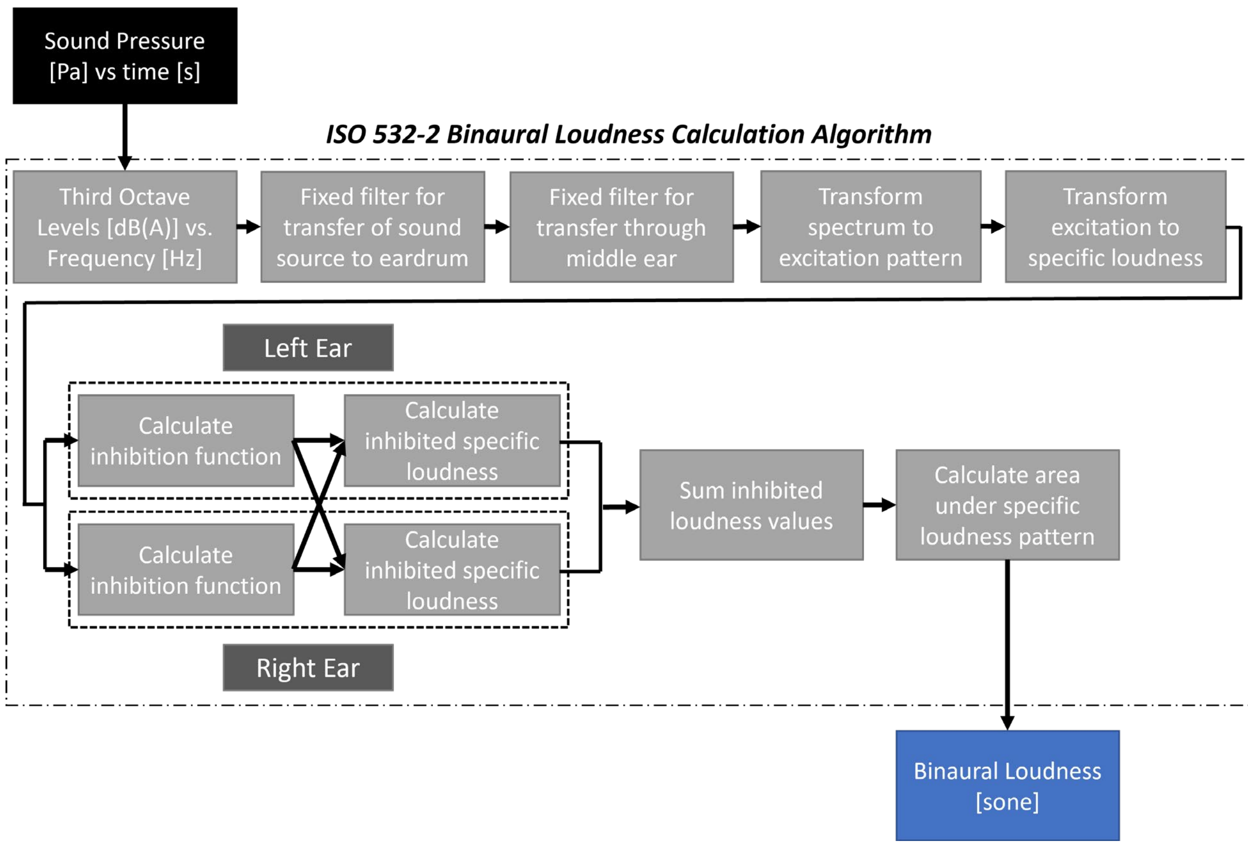


**Figure 6:** The ISO 532-2 algorithm for binaural loudness (BL) calculations. See Figure 4 (right) for BK Connect software setup for this calculation.

### Procedure for Localization Evaluation (Part III)

The participants of the acoustic perception evaluation (Figure 3) were asked to indicate verbally to the research personnel whether they were able to hear particular sounds (warning signals and speech), and whether they were able to determine the direction of sound (localization).

