Safety and Health at Work 12 (2021) 184–191

Contents lists available at ScienceDirect

Safety and Health at Work

journal homepage: www.e-shaw.net

Original Article

Field Attenuation of Foam Earplugs

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ARTICLE INFO

Article history:
Received 19 September 2019
Received in revised form
7 May 2020
Accepted 10 September 2020
Available online 2 October 2020

Keywords:
Fitting instructions
Hearing protection devices
HPD discomfort
Personal attenuation rating
Workplace safety

ABSTRACT

Background: Hearing protection devices (HPDs) are often used in the workplace to prevent hearing damage caused by noise. However, a factor that can lead to hearing loss in the workplace is improper HPD fitting, and the previous literature has shown that instructing workers on how to properly insert their HPDs can make a significant difference in the degree of attenuation.

Methods: Two studies were completed on a total of 33 Hydro One workers. A FitCheck Solo field attenuation estimation system was used to measure the personal attenuation rating (PAR) before and after providing one-on-one fitting instructions. In addition, external ear canal diameters were measured, and a questionnaire with items related to frequency of use, confidence, and discomfort was administered.

Results: Training led to an improvement in HPD attenuation, particularly for participants with poorer PARs before training. The questionnaire results indicated that much HPD discomfort is caused by heat, humidity, and communication difficulties. External ear canal asymmetry did not appear to significantly influence the measured PAR.

Conclusion: In accordance with the previous literature, our studies suggest that one-on-one instruction is an effective training method for HPD use. Addressing discomfort issues from heat, humidity, and communication issues could help to improve the use of HPDs in the workplace. Further research into the effects of canal asymmetry on the PAR is needed.

1. Introduction

High noise levels are a serious health hazard affecting millions of workers worldwide. In a recent survey of working adults in Canada, 42% reported being exposed to hazardous noise levels in the workplace [1]. Although the majority of these workers reported using hearing protection devices (HPDs), long-term work-related noise exposure was still associated with hearing loss. Most cases appear to be related to improper fitting of the HPD rather than shortcomings of the HPD itself. An improper fit typically arises from an incomplete seal of the external ear canal. An incomplete seal leads to reduced performance of the HPD, which increases the risk of hearing loss for the user.

A possible cause of an incomplete seal of the external ear canal may be a mismatch between the canal size and the size of the HPD. For example, individuals with asymmetrical ear canals may have difficulty obtaining a proper fit in both ears. However, for most cases, the reason for an incomplete seal stems from a lack of knowledge with regard to proper insertion of HPDs. Voix et al [2] emphasized the importance of motivating workers to correctly and consistently fit their HPDs before being exposed to noise. But how does one measure the effectiveness of an HPD fit to ensure that it is fit correctly?

One method for measuring HPD performance is the personal attenuation rating (PAR, measured in dBA). At here, attenuation is defined as “the reduction in sound pressure level incident upon the ear due to the application of a hearing protector or, specifically, the change in hearing threshold level that results when a hearing protector is worn” [16]. The PAR refers to the level of attenuation achieved by an HPD fit at the level of the individual. Thus, PAR allows users to verify whether an attenuation level is suitable for their specific noise environment, such as that encountered in the workplace [3]. With the aid of a device called the field attenuation estimation system (FAES), a user can perform ecologically valid experiments that serve as a sufficient alternative to the laboratory-controlled conditions of the noise reduction rating (NRR).

A number of field research studies have found that providing training can improve HPD attenuation. Williams [4] posited that the performance of HPDs can be reliably increased through training on HPD use and maintenance. In a study of workers in the offshore

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2093-7911/$ – see front matter
https://doi.org/10.1016/j.shaw.2020.09.006

oil industry, less than 50% of these individuals were achieving a sufficient PAR with their HPDs. After an intervention that included HPD training and refitting, up to 85% of workers were able to achieve a PAR that was sufficient to protect hearing in their noise exposure environment [5]. In another study comparing a control group with a group trained on HPD use, individuals in the trained group reported significant increase in the attenuation obtained with their HPDs compared with those in the control group [6]. In a meta-analysis of seven HPD intervention studies, individually targeted HPD training was found to be significantly more effective than HPD training that addresses more general work habits [7]. Some studies have found that one-on-one HPD training with an experimenter was more effective than printed instructions or videos [8], and only 15–20 minutes of training could improve attenuation as much as 15 dB [9]. To provide adequate protection, attenuation measurements should thus be personalized using in-person PAR measurements to consider individual differences [10].

