ESTIMATING THE PERFORMANCE OF SOUND RESTORATION HEARING PROTECTORS BY USING THE SPEECH INTELLIGIBILITY INDEX

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ABSTRACT

Despite advances in engineering noise controls and the use of administrative controls, miners are still dependent on hearing protection devices for prevention of noise-induced hearing loss. However, miners often raise concerns about the audibility of spoken communication when wearing conventional hearing protectors. Electronic technologies that selectively process and restore sounds from outside of hearing protectors have been suggested as a partial remedy to the audibility problem.

To assess the potential benefits of this technology for miners, NIOSH tested the impact of nine electronic sound restoration hearing protectors on speech intelligibility in selected mining background noises. Because of the number of devices and potential settings of those devices, it was necessary to narrow the choices before conducting human subject testing. This was done by testing the nine devices on an

acoustic test fixture (ATF) to acquire one-third-octave-band data, and then calculating the speech intelligibility index (SII) to determine estimates of performance across device, noise and setting. The estimates of speech intelligibility obtained with the SII are highly correlated with the intelligibility of speech under adverse listening conditions such as noise, reverberation, and filtering. The results of fixture based testing indicate that performance varies little between most devices, with few showing exceptionally good or poor estimated speech intelligibility. The most significant differences in estimated performance using the devices were between the different noise sources used, regardless of device or setting.

The findings of this research were used to select the devices and settings for subsequent human subject based speech intelligibility testing. The human subject testing results largely concurred with the findings from the acoustic test fixture testing and calculation of speech intelligibility index. Specifically, variations in background noise led to the greatest differences in speech intelligibility.

INTRODUCTION

The mining workforce experiences high levels of noise exposure and in turn suffers from high rates of noise-induced hearing loss (NIHL). The mining sector has the highest prevalence of hazardous workplace noise exposures (76%) among all industrial sectors [1]. Despite engineering and administrative controls implemented to reduce noise, miners report a high prevalence (24%) of hearing difficulty [2]. It therefore remains necessary for miners to use hearing protection devices (HPDs) to reduce the chance for acquiring NIHL. There are complaints, however, that HPDs have a negative impact on hearing some desired sounds. Specifically, miners have expressed concerns that wearing HPDs inhibits their ability to communicate with co-workers and reduces the audibility of alarms and other auditory warnings. Decreased audibility is not only a communication nuisance, but it can contribute to unsafe working conditions. For miners who exhibit some degree of hearing impairment, the degradation in audibility can be even greater. HPD manufacturers have recognized these issues, and they have developed HPDs with technology aimed to remediate them.

To improve the function of the devices in environments where sound awareness is vital, electronic technology has been integrated into conventional hearing protectors. Several types of electronic hearing protectors with different intended purposes are available today, so an important distinction must be made. Electronic level-dependent, (also known as sound restoration) hearing protectors are designed to amplify some ambient sounds that are within a safe listening level and, by reverting to passive attenuation, to limit sounds that exceed the safe level. Active noise reduction (ANR) and impulse reduction electronics have also been integrated into conventional hearing protectors for improved audibility or attenuation in certain noise environments. This research focuses on sound restoration hearing protection devices (SRHPDs).

Electronic SRHPDs have one or two microphones outside of the ear cup and a speaker inside so that ambient sound may be picked up and selectively transmitted to the ear. The devices are designed to limit, typically to 82 or 85 dB(A), sounds reaching the ear. Below that limit, the devices provide adjustable amplification to potentially improve audibility of sounds that are at a safe level. As ambient sound approaches or exceeds the limit, the electronic circuitry performs limiting, compression, or other processing to keep the sound transmitted inside the protector below hazardous levels. Most of these devices can also be worn in a passive mode by simply turning them off, at which point they act as a conventional hearing protector. Some type of control mechanism is accessible to the wearer of SRHPDs for activating the electronic processing and, in some cases, adjusting the gain or frequency response of the device.

Previous research has examined the benefit of SRHPDs as compared to conventional hearing protectors or the open ear [3-6]. However, this research varies greatly in respect to methodology, devices tested, and subject population. This has led to disparity in research results. Therefore, additional work is needed to determine the possible benefits of such devices for users in mining. The aim was to determine whether the sound restoration technology provides any benefit as compared to devices functioning in a passive, conventional mode in background noises specific to those found in mining.