It should be noted that, due to the nature of heavy construction equipment, warning signal measurements used for the acoustic perception evaluation, could not be obtained separately from the background noise while the equipment was operating, as originally planned. Therefore, in this project, a comprehensive warning signal audibility and localization assessment could not be conducted. Such assessment would require advanced noise filtering algorithms to separate warning signal and noise measurements and to then adjust the signal-to-noise ratio (SNR) to ultimately determine warning signal audibility threshold levels. A methodical data collection with a wider variety of listener/receiver directionality configurations for signal localization studies is recommended in future research, as well as research and development of appropriate noise filtering algorithms.

## Accomplishments, Including Relevance and Practical Application

Significant deficiencies were discovered in the results supplied by the dosimeter measurements, currently the most commonly used occupational noise exposure assessment method. For example, the format of the dosimeter recordings does not allow for the extraction of time-varying acoustic parameters or raw data; it is impossible to extract and analyze specific loud events, such as impulses perceived by the workers at various times throughout the day. The calculation of the dose (%), was provided as a single calculated value for the entire sampling period, i.e. duration of the entire work day.

Additionally, there was also an inherent inconsistency in the placement location of the dosimeter with respect to the source of noise that depended on the handedness of the worker and the type of work. In terms of the analysis, the hazardousness of different types of sounds could not be identified using dosimeter measurements and dosage calculations based on the physical measurements of the SPL.

The sound level meter (SLM) results were not comparable to the dosimeter and binaural measurements due to the fact that, for practical and safety reasons, they could not be placed at the exact work locations where noise was perceived by the workers. For greatest accuracy, noise exposure assessment needs to be obtained by a wearable device, ideally using a binaural data acquisition and analysis method.

The binaural measurement method was validated on two construction sites with minimal risk to the subjects. These minimal risks of wearing the devices are limited to, for example, embarrassment or annoyance over wearing the device or mild discomfort due to wearing it. Using the measurements, cases of asymmetric noise exposure were identified and impulsive, more dangerous, noise was quantified using a binaural loudness metric (ISO 532-2. Figure 6).

The study exposed the need to quantify situational awareness on construction sites with detailed and methodical measurement of signal and noise. The inability to localize warning signals was revealed in a laboratory setting using human participants, with measured locations, directions and equipment. For a future study, an advanced filtering algorithm needs to be developed in order to extract the warning signal from the noise (measured concurrently), to be able to adjust the signal to noise ratio in an acoustic perception evaluation, in a laboratory setting, for studies of sound localization in noise and hearing protection device (HPD) development and optimization.

## Results

**Part I** – The analysis is based on evaluating whether the traditional SPL-based and loudness-based assessment can reveal differences in impulsiveness of sounds; A louder impulsive sound known to be more dangerous than a steady-state sound, perceived as less loud, may both have the same SPL/SPL-based noise dosage. Figure 7 exemplifies this phenomenon using the construction site noise.