Aside from an improper fit, another reason for high levels of hearing loss in the workplace could simply be due to lack of use of hearing protectors. Some research studies have shown that as much as 25% of workers who are exposed to levels loud enough for a risk of hearing loss do not wear hearing protection [11]. Other studies have assessed the reasons for lack of hearing protector use, but none have correlated these with PAR ratings.

In the current project, we conducted two field studies (Study I and Study II) aimed at measuring the attenuation of HPDs in the workplace and assessing the effects that one-on-one training has on HPD attenuation. For both studies, we hypothesized that the PAR would increase after one-on-one training on proper HPD insertion. Both studies also had a secondary aim examining whether asymmetrical ear canals might influence PARs independently of training effects. We expected that PARs would be lower for individuals with asymmetric ear canal diameters. Participants in Study II performed all the same tasks as those in the first study but were administered an additional questionnaire (see Appendix) with the objective of correlating the PAR measurement results with subjective participant data on comfort, familiarity, and usage of protectors. We hypothesized that questions with regard to frequency of usage and familiarity would positively correlate with PARs. We included questions on discomfort to assess the reasons that contribute to inconsistent hearing protector use.

2. Materials and methods

2.1. Participants

2.1.1. Study I

Nineteen workers were recruited from Hydro One, the energy distribution company in the province of Ontario. Workers were primarily men who fell between the ages of twenty and forty years. These participants were selected as a convenience sample. Participants were not compensated for their involvement, and their participation was completely voluntary. We thank Jason Hoffman (Hydro One Health and Wellness Manager) for providing formal permission for our researchers to enter the facility on two separate occasions and recruit participants. All of the participants were staff members who regularly use HPDs as part of a condition of employment. None of the participants had undergone individual training on HPD fitting before this study. One participant's data were excluded owing to an equipment malfunction during testing.

2.1.2. Study II

Fourteen workers who had not participated in Study I completed the same set of measurements reported in Study I. In addition to these measurements, they also completed a self-report questionnaire concerning HPD use (frequency, confidence, comfort, and ease of communication; see Appendix 1). As with Study 1, the participants were a convenience sample, all were regular users of HPDs, and none had received individual training on HPD fitting before the study. Again, the participants were not compensated for their involvement. Both Study I and Study II protocols were submitted to the Ryerson University Research Ethics Board. The board deemed that an ethical review was not necessary as the studies were designed to determine the usability of a product that was regularly used by the participants and further, that the use of the product in the context of usability testing presented low risk (protocol 2018-218).

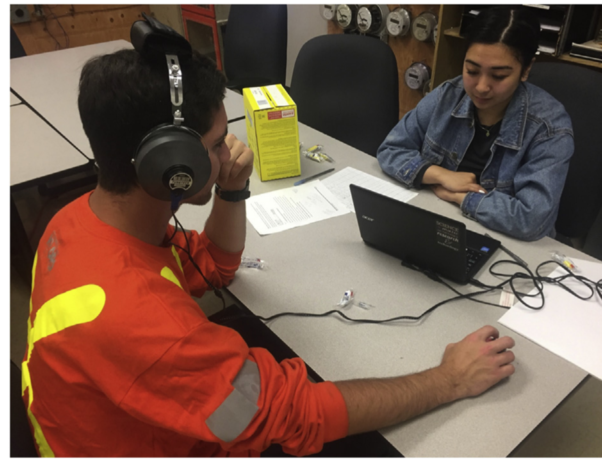

Fig. 1. FitCheck Solo procedure. The experimenter sits facing the laptop and uses the laptop touchpad to progress through the experiment. The participant wears circumaural headphones to hear the stimuli and selects the threshold levels using a computer mouse. A new pair of HPDs is used after each occluded measurement. HPD, hearing protection device.

2.2. Materials

The HPDs used were 3MTM E.A.R. classic uncorded earplugs, 312-1201. The manufacturer reported an NRR for this HPD as 29 dB. Ear canal diameter was measured using a plastic ear canal device made by E.A.R in accordance with ANSI/ASA S12.6 [12]. Measurements were taken for both left and right ears. The values ranged in six steps from XS to XL. PAR measurements were performed using the FitCheck Solo FAES manufactured by Kevin Michael & Associates. An Acer Aspire laptop with Windows 10 operating system and a 24-bit audio card was used to run a FAES called FitCheck Solo. The FitCheck Solo test signals were presented with circumaural headphones, and the participants made their responses with a wireless USB mouse.

