

Musician earplugs: Appreciation and protection

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Abstract

Recreational music exposure is a potential risk factor for noise-induced hearing loss (NIHL). Augmented hearing protectors have been designed with modified attenuation characteristics to combine hearing protection and listening comfort. However, to date, only a few independent studies have assessed the performance of those augmented protectors in realistic exposure conditions. This study compares the listening experience and temporary effects on cochlear status with different types of earplugs after exposure to contemporary club music. Five different types of commercially available hearing protectors were worn, all commonly used during leisure-time music exposure. Four of them were augmented premolded earplugs and the fifth type was an inexpensive, standard earplug frequently distributed for free at music events. During five different test sessions of 30 min each, participants not professionally involved in music wore one particular type of protector. Contemporary club music was played at sound pressure levels (SPLs) representative of concerts and bars. After each listening session, a questionnaire on sound quality and general appreciation was completed. In addition, otoacoustic emissions (OAEs) were measured directly before and after music exposure. The reported appreciation clearly differed depending on the addressed characteristics and the specific earplug type. In this test group, the reported appreciation mainly depended on comfort and looks, while differences in sound quality were less noticeable. The changes in OAE amplitude before and after noise exposure were small in terms of clinical standards. Nevertheless, the observed temporary shifts differed systematically for the different types of hearing protectors, with two types of musician earplug showing a more systematic decline than the others. Further research with respect to actual use and achieved protection for real, unsupervised music exposure is warranted.

Keywords: Music exposure, noise-induced hearing loss (NIHL), otoacoustic emissions (OAEs), personal hearing protection

Introduction

Music exposure is one of the possible causes of leisure-time noise-induced hearing loss (NIHL).^[1-3] The risk can be reduced by wearing personal hearing protection. Standard hearing protectors used in the industry might not be ideal in a leisure-time context because their attenuation generally increases with increasing frequency. Hence, they distort the spectrum of the music^[4,5] and potentially deteriorate listening quality.

As an alternative, augmented “musician” earplugs have been developed to offer a perceptually undisturbed listening

experience at safe exposure levels. At first these augmented protectors were custom-made devices,^[6] but currently a wide range of premolded earplugs is available in different designs, styles, and price categories. In addition, they are no longer exclusively intended for professional music exposure, but also address the vast population of young adults occasionally exposed during leisure-time activities. Judging from the advertisements for the earplugs, they appear to be mostly sold for exposure to contemporary club/pop music.

Musician earplugs mostly aim for spectrally flat attenuation characteristics to prevent the spectrum of the music from being distorted when hearing protectors are worn. In general, musician earplugs also attenuate less than standard earplugs. Less attenuation can be an advantage if music exposure levels are indeed lower than industrial noise exposure, as overattenuation hampers communication and consistent use.^[7] Nevertheless, the question arises whether less attenuation is still sufficient.

Nominal attenuation or the assumed protection value (APV)^[8] reported by the manufacturer is not the only factor

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determining the finally offered protection. The capability of the user to fit the earplug correctly in the ear canal is crucial when hearing protectors are fitted unsupervised, i.e., without guidance from a professional.^[9] The fitting of an earplug depends on the interplay between, among other factors, the user's handiness, external ear canal morphology, the shape of the earplug, and perceived comfort.^[10]

Apart from correct fitting, consistent use is equally important to achieve actual protection. In this regard, consistent use strongly benefits from a general positive attitude with respect to hearing protectors.^[11] Here, the more spectrally flat attenuation of musician earplugs, aiming for better sound quality, might enhance positive appreciation of the protectors.

With respect to appreciation, most available studies focus on professional musicians or people very much involved in music, often with custom-made augmented protectors instead of premolded. As expected, sound quality is of major concern for this population.^[5,12-14] The question is whether untrained listeners value sound quality to the same extent, or whether other aspects like comfort and esthetic contribute more to their appreciation of earplugs. In this regard, Chesky *et al.*^[12] have shown that both music college students and non-music college students report some comfort and communication issues with one particular type of musician earplug, but that in general the earplugs are well appreciated.