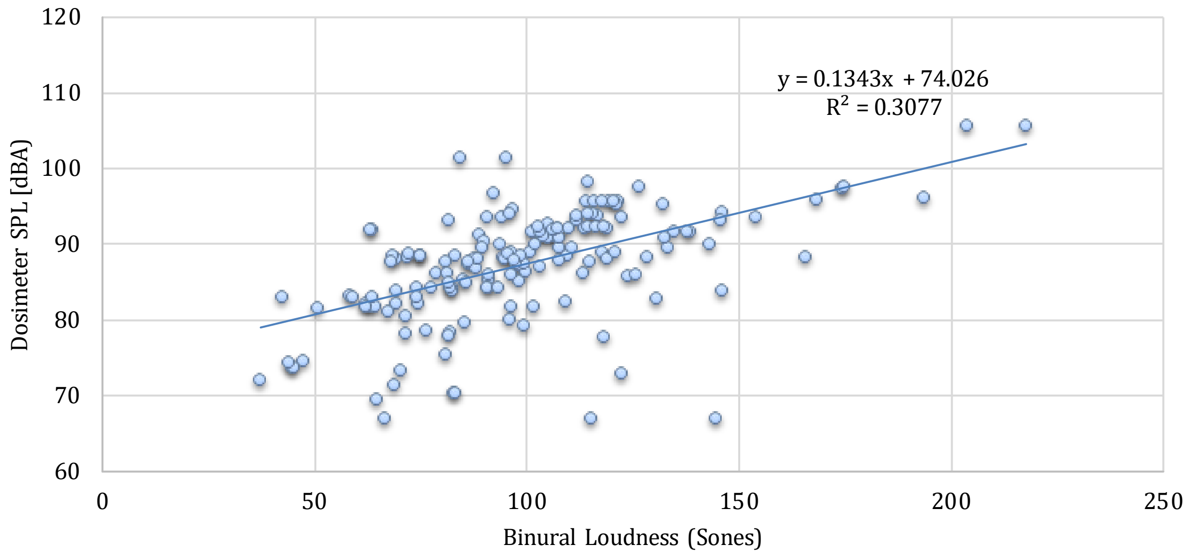


**Figure 7:** Binaural loudness (from binaural measurements) vs dosimeter

The traditional single-channel dosimeter measurement of an impulsive sound of a particular SPL (in dBA) is not well correlated with binaural loudness (in sones) of the same sound. In other words, the sound exposure characterized by a particular SPL, and the resulting noise exposure assessment, can have different loudness levels, and potentially different hearing damage risks, given that impulsive (more dangerous) sounds are louder sounds.

**Part II** – Testing a working hypothesis that binaural measurements and analysis can reveal:

A) clinically significant differences (>3 dB) between traditional SPL-based single-channel dosimeter noise exposure assessment

We found that SPL values from the binaural measurements were always higher than those from the single-channel dosimeter measurements. The SPL difference across ears, an indication of asymmetrical noise exposure, particularly for impulsive events throughout the day, was between 5 to 10 dB. The difference between the dosimeter measurement and the average SPL between ears (captured by the binaural DAQ), especially for impulsive events, was between 5 and 20 dB. These SPL differences are clinically significant (>3 dB): The daily, permissible noise dose calculation is based on the noise exposure level and the duration of the exposure. For each noise level increase of 3 dB (NIOSH, 1998) or 5 dB (OSHA, 1983), the noise dose doubles. The SPL differences found using binaural measurement, compared to the dosimeter measurements, in the preliminary data collection would inevitably result in critical differences in interpreting the hearing loss risk (dose) calculation and would yield underestimation of true noise exposure.

A T-test was used to compare the means of two sample data sets (binaural and dosimeter/single-channel). The null hypothesis was accepted if the mean SPL difference of sample data sets was 3 dB. Alternative hypothesis was be accepted if the mean difference of the samples was not 3 dB. This will determine if data sets are significantly different or not. All of the collected data sets are normally distributed (a requirement for using a t-test). It should be noted that, for first test, the alternative hypothesis will be a mean difference that is greater than 3 dB. The statistical analysis performed using Minitab software yielded the results in **Table 1**.

**Table 1: Statistical analysis of binaural and single channel noise exposure measurements (Part II, A)**

| Sample | N | Mean | StDev | SE Mean | Difference | 98% Lower Bound for Difference | Null hypothesis* / Alternative hypothesis* | $H_0: \mu_1 - \mu_2 = 3$ / $H_1: \mu_1 - \mu_2 > 3$ | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **T-Value** | **DF** | **P-Value** |
| Louder Ear A-Weight | 167 | 95.37 | 6.22 | 0.48 | 7.975 | 6.456 | 6.76 | 325 | 0 |
| Dosimeter A-Weight | 167 | 87.39 | 7.2 | 0.56 | | | | | |

* $\mu_1$: population mean of Louder Ear A-Weight
$\mu_2$: population mean of Dosimeter A-Weight
Difference: $\mu_1 - \mu_2$

B) asymmetrical noise exposure (≥ 1 dB between left and right ear based on the fact that 1 dB would be a perceptible difference in sound).

The statistical analysis performed using Minitab software yielded the results in **Table 2**. The P-value is .002, which is less than the significant value of .02. This means there is a statistical difference between data sets. We can reject the null hypothesis that there is a difference of 3 dB in the means and accept the alternative hypothesis that the mean difference between data sets is different from 3. There is a 98% confidence interval the average difference between each of the samples will be between -.695 and 2.512 dB. (Sample 1 – Sample 2). The difference between the two data set's averages is .908 dB. This difference between the ears (approximately 1 dB) is perceptible and therefore significant.