2.3. Procedures

At the beginning of each test, the participants completed a consent form. The experimenter stood behind the participant to measure ear canal diameters for both left and right ears. Next, the experimenter sat in front of the participant. The laptop faced the experimenter so the participant could not see the screen (see Fig. 1).

The experimenter read the procedure instructions from the FitCheck Solo manual: “When the test begins, FitCheck Solo will present a pulsing test sound. Use the scroll wheel on the mouse to adjust the volume of the pulsing test sound so that you can barely hear it. You can lower the sound until you don't hear it and then bring it up until you can barely hear it if that is easier. After you are satisfied with your adjustment, click the left mouse button. The sound will then get louder, and you are to repeat the process. Eventually the test sounds will change frequency, or pitch as the test proceeds through multiple frequencies. Keep performing the same operation with the mouse wheel and left button. I will monitor the test and tell you when it is complete."

To obtain hearing thresholds, one-third of the octave-band noise stimuli were presented binaurally at a presentation level that was well above the threshold (80 dB Sound pressure level (SPL)). The selected presentation frequencies were 500, 1000, 2000, and 4000 Hz. For each frequency, the participants adjusted the noise stimulus to the minimum level possible before becoming inaudible. Once this level was selected by the participant, the presentation level was increased from 10 to 20 dB. The participant was required to select three consecutive threshold values within a range of less than 6 dB before moving on to the next frequency. The threshold level was recorded as the average of the three consecutive values.

Initial hearing thresholds were measured in the unoccluded ears. After obtaining unoccluded thresholds, the participants were instructed to insert their HPDs the way that they normally would to perform an HPD PAR test. For occluded conditions, a two-minute waiting period automatically preceded the testing to ensure that the foam earplugs had fully expanded. The test was then performed to obtain the occluded threshold. The PAR was automatically calculated by subtracting the open threshold from the occluded threshold.

After obtaining the untrained occluded threshold, the participants removed their HPDs and were instructed by the experimenter on how to properly insert a new pair of HPDs as per the following written instructions:

1. Grab the plug with your two hands between the thumb and the index finger.
2. Roll the plug slowly into a thin cylinder.
3. Grab the tip of your right ear with your left hand (over your head), and pull it backwards and upwards to straighten your ear canal.
4. Push the previously formed cylinder as far as possible inside your ear canal.
5. Grab the tip of your left ear with your right hand (over your head), and pull it backwards and upwards to straighten your ear canal.
6. Push the previously formed cylinder as far as possible inside your ear canal.

The experimenter ensured that the procedure was followed and that the HPD was properly inserted. The PAR was automatically calculated by subtracting the open threshold from the post-training HPD threshold.

In Study II, an additional measure was included. We assessed the following in the questionnaire: participants' subjective measures of discomfort of HPD use, how frequently they use them, and how knowledgeable they are on HPD insertion (see Appendix 1). After completing PAR measurements, the participants moved to a second table with a questionnaire. The participant was allowed to ask any clarifying questions needed. Once completed, the participants were debriefed on the purpose of the experiment and thanked for their participation. In Study I, the participants were debriefed after the last PAR measurement.

2.4. Analysis

PAR dB values are an average of 4 frequencies for right and left ears in (1) an unoccluded condition, (2) an occluded pretraining condition, and (3) an occluded post-training condition. Questionnaire data were scored on a scale from 1 to 4. Pearson correlations were calculated using the Excel CORREL function, and paired sample t-tests were performed using the Excel T.TEST function. Scatterplots were generated using the Excel Scatter Chart, and bar graphs were generated using the Excel Bar Chart. The line of best fit, regression formula, and the coefficient of determination were obtained using Excel. An analysis of variance was performed using IBM Corp. 2017. 017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp. using the repeated measures function in the "Analyze" menu with post hoc testing selected.

Table 1
Study I data.

Participant	Ear canal diameter		PAR HPD before training	PAR HPD after training	PAR HPD improvement
	L	R			
1	XL	XL	25.9	22.1	-3.8
2	L	L	32.0	23.2	-8.8
3	M	M	22.4	28.7	6.3
4	L	M	9.4	27.3	17.9
5	L	L	22.7	5.3	-17.4
6	M	M	19.1	16.9	-2.2
7	L	XL	31.8	30.1	-1.7
8	XL	L	24.1	26.5	2.4
9	M	L	18.2	28.2	10.0
10	L	L	29.3	32.5	3.2
11	M	M	30.5	28	-2.5
12	S	M	15.0	29.8	14.8
13	M	L	29.3	35.4	6.1
14	L	L	22.2	24.6	2.4
15	M	M	28.9	29.7	0.8
16	M	M	27.0	32.5	5.5
17	M	L	25.9	29	3.1
18	S	S	23.8	23.3	-0.5
Average					2.0
Standard error					1.9

HPD, hearing protection device; PAR, personal attenuation rating.
Data include canal diameter of both left and right ears, pretraining PAR, post-training PAR, and the level of PAR improvement (measured as the difference before and after training).