To assess the actual quality of protection offered by earplugs, changes in cochlear status before and after noise exposure can be assessed using otoacoustic emissions (OAEs). These signals are the epiphenomenon of energy-consuming cochlear amplification associated with outer hair cell activity in the organ of Corti. High-intensity noise primarily damages the outer hair cells. This way, OAEs offer an objective and reliable way to detect early signs of NIHL.^[15,16]

This study aimed to systematically compare the subjective appreciation and protective capacities for different types of commercially available premolded musician earplugs. Laboratory experiments with one standard and four musician earplugs were carried out. The four musician earplugs differed markedly in design, attenuation, and price. Participants not professionally involved in music were asked to fit the protectors without supervision, following which they listened to contemporary club music. Listening experience was reported afterward using a multiple-choice questionnaire. In addition, immediately before and after music exposure, OAEs were measured to assess subtle changes in cochlear status.

Methods

Musician earplugs

The five earplugs included in this study are depicted in Figure 1. They were acquired through the regular

commercial circuit; none of the relevant companies was actively involved in this project. The standard earplug (Earplug 5) has been chosen because it is often distributed for free at concerts and other music events. All musician earplugs (Earplug nos. 1 to 4) are advertised to be used in leisure-time music exposure and their prices range between €6 (Earplug 1) and €20 (Earplug 2).

The standard Earplug 5 has to be rolled down and it expands in the ear canal. The musician earplugs were all premolded with flexible flanges, but while Earplug 2 and Earplug 3 had stems extending from the plug, Earplug 1 and Earplug 4 were shorter and hence less visible when placed in the ear canal. Especially for Earplug 1, the stem was made particularly short, approximately 4 mm compared to 8 mm for Earplug 4 and 16 mm for Earplug 2 and Earplug 3. With respect to the diameter of the plugs fitting the ear canal, Earplug 1, Earplug 4, and Earplug 5 have a similar maximal diameter of around 11 mm. Earplug 2 is somewhat larger (13 mm) and Earplug 3 somewhat smaller (9 mm).

The attenuation or APV^[8] reported by the manufacturers are depicted in Figure 2. Earplug 2 and Earplug 3 used the same technology to obtain a more or less flat attenuation; Earplug 4 shows a similar spectrum. By contrast, for Earplug 1 the attenuation clearly increased with increasing frequency. As expected, standard Earplug 5 had the highest attenuation.

Music exposure

With each hearing protector, participants listened to exactly 30 min of contemporary club music in a decorated listening room of 4.30 × 4.50 m. Apart from the loudspeakers, electronic equipment was hidden behind a curtain to avoid drawing the subjects' attention. Two bar stools and a bar table were placed centrally in the room so that the subject could listen comfortably to the music.

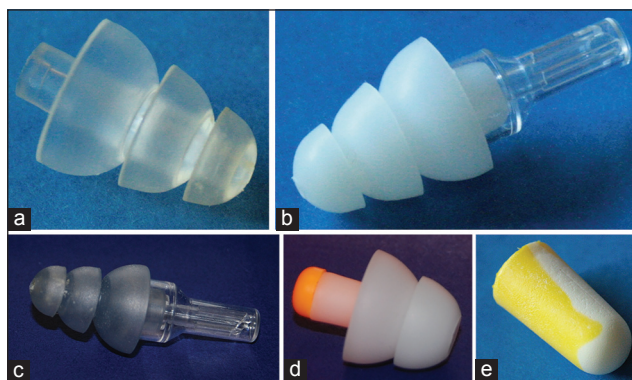


Figure 1: Included earplugs (1 to 5). Between brackets, the approximative maximal diameter of the plug fitting the ear canal is given, followed by the length of the stem for the musician earplugs. (a) Earplug 1 (11 mm; 4 mm); (b) Earplug 2 (13 mm; 16 mm); (c) Earplug 3 (9 mm; 16 mm); (d) Earplug 4 (11 mm; 8 mm); (e) Earplug 5 (11 mm)

Music fragments were played through six active loudspeakers (S1X, ADAM Audio, Berlin), four in each corner of the test space about 3 m above the ground and two at the side at 1.5 m height. Two subwoofers (Adam Sub8) were also placed at the side. The loudspeakers were connected to a desktop computer with a high-class sound card (Alpha-Link Madi AX, Solid State Logic, United Kingdom). Playback settings were adjusted beforehand so that the sound pressure level (SPL) at the central bar table varied approximately between 90 dB L_{Aeq} and 95 dB L_{Aeq} , measured with a Svantek 959 sound level meter (Svantek, Poland). This way, Flemish legislation^[17] concerning electronically amplified music levels was clearly respected.

While the listening tests were carried out, levels were continuously registered with the Svantek sound level meter in one-third octave bands at 0.1-s intervals. The microphone was hung above the bar table at 2.5 m above the ground and the registered A-weighted spectrum of the music is depicted in Figure 3.