**Table 2: Statistical analysis of asymmetry of noise exposure using left and right ear measurements (Part II, B)**

| Sample | N | Mean | StDev | SE Mean | Difference | 98% CI for Difference | Null hypothesis* / Alternative hypothesis* | $H_0: \mu_1 - \mu_2 = 3$ / $H_1: \mu_1 - \mu_2 \neq 3$ | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | **T-Value** | **DF** | **P-Value** |
| Left Ear A-Weight | 167 | 94.74 | 6.22 | 0.48 | 0.908 | (-0.695, 2.512) | -3.05 | 331 | 0.002 |
| Right Ear A-Weight | 167 | 93.83 | 6.32 | 0.49 | | | | | |

* $\mu_1$: population mean of Left Ear A-Weight
$\mu_2$: population mean of Right Ear A-Weight
Difference: $\mu_1 - \mu_2$

**Part III** – The result of the evaluation was that, for the three configurations tested, all of the participants were able to hear warning signals. However, none of the participants were able to identify the direction of the warning signal emitted from the equipment. Further, there are no known acoustical metrics for objective evaluation of localization of warning signals in noise. This research paves the way for this important area of future construction safety research.

For more sample measurement analysis examples, **Appendices A, B and C** are included. **Appendix A** indicates a significant (greater than 3 dB) difference between the monaural/dosimeter and binaural/SQobold sound pressure level (SPL), for an example event (Part I of analysis), analyzed in the same time period and duration on both devices. **Appendix B** indicates a difference of approximately 8 dB between the dosimeter and the SQobold DAQ system (averaged across ears) SPL values, as well as a 3 dB difference across ears, using another example event (Part II of analysis). **Appendix C** illustrates an example of a traditional single-channel dosimeter measurement results, using the Work Noise Partner software.

## Changes/problems that Resulted in Deviation from the Methods

The warning signal audibility and speech intelligibility evaluation could not be performed using the adaptive procedure. The adaptive procedure implies that presentation levels of the warning signal or speech in noise would be increased or decreased by a fixed amount, depending on the listener's ability to hear the recorded signal, all in a laboratory environment (Phono Lab), as judged by the research personnel. Warning signals and noise on the construction sites could not be measured separately, due to the nature of operation of the equipment (warning signals had to be emitted as the equipment is operating), the challenge was separating the warning signal from the background noise. Acoustic perception evaluation was still performed (**Figure 7**) by evaluating warning signal audibility and localization. In all cases, based on the auditory cues from the headphones (i.e. recorded signals), the study participants could not correctly distinguish the direction of the warning signal.

## Future Funding Plans

The goal of this study is improving the accuracy of the assessment of noise and warning signal perception on construction sites. The effectiveness of the hearing protection devices was not assessed in this study. However, an improvement in the acoustic assessment methods and accurate evaluation of the sound field on a construction site can potentially improve the development and the optimization of the hearing protection devices and, in the case of the warning signals, sound enhancement algorithms for improved audibility. PI Samardzic and Co-Is Karatas and Esmaeili are planning to resubmit an R21/NIH grant application in March 2023 (originally submitted in June 2022) in order to expand the scope of this research.

## List of Presentations/publications, Completed and/or Planned

There are currently two journal papers under development, to be submitted to possibly the Journals of Professional Safety, Safety Science, Safety Research or Noise Control Engineering Journal.

## Dissemination Plan

This research will be to disseminate the result of the study locally, regionally, and nationally through multiple concurrent efforts.

- Research outcomes and tools will be available on the websites of CPWR, Lawrence Technological University, University of Illinois – Chicago, and Purdue University.
- Social networking accounts of PIs (e.g., LinkedIn, Research Gate) will be used to disseminate the outcomes of research.
- To encourage students to pursue a career in construction safety, a workshop will be provided for the AGC student chapters at the Lawrence Technological University, University of Illinois – Chicagom and Purdue University. In addition, we will train graduate and undergraduate students on the importance of construction noise exposure and improve noise management on construction sites as part of the Construction Management curriculum in our universities.