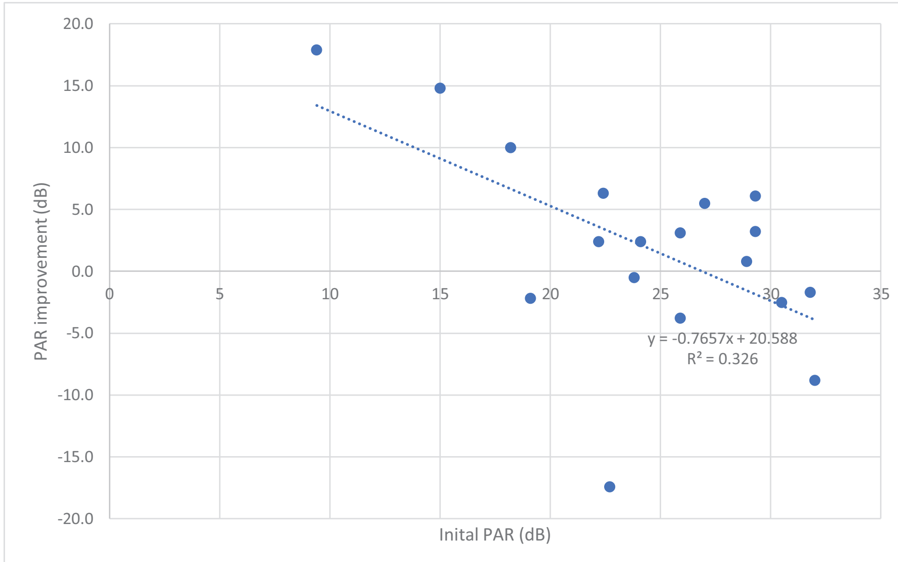

Fig. 2. Improvement as a function of pretraining PAR in Study I. A negative correlation was observed between the pretraining PAR and level of PAR improvement, r(17) = -.571, *p* = .013. PAR, personal attenuation rating.

3. Results

3.1. Study I

3.1.1. Personal attenuation rating

Table 1 shows the data of the participants in Study I. Column 1 has the participants' number, Column 2 has ear canal diameter for their left and right ears, Column 3 has their pretraining PAR, Column 4 has their post-training PAR, and Column 5 has the difference between the two PARs (i.e., the level of improvement).

The post-training PAR was significantly higher than the pretraining PAR, $t(17) = -7.521$, $p < 0.001$. The pretraining PAR correlated with the level of improvement, $r(17) = -.571$, $p = .013$. As seen in Fig. 2, the direction of the relationship is negative, indicating that a higher pretraining PAR (i.e., better) is associated with less PAR improvement after fit training.

3.2. Study two

3.2.1. Personal attenuation rating

Table 2 shows the data of the participants in Study II. Consistent with Study 1, the post-training PAR was significantly higher than the pretraining PAR, $t(13) = -6.468$, $p < 0.001$, and the pretraining PAR correlated with the level of improvement, $r(13) = -.663$, $p = .010$; see Fig. 3.

3.2.2. Questionnaire

Table 3 shows the questionnaire data of the participants in Study II. Each column corresponds to a question in the questionnaire, and the answers have been coded so that a = 1, b = 2, c = 3, and d = 4. The rows indicate the responses from each participant, as well as the mean and mode for each question.

Table 2
Study II data.

Participant_ID#	Ear canal diameter		PAR before training	PAR after training	PAR improvement
	L	R			
19	S	S	27.8	30.9	3.1
20	L	L	34.9	35.2	0.3
21	S	S	16.5	28.2	11.7
22	XS	XS	14.0	33.8	19.8
23	L	L	22.4	27.4	5.0
24	XS	XS	33.0	36.3	3.3
25	M	XL	32.7	26.4	-6.3
26	L	L	21.4	28.0	6.6
27	L	M	21.2	15.8	-5.4
28	L	L	40.6	37.6	-3.0
29	L	M	22.5	29.0	6.5
30	S	S	28.9	29.8	0.9
31	M	M	19.3	18.4	-0.9
32	S	S	32.2	26.0	-6.2
Average					2.5
Standard error					1.9

PAR, personal attenuation rating.
Data include ear canal diameter of both left and right ears, pretraining PAR, post-training PAR, and the level of PAR improvement (measured as the difference before and after training).