Listening experience

The survey on music-listening experience with hearing protectors started with 11 questions about general satisfaction, portability, design, and sound experience. The survey was based on existing surveys^[11,18] and reviewed by international experts on sound quality. Questions were to be completed on a forced-choice four-point scale (totally agree, agree, disagree, and totally disagree). The wording was varied so that agreement could reflect a positive or a negative attitude toward hearing protectors depending on the specific question.

To address specific aspects of sound quality, an approach based on hearing aid assessment was used,^[19] where different aspects of sound quality are represented by two opposite adjectives (for instance, “pleasant” and “unpleasant”). These antonyms formed the two extremes of a ten-point

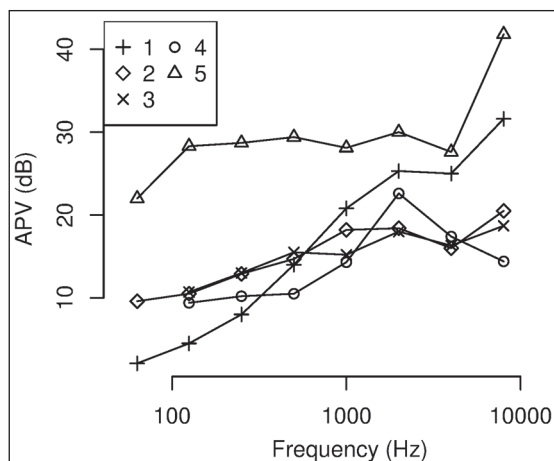


Figure 2: Assumed protection value (APV) reported by the manufacturer for the five hearing protectors tested

scale represented by 10 plain boxes. Participants had to check the box they felt most appropriate. On this scale, no indications were present except for a colored box in the middle between the two extremes, representing a more neutral experience.

OAE measurements

Distortion-product otoacoustic emissions and transient-evoked otoacoustic emissions (DPOAEs and TEOAEs respectively) were measured in a relatively quiet but not soundproof room close to the listening room using the ILO 292 USB device (Otodynamics, United Kingdom) and ILO v6 software. The equipment was calibrated daily using a 1-cc cavity. Each time after sealing the probe in the external ear, a check-fit procedure of the probe was performed to ensure a biphasic deflection on the oscillogram and a spectrally flat stimulus between 500 Hz and 6000 Hz.

DPOAEs were recorded in accordance with the $2f_1 - f_2$ DP-gram procedure presenting the primary frequencies f_1 and f_2 simultaneously at stimulus levels of 65 dB SPL and 55 dB SPL respectively. DPOAE amplitude and noise levels were measured at frequencies $2f_1 - f_2$ for f_2 ranging from 841 Hz to 8000 Hz at 8 points per octave band. The ratio between the frequencies f_2/f_1 was set at 1.22. Per measurement, the whole frequency span was looped over twice in descending order. The artifact rejection level was set at 6 mPa.

TEOAEs were recorded in accordance with the nonlinear differential method of presentation, using a rectangular pulse with duration of 80 μ s. The clicks were presented at a rate of 50 per second. Stimulus level was set at a 80 dB SPL peak, and signals were averaged over 260 repetitions. The artifact rejection level was set at 6 mPa. The TEOAE amplitude levels were examined for frequency bands with central frequencies 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, and 4000 Hz.

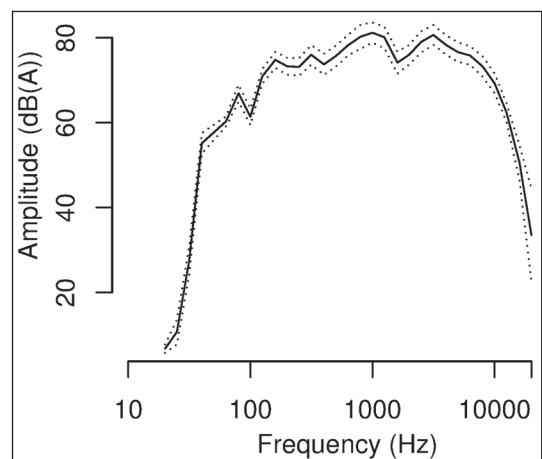


Figure 3: A-weighted spectrum of music exposure in one-third-octave bands: average over all listening episodes (full line) and average \pm one standard deviation (dashed lines)

Selection of test participants

The study was approved by the local Ethical Committee of Ghent University Hospital, and all volunteers agreed to give informed consent in accordance with the statements of the Declaration of Helsinki.