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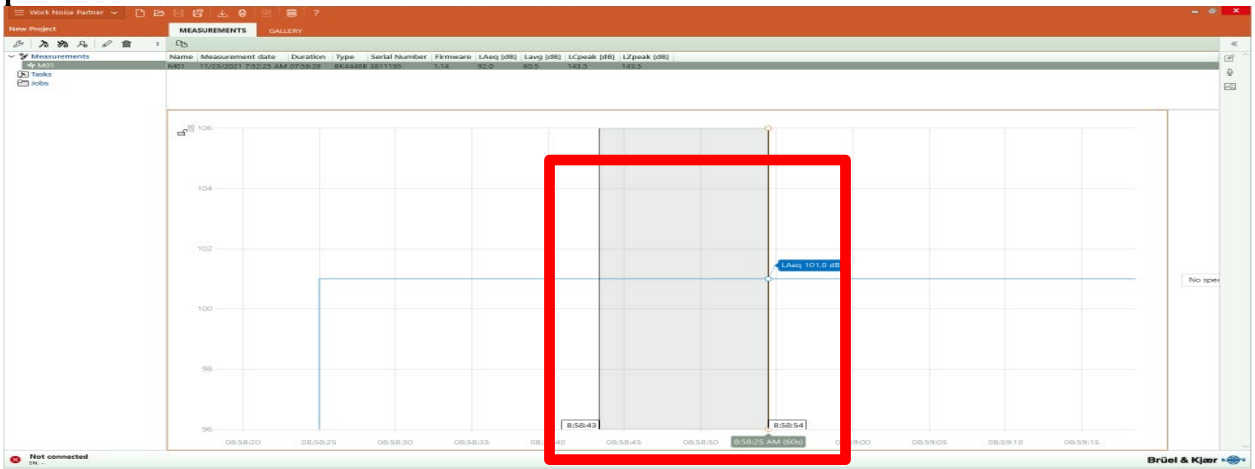
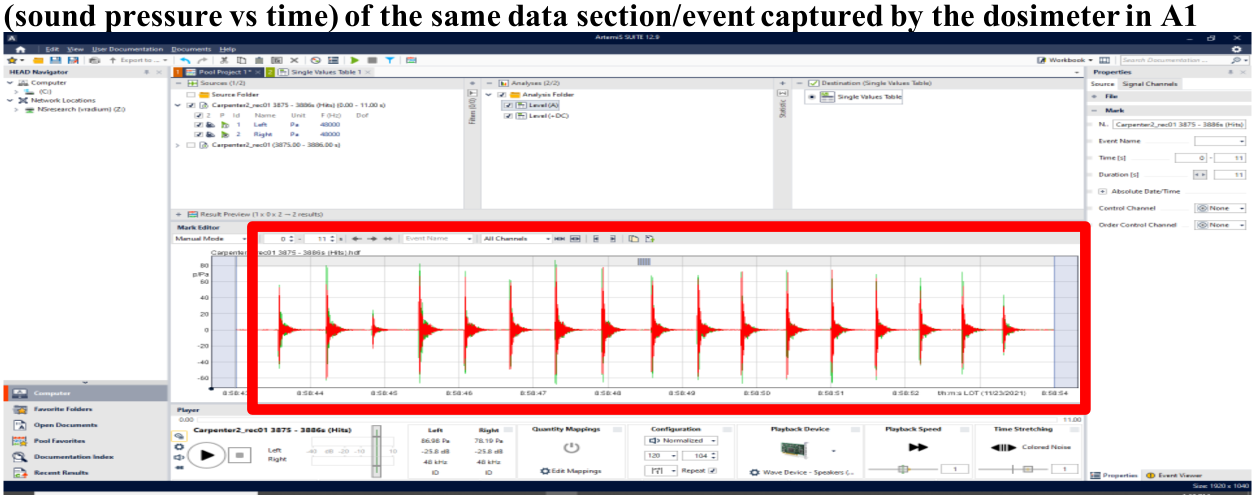
# APPENDIX