Sound restoration HPDs are available from multiple manufacturers. At the time of this research, nine devices could be purchased through standard commercial means, all with small variations in product design and performance. This collection of devices was found through a search of hearing protector manufacturer's Web sites, Internet search engines, and occupational safety Web sites. Although there may be similar devices available, they were not found through common search methods and therefore were not included in this research. To fully evaluate the potential benefits of this technology for improving audibility in underground mining, human-subject speech intelligibility testing must be conducted on subjects using the devices in several background noise conditions typical of those found in underground coal mining. However, because of the many possible combinations of device, device setting, and mining background noise, the choices must be narrowed in order to conduct subject testing within a reasonable time frame. This was done through application of the Speech Intelligibility Index (SII) [7].

The SII (ANSI S3.5-1997) is computed from the frequency spectrum of a specific background noise, estimates of speech spectrum level, and actual or estimated hearing threshold. The SII is highly correlated with speech intelligibility under adverse listening conditions. The SII is not equal to specific speech intelligibility scores; rather, it may be interpreted as a proportion of the total number of speech cues available to the listener. Through application of the SII equation to the speech-to-noise ratio in a selection of contributing frequency bands, the intelligibility of a communication system can be predicted. The type of HPDs evaluated in this study can be considered to represent a "communication system" because of its active function, which is designed to improved communication while in use. Because the interest of this study lies with speech intelligibility performance instead of the attenuation properties of SRHPDs, this type of evaluation provides more relevant data than standard methods used to test hearing protection devices such as ANSI S12.6-1997 (R2008) [8]. As stated within the standard, the SII is not intended to serve as a replacement for determining the speech intelligibility with human subjects as described in ANSI S3.2-1989 (R 1995) [9]. Human-subject testing in accordance with ANSI S3.2 methodology was followed subsequent to use of the SII. The SII was implemented to reduce the possible combinations for subject testing by determining the SRHPDs and corresponding settings most likely to impact audibility of speech in mining noise. Additionally, the results of objective fixture-based testing were compared with subjective human-subject testing results to determine the accuracy of applying the SII for this purpose.

METHODS AND DESIGN

A three-stage approach was used to determine SII values. First, the dial settings corresponding to one quarter, one half, and three quarters of the maximum output provided by each HPD were determined. Next, one-third-octave band sound pressure level (SPL) spectra were measured at those settings with each device on the test fixture. Finally, the SII formula was applied to the measured one-third-octave band data to calculate the SII.

Test environment and apparatus

All testing was conducted in the Auditory Research Laboratory at the Pittsburgh location of the NIOSH Office of Mine Safety and Health Research (OMSHR). Testing occurred in a double-walled, sound-treated hearing test booth. The stimulus sounds were stored in digital format and were routed into the booth through an MPX 300 amplifier and a Grason-Stadler clinical audiometer. The audiometer was used to adjust stimulus loudness (volume) to 1 dB accuracy. The sound-treated booth was outfitted with two diagonally-situated Cambridge Soundworks Model 6 speakers. A G.R.A.S. 45 CA acoustic test fixture (ATF) with binaural G.R.A.S. Type 40AO ½-inch pressure-field microphones was used for measuring the output of the SRHPDS. IEC 711 couplers were used with the fixture to simulate the ear canal; this is necessary for accurate calculation of the SII. The ATF was positioned in the center of the booth atop a heavy-duty surveying tripod. Figure 1 depicts the orientation of the speakers and ATF inside the test booth.

FIGURE 1: ORIENTATION OF ATF AND SPEAKERS INSIDE THE SOUND-TREATED TEST BOOTH

Data acquired from the G.R.A.S. ATF was fed to a National Instruments PXI 4462 4-channel data acquisition system and analyzed using Nelson Acoustics Trident software. The Trident software provides a real-time display of the sound levels and one-third-octave-band sound pressure levels for each microphone. The sound levels in the booth were confirmed using a Bruel and Kjaer 4188-A microphone hanging in the center of the room routed through the same data acquisition system and analyzed with the same software.