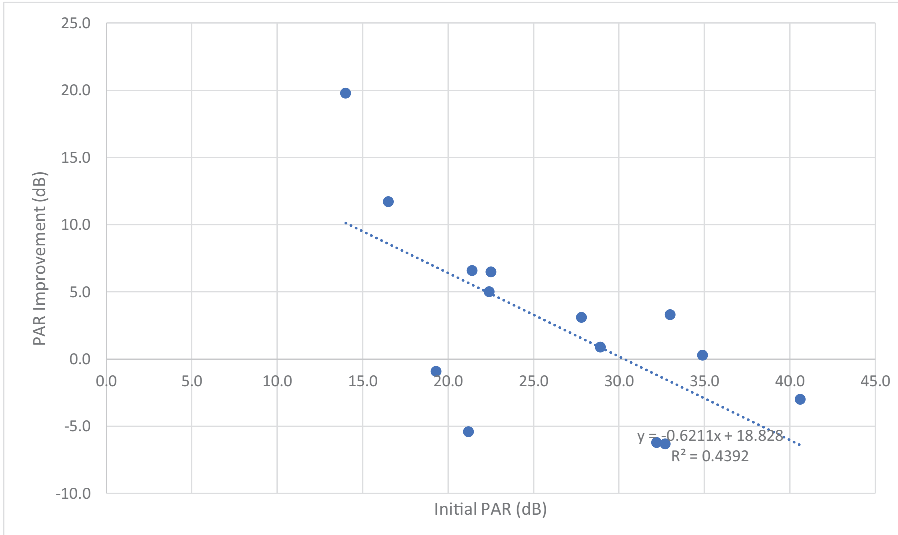

Fig. 3. Improvement as a function of pretraining PAR in Study II. A negative correlation was observed between the pretraining PAR and level of PAR improvement, r(13) = -.663, p = .010. PAR, personal attenuation rating.

3.2.2.1. Frequency of use. The most common response to Question 1 "How often do you use earplug hearing protectors on the job?" was "2; Once or twice a week." The most common response to Question 2 "How often do you think you should be wearing hearing protectors on the job to protect your hearing?" was "1; Daily." The most common response to Question 3 "On days when you do use earplugs how long are they worn for?" was "2; 1–2 hours." None of these questions were shown to correlate with PAR measures.

3.2.2.2. Confidence. The most common response to Question 4 "Please evaluate your confidence with proper insertion of earplugs prior to tutorial" was "3; Medium." The responses to this question correlated with the pretraining PAR, r(13) = .676, p = 0.008 (see Fig. 4).

The most common response to Question 5 "Please evaluate your confidence with proper insertion of earplugs after completion of tutorial" was "4; High." The responses to this question did not correlate with the PAR, but the difference between Question 4 and 5 (calculated by subtracting Question 4 from Question 5) gave us a confidence improvement value that correlated with PAR improvement, r(13) = .698, p = .006 (see Fig. 5).

3.2.2.3. Discomfort. The most common response to Question 6A "Discomfort from earplugs upon insertion" was "1; No discomfort." The most common response to Question 6B "Discomfort from earplugs due to heat after prolonged use" was "1; No discomfort." The most common response to Question 6C "Discomfort from earplugs due to humidity after prolonged use"

Table 3
Study II questionnaire data.

ID	Q1. How often do you use earplug hearing protectors on the job?	Q2. How often do you think you should be wearing hearing protectors on the job to protect your hearing?	Q3. On days when you do use earplugs how long are they worn for?	Q4. Please evaluate your confidence with proper insertion of earplugs prior to tutorial.	Q5. Please evaluate your confidence with proper insertion of earplugs after completion of tutorial.	Q6a. Physical discomfort from earplugs upon insertion.	Q6b. Physical discomfort from earplugs due to heat after prolonged use.	Q6c. Physical discomfort from earplugs due to humidity after prolonged use.	Q6d. Discomfort (or inconvenience) due to communication difficulties (e.g., interference with speech or alarms).
P01	2	1	2	3	4	2	2	2	3
P02	1	1	2	4	4	1	1	1	1
P03	2	1	2	3	4	1	2	2	3
P04	1	1	2	2	4	1	1	1	1
P05	2	2	1	2	3	3	2	3	2
P06	4	3	2	2	4	1	1	1	3
P07	2	1	3	4	4	1	1	1	1
P08	2	1	1	2	4	1	1	1	2
P09	4	1	4	3	4	2	3	3	3
P10	4	1	1	4	4	1	1	1	3
P11	4	1	1	3	4	1	1	1	3
P12	3	2	1	3	4	1	1	1	1
P13	2	4	2	2	2	3	4	4	4
P14	1	1	2	4	4	1	3	3	3
Mean	2.43	1.50	1.86	2.93	3.79	1.43	1.71	1.79	2.36
Mode	2	1	2	3	4	1	1	1	3

Data include all questionnaire results.