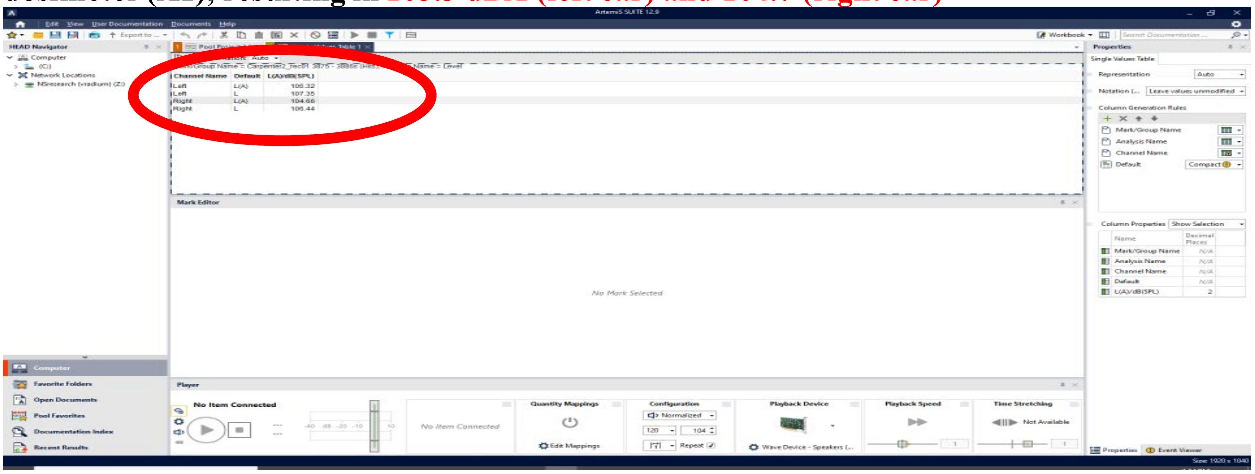
**A1 – Dosimeter Measurement Example: <u>Work Noise Partner software</u> indicating sound pressure level of 101.0 dBA for a work event**



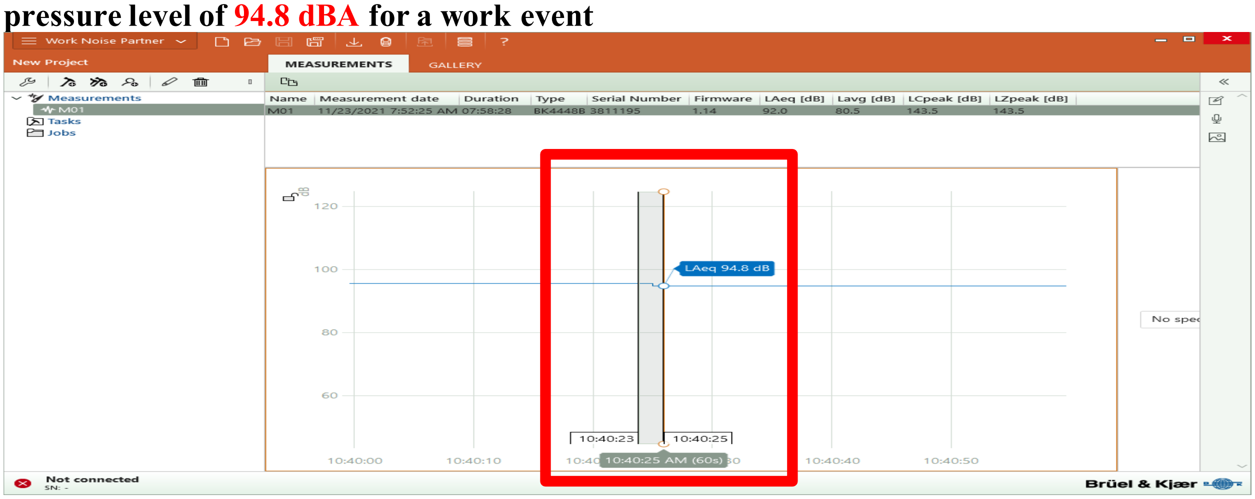

**A2 – SQobold DAQ system Binaural Measurement Example: <u>Artemis software</u> presentation (sound pressure vs time) of the same data section/event captured by the dosimeter in A1**