Stimuli

Mining noise sources served as the background noise for SII and human-subject testing. The noises of machinery common in underground coal mining were taken from recordings collected during other field studies by NIOSH researchers in the Office of Mine Safety and Health Research. The noises were from various operations performed with continuous mining machines (cutting/conveying and tramming) as well as the drilling operation of roof bolting machines (RBMs). According to data collected from 2000 to 2002 by the Mine Safety and Health Administration (MSHA), 65% of miners who had noise overexposures operated at least one of seven types of mining equipment. Continuous mining machine operators accounted for 35% of those overexposures, and roof bolting machine operators accounted for 17% [10]. Continuous mining machines (CMMs) are among the principal pieces of equipment used in underground coal mining and generate some of the highest sound levels. Sound levels around these machines can range from 78 to 109 dB(A) depending on the machine emissions, acoustic environment, task being performed, and distance from the machine [11]. Roof bolting machines (RBMs) are also used widely in underground coal mining and can produce sound levels ranging from 97–108 dB(A) while drilling [12]. The original recordings consisted of sound from the CMM or RBM as well as workers talking and other extraneous sounds. The sound files were edited using Adobe Audition 2.0. The resulting sounds were 4.5 minutes long and contained only the sound emitted by the machine.

The playback levels of the mining noises were manually adjusted using the GSI audiometer to achieve the desired sound level inside the booth. This was done using the hanging reference microphone and Trident software to monitor the level. CMM cutting/conveying at 80 and 95 dB SPL, CMM tramming at 78 dB SPL, and RBM drilling at 80 dB SPL were used as background noise during this stage of research. The 78 and 80 dB SPL noises used in this study are somewhat lower than typically experienced by the operators of these machines. However, the noise levels are realistic for the levels experienced by other workers in the general area of the machine.[1]

Procedure

The first stage of the procedure involved determining one quarter, one half, and three quarters of potential acoustic output, as well as passive and maximum output conditions for each SRHPD. First, the full range of response of each SRHPD from passive to maximum was measured in a background of 80 dB SPL pink noise inside the sound-treated booth. To determine the full range of performance, the linear SPL for passive and maximum was measured using the Trident software with each SRHPD placed on the ATF. The SPL measured from the right and left sides of the device were averaged to obtain one overall number. If the two sides were not within 3 dB of each other, the device was adjusted for better fit on the fixture and re-measured.

The minimum averaged output was subtracted from the maximum averaged output to determine the range of device amplification. Once the full range of amplification was determined for a device, the

[1] During machine operation it would be very difficult for the operators to understand speech, regardless of hearing protector use, because of their proximity to the high noise levels emitted by the machine. By representing sound levels experienced by other workers in proximity of the machines, not necessarily the operator, we are able to determine the effects of the SRHPDS for a larger portion of mining occupations and with better speech intelligibility expectations.

amplification corresponding to one quarter, fourth, half, and three quarters of the maximum amplification were calculated. For example, if the minimum output for a device was 58 dB and the maximum output was 78 dB, the range of amplification is 20 dB, and the dial positions for outputs of 63, 68, and 73 dB would relate to one quarter, one half and three quarters of the maximum amplification. This determination was made for 3 samples of the nine SRHPDs. For simplicity, the dial positions corresponding to one quarter, one half, and three quarters of the maximum amplification will be referred to as the "quarter points".

Next, an iterative process was followed to determine the dial positions that correspond to each of the calculated quarter points. Once again, pink noise was used to generate sound with an overall SPL of 80 dB inside the test booth. A device was placed on the ATF and the output control was adjusted to a dial position that was expected to produce roughly one quarter of the maximum output. The 30-second equivalent continuous sound pressure level (LEQ) was measured and compared to the level corresponding to one quarter of the maximum output. Based on the comparison of these values, the dial position was adjusted up or down and the LEQ was once again measured and compared to the target level. For each device, this process was repeated until the dial positions corresponding to the quarter points were found. The outputs obtained from the two sides of each device were averaged to achieve one overall output.