In this study, 59 subjects were included, of whom 31 were men and 28 were women. Participants had to be between 18 and 30 years old; male subjects were on average 23 years old (3.2 years standard deviation) and female 22 years (3.0 years standard deviation). Subjects were mainly recruited from among university students and employees; people professionally involved in music were *a priori* excluded.

Before the actual testing, each participant's auditory status was checked on a separate test day. For the left and right ear separately, otoscopy, tympanometry, and tonal audiometry were done and OAE measurements taken by a qualified audiologist.

For tympanometry, an AA222 impedance meter (Interacoustics, Denmark) was used. Most participants appeared to have normal middle-ear status (type A tympanogram based on the Liden-Jerger classification). In case of minor deviation from normal results, subjects were still included if tonal audiometry and OAEs gave normal results.

Tonal audiometry was measured under TDH39 headphones (Interacoustics) using an AA222 audiometer from Interacoustics and in accordance to the modified Hughson-Westlake technique at octave-band frequencies between 125 Hz and 8000 Hz. For inclusion in this study, air-conduction thresholds had to be better than 30 dBHL for all frequencies.

Furthermore, DPOAEs and TEOAEs were assessed using the same settings as the actual experiment (see Section 2.4). Obviously, OAE signals needed to be clearly present at the beginning of the experiment to be able to monitor any change due to music exposure. The measured signals were considered true OAE responses if they were at least 3 dB stronger than the noise in the corresponding frequency band. To be included in this study, participants needed to show such a response for at least four frequency bands for TEOAE and DPOAE separately.

Protocol

On separate days, each subject tested one of the five types of musician earplugs. The test order of the protectors was randomized across subjects. At the end, the vast majority of the test group had used all five hearing protectors. Due to practical circumstances, one person tested three protectors, five tested two protectors, and three tested only one protector.

The experiment was introduced as a listening experiment for music with hearing protectors without giving the subjects

further information about the hearing protectors. First, DPOAEs and TEOAEs were measured for the left and right ears. Both the order of the OAE measurement (DPOAE and TEOAE) and the test ear (left and right) were randomized. Subsequently, the earplugs were given to the participant in their original packaging, including the manual. Earplugs were fitted by the subjects themselves without any additional instruction or feedback from the researcher. The participant then proceeded to the listening room where music was continuously playing, and was instructed to immediately enter his/her personal code on a desktop PC. An in-house developed LabVIEW routine started a 30-min countdown and showed at the end again the personal code, prompting the participant to leave the room. The subjects had to click the "ok" button when leaving the room: This way, the exact exposure time was stored.

After the music exposure, each subject promptly proceeded to the test room, where DPOAEs and TEOAEs were measured again in random order for the left and right ears. As the listening room and the test room were close together, OAE measurements were started within 2 min after noise exposure so that a temporary threshold shift could be captured. Finally, each subject completed the questionnaire directly after the OAE measurements and handed over his/her copy immediately.

Statistical analysis

First, systematic differences between earplugs brands were assessed for general satisfaction, portability, design, and/or general sound experience. Those aspects were rated on a four-point scale, and for analysis the four-scale responses were recoded into a dichotomous variable. Recoding was done by aggregating "totally agree" and "agree" into the single outcome "agree" and "totally disagree" and "disagree" into "disagree." For the 11 questions from the survey, separate mixed logistic regression models were fitted with the chance of agreeing on the respective question as outcome variable, and as independent variables *hearing protector type* (fixed) and *subject* (random factor, to account for the fact that one subject has rated different protectors). The possible confounding factors *music compilation*, participant's *age*, *gender*, *ear*, and *experience with protectors* were also taken into account. Only those confounding factors are explicitly mentioned in the Results section that contributed significantly to the statistical model ($\alpha = 0.05$).

Before the models were interpreted, modeling assumptions were thoroughly assessed using standard statistical techniques.^[20] Tukey's *post hoc* analysis was carried out to compare the ratings pairwise between the different types of protectors.

Second, sound quality was rated between opposite adjectives. Principal component analysis was used to detect the underlying dimensions in the construct "sound quality" and to evaluate

possible variation in ratings between the different hearing protectors. Biplots were drawn to visualize these results.^[21]

Third, variation in DPOAE and TEOAE amplitudes was assessed before and after music exposure using mixed-model linear regression. Data with potential artifacts (instead of true OAE responses) in the preexposure condition were *a priori* excluded to ensure that no artificial fluctuation would be wrongly included as true cochlear changes. To define artifacts, the amplitude of the OAE signals was compared to the noise level in the corresponding frequency band. If the signal-to-noise ratio in the preexposure condition was 0 dB or less, this signal and the corresponding signal in the postexposure condition were excluded.