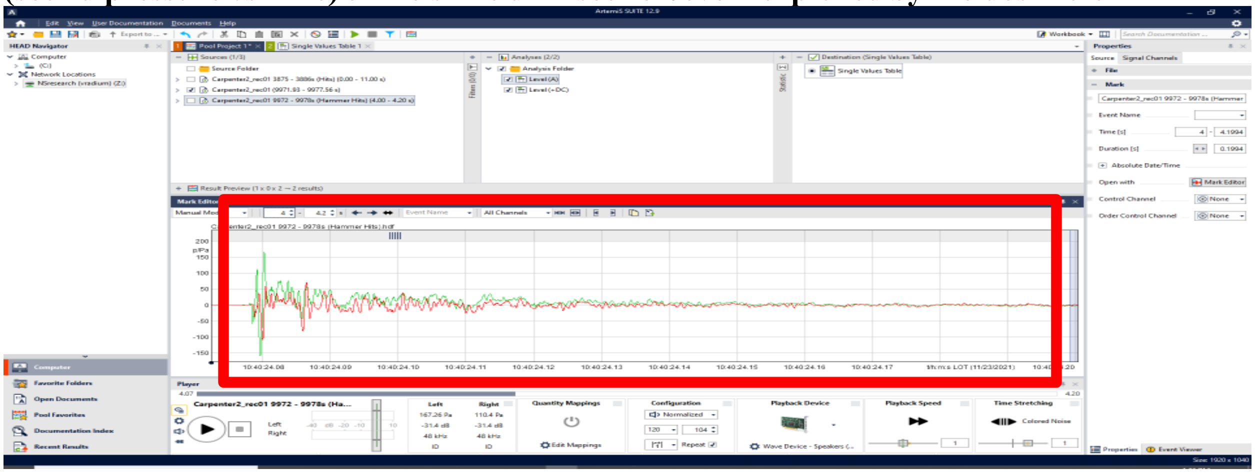
**A3 –<u>Artemis software</u> sound pressure level calculation of the data section captured by the dosimeter (A1), resulting in 105.3 dBA (left ear) and 104.7 (right ear)**



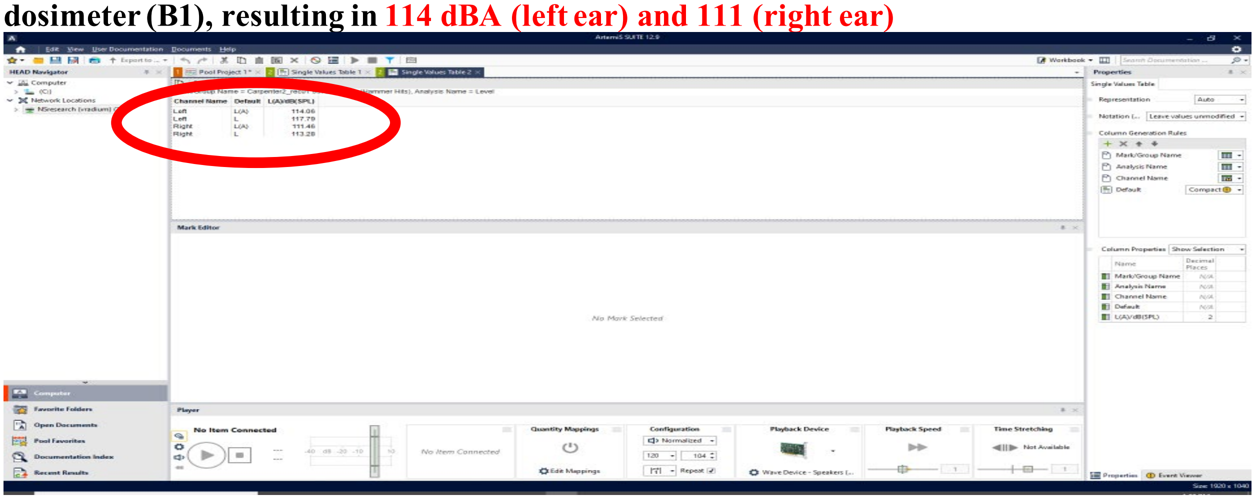

**B1 – Dosimeter Measurement Example: <u>Work Noise Partner software</u> indicating sound pressure level of 94.8 dBA for a work event**



**B2 – SQobold DAQ system Binaural Measurement Example: <u>Artemis software</u> presentation (sound pressure vs time) of the same data section/event captured by the dosimeter in B1**



**B3: – <u>Artemis software</u> sound pressure level calculation of the data section captured by the dosimeter (B1), resulting in 114 dBA (left ear) and 111 (right ear)**



## C1: – Dosimeter Measurement Example Result, Work Noise Partner software

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