This procedure was carried out for three samples of each of the 9 SRHPD models. The setting in relation to quarter points was marked on the device. The settings were acoustically and mathematically determined and did not necessarily reflect the visual or physical settings of any output controls on the devices in reference to percent of dial turn from the off or passive condition. There also were differences in range and quarter points across devices and within samples of devices of the same make.

Next, one-third-octave-band SPLs were determined for the quarter points, passive, and maximum settings of each device in four mining background noises: CMM cutting/conveying at 80 dB and 95 dB SPL, CMM tramming at 78 dB SPL, and RBM drilling at 80 dB SPL. Each HPD was placed on the ATF, and one of the noises was played in the test chamber, again using the audiometer to adjust the SPL in the test booth. A 15-second LEQ was measured at each device setting, and the resultant one-third-octave-band SPLs were acquired through the National Instruments system and exported to Microsoft Excel spreadsheets. For each device setting and test noise, three tests were performed and the average of the three tests was calculated. This process was followed for three samples of all nine SRHPDs.

For the last stage of testing, the SII formula was applied to the one-third-octave band data acquired in the various mining noise backgrounds. Application of the SII formula provides an estimate of speech intelligibility based on the frequency spectra of the background noise, the speech spectrum level, and the band audibility function. There are four possible computational procedures, which take into account variations in band importance function, speech spectrum level, and noise spectrum level. Based on the characteristics of individual applications, the most applicable computation method can be chosen from these four options. For this research, the one-third-octave-band SII procedure was implemented. Equation 1 is for the calculation of SII, where n is the number of SII computational bands, while l_i and A_i are the values of the band importance function and the band audibility function.

$$\mathrm{SII} = \sum_{i=1}^{n} l_i \ A_i \quad (1)$$

Table 3 within the standards document [7] provides details for specific formula application, such as details regarding the SII computational bands as well as band importance and band audibility function as used for the one-third-octave band computational procedure.

A MATLAB program to calculate the SII was obtained from the SII website (http://www.sii.to/html/programs.html). The program was modified to meet our needs. First, the SPLs measured at the center of room microphone and the fixture microphones were read into the program. Next, the average SPL was calculated for the left and right microphones. The gain specific to a device, device setting, and noise was calculated for each one-third-octave band by equation 2:

$$G_i = SPL_{fix,i} - SPL_{noise,i} \quad (2)$$

where G_i is the gain for the i^{th} one-third-octave band, $SPL_{fix,i}$ is the average SPL at the fixture for the i^{th} one-third-octave band, and $SPL_{noise,i}$ is the SPL at the microphone in the center of the test booth for the i^{th} one-third-octave band due to the played noise recording. This gain accounts for the passive attenuation of the HPD combined with the amplification due to the electronics. The noise spectrum level was then computed using equation 3:

$$N_i = SPL_{noise,i} - BW_{adj,i} \quad (3)$$

where $BW_{adj,i}$ is the bandwidth adjustment for the i^{th} one-third-octave band from Table 3 in the standard and Ni is the noise spectrum level for the i^{th} one-third-octave band.

Next, the program calculates the equivalent speech and noise spectrum levels based on the measured noise using the standard speech spectrum levels for normal, raised, loud, and shout as listed in Table 3 of the standard. For these calculations, a distance of 1 m was used for the noise source to listener distance and binaural listening was assumed. In addition, normal hearing was assumed for all calculations (i.e. hearing level of 0 dB).

RESULTS

All responses for each device tested were averaged for the same setting and noise source to arrive at composite SII scores for each device by noise and setting. Devices were assigned an alphabetic code to assure that during analysis the devices remained unidentified. The results of the SII analysis showed that differences in the background noise source led to the greatest variation in estimated available speech cues, but little variation occurred by device or setting within that noise source.

All results referenced are derived using the standard speech spectrum levels for “shout”. Calculated SII values ranged from 0.14-0.89. For the CMM cutting/conveying at 95 dB SPL no device or setting achieved an SII greater than 0.14. Based on recommendations within the standard for applying the SII [7], one cannot reasonably expect auditory communication with such a low SII, therefore CMM cutting/conveying at 95 dB SPL was not used for subject testing. Based on the improved SII values from the remaining noise sources (0.54-0.95), it was decided to use both remaining CMM noises and the RBM noise for subject testing.