Mixed-model linear regression was carried out with post/preexposure shift as the outcome variable separately for DPOAE and TEOAE results. Before the linear regression outcomes were interpreted, the aptness of the analysis' assumptions was again verified by inspecting the standardized and studentized residuals, as well as the influential observations.^[20]

Results

Appreciation of listening experience with different types of earplugs

Appreciation of looks

The rating of the earplug's looks, once fitted in the ear canal, depended most strongly on the earplug type ($P < 2e-16$). The rating on discretion also depends on the participants' previous experience with hearing protectors ($P < 0.01$): Participants who have used standard earplugs before reported more frequently that they found the earplugs less visible. The effect of previous experience on the discretion rating appears to be similar for all included types of earplugs.

Pairwise comparison between earplugs using Tukey's *post hoc* analyses [Figure 4] showed that Earplug 1 and Earplug 4 were significantly more discrete than the three others ($\alpha = 0.05$). As explained in Section 2.1, these earplugs do have a shorter stem than the others.

In line with findings on the discretion of the earplugs, participants' appreciation of their own looks also significantly depended on the type of earplug worn ($P = 2.2e-8$). Not surprisingly, again the overall smallest earplugs Earplug 1 and Earplug 4 were found to be the most esthetical, clearly compared to the standard earplug (Tukey's *post hoc*, $P < 0.001$) but also compared to the other musician earplugs (Tukey's *post hoc*, $P < 0.05$) [Figure 4].

Appreciation of sound quality

Sound quality also appears to be a distinct feature between earplugs ($P = 6.8e-11$). Here all musician earplugs

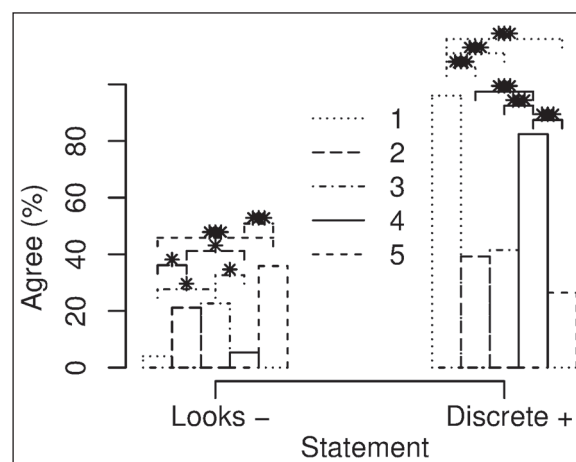


Figure 4: Percentage of participants agreeing with the statement that the protectors make them look ridiculous (looks-) and are discrete once fitted (discrete +) per hearing protector type (1 to 5). Significant pairwise contrasts are indicated by * for $P < 0.05$ and * for $P < 0.001$**

consequently obtained a significantly higher score than the standard earplug (Tukey's *post hoc* analysis, $\alpha = 0.05$), but responses do not differ significantly between the different types of musician earplugs [Figure 5]. The ratings on the participant's preference to hear the music without earplugs differ less strongly between the earplugs types ($P < 0.01$). The only clearly significant pairwise comparison [Figure 5] was found to be in favor of Earplug 1 compared to the standard earplug (Tukey's *post hoc*, $P < 0.01$). A slight preference for Earplug 2 over the standard earplug was also seen (Tukey's *post hoc*, $0.05 < P < 0.1$).

Appreciation of fit

Respondents observed that some earplugs had a better fit than others ($P = 1.9e-8$). A two-way mixed regression model with gender and earplug type showed that male subjects found the fit to be better than did female subjects ($P < 0.01$). This gender effect held true regardless of the type of hearing protector under study.

For the variable earplug, all musician earplugs had a better score than the standard earplug (Tukey's *post hoc* analysis, $\alpha = 0.05$) [Figure 6]. In addition, Earplug 2 was rated significantly worse than Earplug 4 (Tukey's *post hoc* analysis, $\alpha = 0.05$). In fact, Earplug 2 and Earplug 4 have clearly different designs with, respectively, three and two flanges [Figure 1]. Earplug 2 also has the largest plug diameter of all musician earplugs.