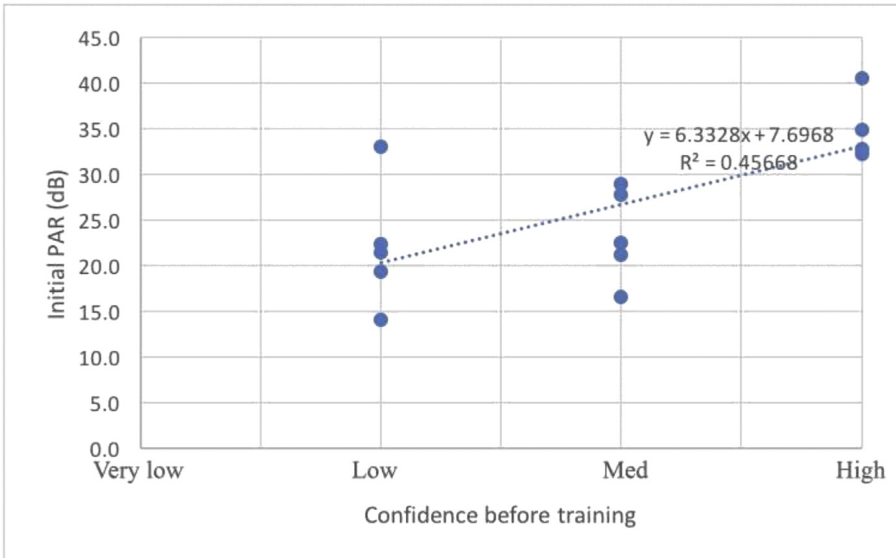

Fig. 4. Correlation between the pretraining PAR and pretraining confidence. A positive correlation was observed between the pretraining PAR and confidence with proper insertion of earplugs before the tutorial, r(13) = .676, p = .008. PAR, personal attenuation rating.

was "1; No discomfort." The most common response to Question 6D "Discomfort from earplugs due to communication difficulties" was "3; Moderately uncomfortable."

A repeated measures analysis of variance with Greenhouse–Geisser correction was performed on the averages of the four types of discomfort, $F(1.917, 24.926) = 7.098$, $P < 0.004$. Post hoc tests using Bonferroni correction revealed that discomfort from communication is significantly worse than insertion ($p = 0.02$), marginally worse than heat ($p = 0.08$), and not significantly worse than humidity ($p = .241$). See Fig. 6 for a bar graph indicating the different averages for the different discomforts.

3.3. *Both studies*

3.3.1. *Ear canal diameter*

A secondary interest in these studies was the influence of symmetry of ear canals on the PAR. We predicted that PARs would be lower for individuals with asymmetric ear canal diameters. Table 4 shows average PARs obtained in Studies I and II for participants with symmetric and asymmetric ear canal diameters. The obtained results were inconsistent across studies and did not align with our prediction.

3.3.2. *Improvement function*

As per the line of best fit computed in the regression model, we can assume that every additional 1 dB in a participant's pretraining PAR leads to a reduction in the post-training PAR improvement by 0.67 dB (see Fig. 7). The participants received no benefit of training if their pretraining PAR was 28.5 dB or higher. Note that this value is the same as the NRR for the HPDs used in our study (29 dB). When the pretraining PAR is approaching an HPD's NRR, people may see less improvement from training because they are already using the HPD as intended.