Differences in SII between the remaining three noise sources ranged from 0.05-0.25. However, within each of the three noise sources the range of SII value differed between each setting and device was less than 0.15 in most cases. Figures 2, 3, and 4 depict the SII value versus device for both the CMM noise sources. The various SRHPDs are alphabetically depicted in the legend. It can be seen that within a particular noise source, most differences between devices at equal settings are less than 0.15 for all three noise sources. Note the scale in Figure 4 is much less (0.1-0.2) than the scale for figures 2 and 3 (0.5-1.0). Also note that as the setting of the SRHPD is increased from passive to maximum, the general trend is for degraded performance (figures 2 and 3), except for CMM cutting/conveying at 95 dB SPL where there is poor performance for all conditions (figure 4).

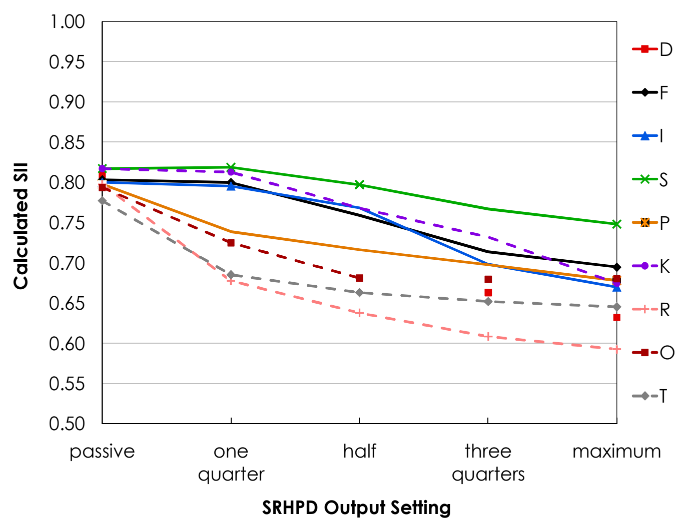

FIGURE 2: CALCULATED SII VALUES BY DEVICE AND SETTING WITH RECORDING OF CMM TRAMMING AT 78 dB SPL AS A NOISE SOURCE.

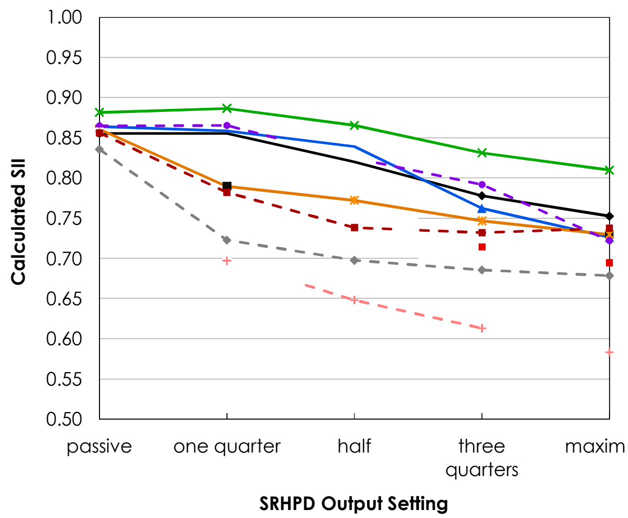

FIGURE 3: CALCULATED SII VALUES BY DEVICE AND SETTING WITH RECORDING OF CMM CUTTING AND CONVEYING AT 80 dB SPL AS A NOISE SOURCE.

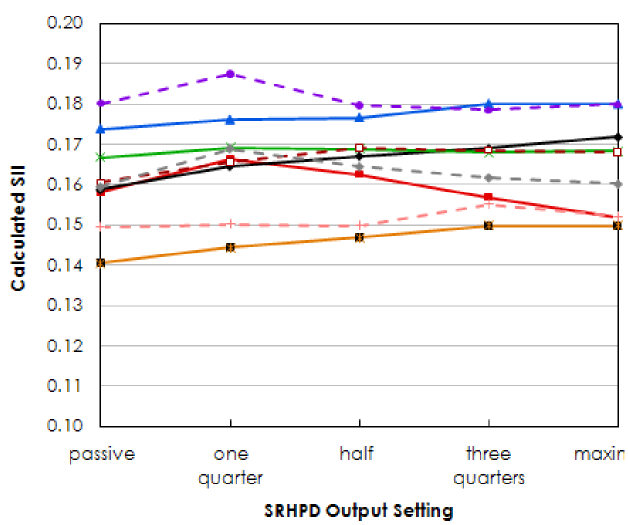

FIGURE 4: CALCULATED SII VALUES BY DEVICE, AND SETTING WITH RECORDING OF CMM CUTTING AND CONVEYING AT 95 dB SPL AS A NOISE SOURCE.

When SRHPD setting was rank-ordered from best to worst calculated SII within each device and noise source, all SRHPD settings showed the same order for all measures except for four cases. The order of settings from best to worst performance (highest SII to lowest SII) was the following: (1) passive, (2) one quarter output, (3) one half output, (4) three quarters output, and (5) maximum. The other four ranks were only switched in that the one quarter output condition led to better estimated speech intelligibility than passive. The results of the consistent rank order, as well as minimal change between settings, led to the decision to implement passive, one quarter, and three quarter output as the subject study variables.

Figures 5, 6, and 7 show examples of the SPLs measured at the microphone in the center of the test booth and under the HPDs at the test fixture with the device outputs set to three quarters for the recordings of CM tramming at 78 dB SPL, CM cutting/conveying at 80 dB SPL, and CM cutting/conveying at 95 dB SPL. These devices were chosen to show a range of calculated SII values, from high (device S) to average (device P) to low (device R). In addition, the figures show the gain for the same test conditions as calculated by equation 2. Note that device R amplified the levels at the fixture much more than the other devices tested, which resulted in overall A-weighted sound levels of 92.1, 98.8, and 89.9 dB for the recordings with levels of 78, 80, and 95 dB SPL. Devices S and P, however, limited the A-weighted sound levels under the HPDs at the fixture to less than 85 dB in each case. Device R would not likely improve speech intelligibility in these background noise sources, nor would it be a good choice for protecting hearing because it amplified relatively low sound levels to levels that exceed recommended allowable levels.

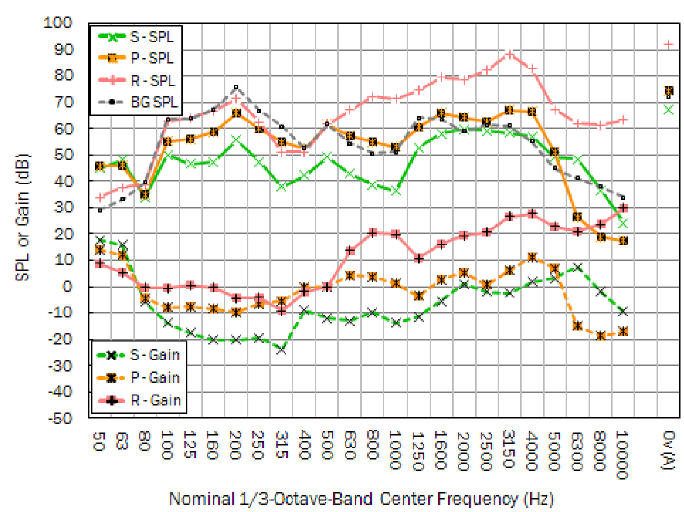

FIGURE 5: CALCULATED GAIN AND OUTPUT AS MEASURED ON ATF FOR DEVICES S, P, AND R IN THE CMM TRAMMING AT 78 dB SPL BACKGROUND NOISE.