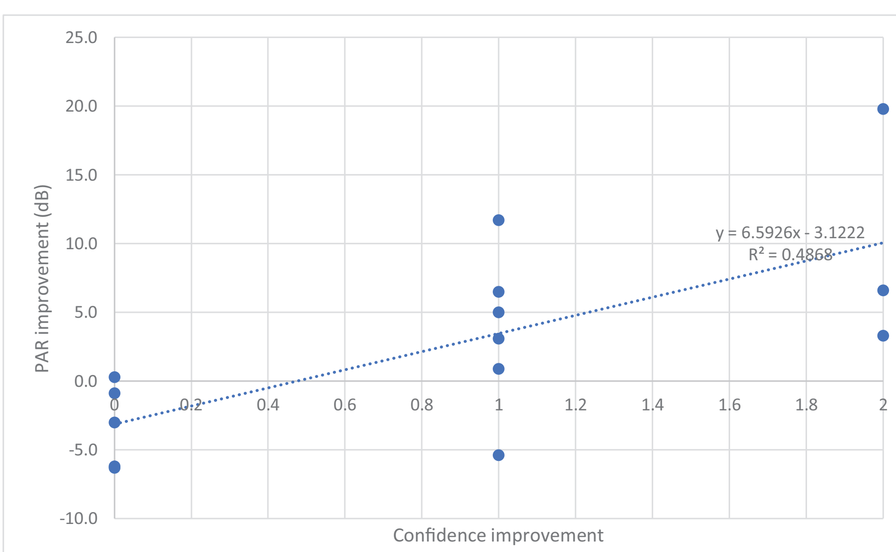

Fig. 5. Correlation between PAR improvement and confidence improvement. A positive correlation was observed between PAR improvement (post-training PAR subtracted by pretraining PAR) and confidence improvement (post-training confidence subtracted by pretraining confidence), r(13) = .698, p = .006. PAR, personal attenuation rating.

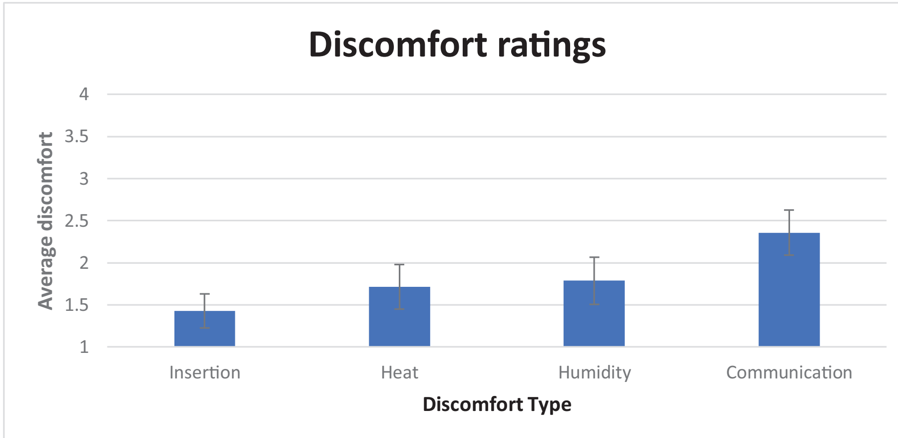

Fig. 6. Discomfort ratings. Average ratings for the level of discomfort from HPD insertion, humidity, heat, and communication difficulties. HPD, hearing protection device.

4. Discussion

In both studies, correlations between the pretraining PAR and level of PAR improvement were significant. This suggests that individuals who had poorer pretraining PARs benefitted the most from training. Our study found that for every decibel less of a participant's pre-training PAR, training improved their PAR by 0.67 dB. Ideally, these individuals would be targeted through a pre-training PAR assessment to streamline the training process. This approach of using a pretraining assessment has been effective in previous studies for improving the PAR [13,14]. Noisy workplaces might consider a pretraining assessment to reduce the training time and focus on those who need training the most.

In both studies, we did not find an effect of ear canal diameter symmetry on the PAR, despite our prediction that asymmetric ear canals would lead to a reduced PAR. This finding suggests that despite differences in ear canal diameter between the ears, users can still achieve a sufficient PAR when using standard foam HPDs. For workplaces, providing standard 3M foam earplugs is sufficient to protect workers against hearing loss despite variability in the ear canal size.

The pretraining confidence measure correlated with the pre-training PAR. This finding suggests that an individual's evaluation of self-performance with HPD insertion is reasonably accurate. If workers are less skilled at insertion, then they are aware of this and therefore less confident. Assessing workers' confidence before training may assist in streamlining the training process to focus on those who need training the most. However, other studies suggest that HPD self-efficacy is not related to the baseline PAR [14], so further research is recommended.

When comparing PAR improvement with confidence improvement, we found another positive correlation. This means that the higher the user's confidence, the higher the PAR achieved, and this suggests that users are generally able to detect whether they are achieving a sufficient seal or not.

Table 4
Earcanal diameter.