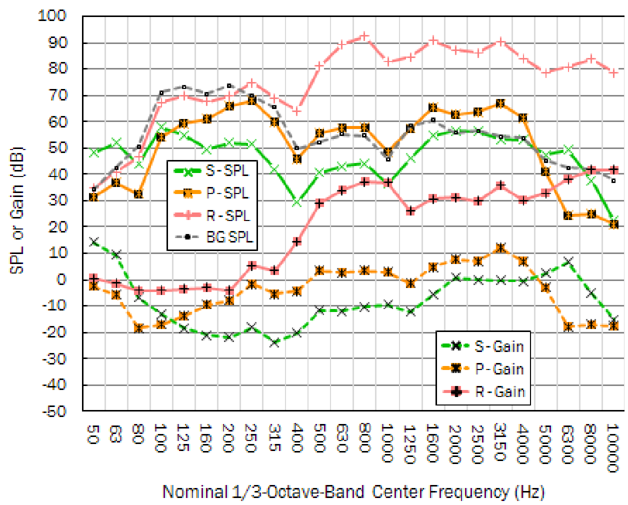

FIGURE 6: CALCULATED GAIN AND OUTPUT AS MEASURED ON ATF FOR DEVICES S, P, AND R IN THE CMM CUTTING/CONVEYING AT 80 dB SPL BACKGROUND NOISE.

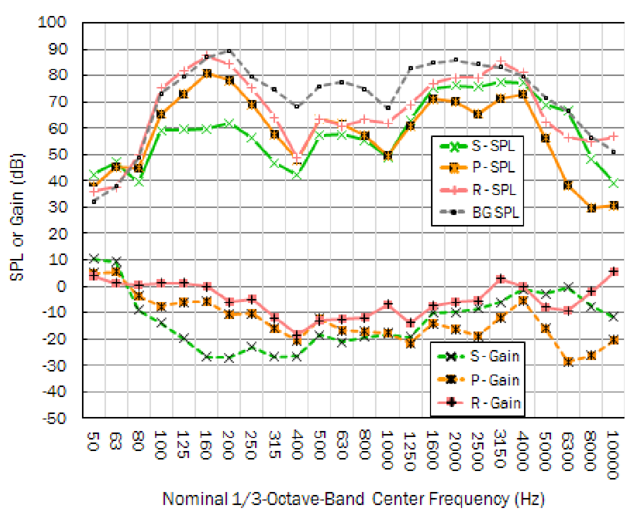

FIGURE 7: CALCULATED GAIN AND OUTPUT AS MEASURED ON ATF FOR DEVICES S, P, AND R IN THE CMM CUTTING/CONVEYING AT 95 dB SPL BACKGROUND NOISE.

Additionally, differences between devices at equal settings and noises were small, on the order of 0.15 or less in many cases. It was determined through a comparison of average scores that, overall, four devices led to slightly better SII estimates. Those devices were chosen for the subject testing portion. The chosen devices based on performance were I, S, K, and O.

Subsequently, human-subject testing was done using the best four performing devices (I, S, K, and O) set to passive, one quarter and three quarters output. The modified rhyme test (MRT) was carried out using the same three mining noises (CMM tramming at 78 dB SPL, CMM cutting/conveying at 80 dB SPL, and RBM drilling at 80 dB SPL) with 30 normal hearing subjects. The MRT requires a subject to determine a spoken word in the presence of background noise from a closed set of rhyming alternative words. Full details regarding that work will be provided in a later publication. A comparison of the rank order from best to worst scores from the SII and human-subject acquired speech intelligibility scores by setting (passive, one quarter, and three quarters) and noise source were the same for 71% of the individual tests. This does not indicate that the acquired scores were equal, only that the ranking of settings from highest to lowest SII or speech intelligibility score were the same. The largest difference in subject speech intelligibility scores was also between the various background noises. The subjects performed better in CMM tramming and RBM drilling background noise than the CMM cutting/conveying regardless of SRHPD used or setting.

CONCLUSION

The results of this research indicate that it is feasible to use the SII to reduce the number of potential variables when attempting speech intelligibility testing with human subjects. However, it must be carefully applied and understood that the results obtained are not to be considered equal to actual speech intelligibility testing. Application of the SII allowed for elimination of devices likely to lead to the worst speech intelligibility scores with human subjects. The SII also showed there was little difference in performance across settings of many of the SRHPDs evaluated in the study. The greater issue is that contrary to intuition; turning the dials of such devices to maximum will not provide the most benefit for speech intelligibility. Both the SII and subject testing found that as the output of SRHPDs is increased there is decreasing, or at best equal SII values or speech intelligibility performance. Use of the SII successfully allowed for reduction in study variables to implement a reasonable subject-testing protocol.

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