Study	Summary			
	Study 1		Study 2	
	N	PAR	N	PAR
All participants	18	1.98	14	2.53
Same diameter	11	1.55	11	3.69
Different diameter	7	7.51	3	1.73

PAR, personal attenuation rating.
PARs for both studies when comparing an asymmetric ear canal group with a symmetric ear canal group. No significant differences were found.

The most common response to the question with regard to how long individuals usually wear earplugs is “1-2 hours.” Considering that work shifts are rarely this short, this is concerning from a health and safety perspective. It is likely that participants are removing the HPDs owing to discomfort, as some research studies show that up to 48.4% of wearers experience discomfort after 1 hour of wearing, and only a quarter of wearers did not have discomfort after 2 hours [15]. In line with our findings on causes of discomfort, the study suggests that the discomfort arises mainly from difficulties in conversation, but also other issues such as itchiness and stuffiness. To improve adherence to proper protocol, workplace managers and earplug manufacturers need to consider how to reduce communication difficulties as these seem to be the top reason for workers to avoid wearing HPDs for an extended period of time.

Interestingly, questions on frequency of HPD use did not correlate with other measures. This suggests that HPD use, unlike other skills, does not require frequent practice to maintain sufficient proficiency. We have demonstrated that the PAR increases immediately after training, and some other research studies also suggest that improvements can last as long as six months after training [14]. Future work should investigate long-term benefits of HPD training and identify the length of time it takes for training effects to diminish. This could help introduce a sufficient retraining cycle into the training schedule.

Our study is not without limitations. An alternative explanation for the correlation between baseline and the level of improvement could be related to regression to the mean. We show that using the change score as the outcome measure neither addresses the problem of regression to the mean nor takes into account the baseline imbalance. Whether the outcome is the change score or post-score, one should always adjust for baseline using analysis of covariance; otherwise, the estimated treat effect may be biased.

The authors acknowledge that another limitation to this study was asking the participants to rate discomfort on closed-ended questions. A better evaluation of discomfort would have been to use open-ended questions so that participants could generate their own causes for discomfort. Future studies could dig deeper into the causes of discomfort with interviews or open-ended questionnaires.

The HPDs used in these studies were of self-expanding PVC foam, so it is possible that they expanded enough to achieve a

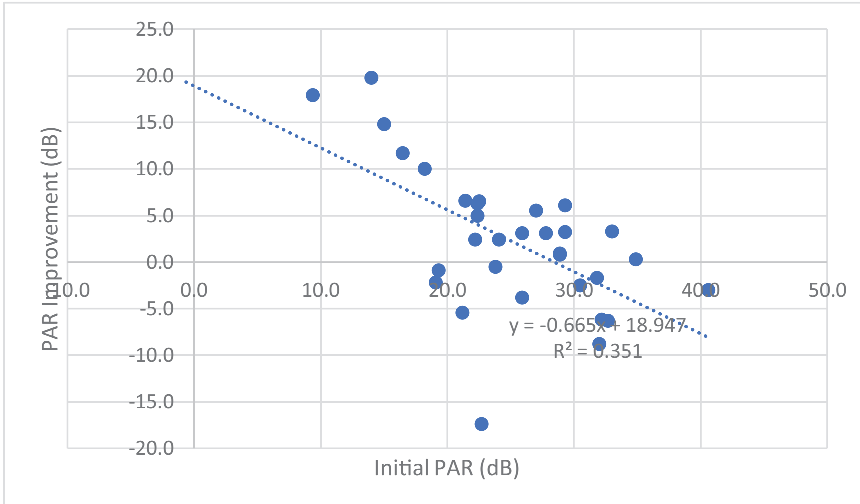

Fig. 7. Line of best fit for Study I and II. The participants received no benefit of training when their pretraining PAR is 28.5 dB. PAR, personal attenuation rating.

sufficient seal in both ears. It is possible that a sufficient seal may not be achieved for HPDs of a different variety that do not expand.

Based on our results, we propose that field assessments of HPD efficacy should include a question on confidence and a pretraining PAR to target individuals who need training the most, and future studies should investigate the length of time that it takes for the training effects to diminish.

Conflicts of interest

The authors confirm that there is no conflict of interest.

Acknowledgments

The authors thank Jason Hoffman (Manager of Health and Wellness at Hydro One) for his facilitation of data collection. The authors thank Michael Associates & Inc. for kindly providing the FAES equipment. The authors thank Elizabeth Earle and the reviewers for their work in revising the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2020.09.006.

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