With respect to comfort, the results were somewhat less pronounced, but the differences between earplugs were still systematic ($P < 0.01$). Here, Earplug 4 with only two flanges was found significantly more comfortable than the standard foam earplug (Tukey's *post hoc*, $P < 0.01$) [Figure 6] and also preferred over Earplug 2 with three flanges and a somewhat larger plug (Tukey's *post hoc*, $P < 0.05$). Earplug 4 was

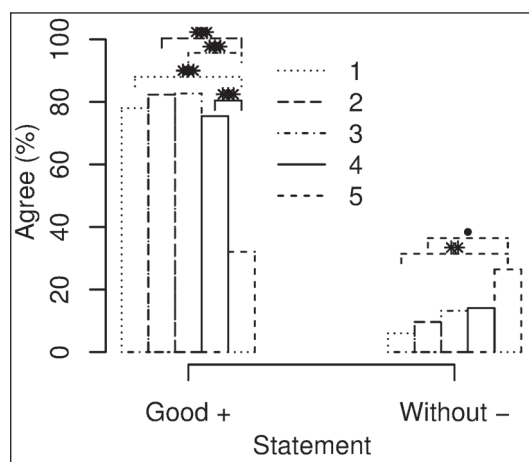


Figure 5: Percentage of participants agreeing with the statement that they enjoyed the music as much as they would probably have done without protectors (good +) and that they would have preferred to listen to the music without protectors (without -) per hearing protector type (1 to 5). (Marginally) significant pairwise contrasts are indicated by • for $0.05 < P < 0.1$, * for $P < 0.05$, ** for $P < 0.01$ and * for $P < 0.001$**

even found slightly more comfortable than the three-flanged Earplug 3 (Tukey's *post hoc*, $P < 0.1$).

General appreciation

Subjects had a clear preference for which earplug they would like to buy ($P < 0.0001$). In this context, it should be noted that the study participants had not been informed about the earplugs' market prices. Earplug 1 was significantly more likely to be bought than both the standard earplug (Tukey's *post hoc*, $P < 0.01$) and Earplug 2 (Tukey's *post hoc*, $P < 0.05$) [Figure 7]. Earplug 4 was also chosen over the standard earplug (Tukey's *post hoc*, $P < 0.05$).

Opinions on general satisfaction appeared less strongly pronounced ($P < 0.05$). The participants were only more clearly pleased about Earplug 1 compared to the standard Earplug 5 ($P < 0.05$) [Figure 7].

Sound quality of earplugs

Despite prominent differences in attenuation between the musician and non-musician earplugs, no strong significant differences were reported between earplugs for perceived loudness or perceived protection ($\alpha = 0.05$). In general, however, almost one-fourth of the participants felt that the music was too loud even with hearing protectors, and they feared that the offered attenuation might be insufficient. On the contrary, no more than 7% judged the music to be too quiet when listening with protectors.

Participants not only rated their appreciation of the sound quality in general, but also rated six major aspects of sound quality (*clear*, *treble*, *distinct*, *near*, *loud*, and *pleasant*) on a ten-point scale. The relationship and importance of these

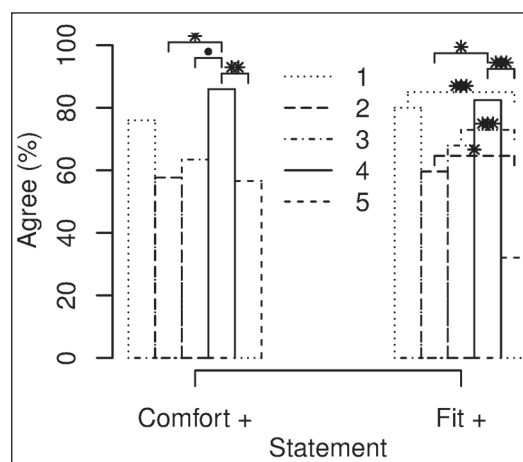


Figure 6: Percentage of participants agreeing with the statement that the protectors are comfortable (comfort +) and stay well-fitted once placed (fit +) per hearing protector type (1 to 5). (Marginally) significant pairwise contrasts are indicated by • for $0.05 < P < 0.1$, * for $P < 0.05$, ** for $P < 0.01$ and * for $P < 0.001$**

variables was addressed using principal component analysis (PCA). The cumulative proportion of variance for the first three PCA components was 86.4%, with 56.7% for the first component, 15.9% for the second, and 13.8% for the third. Components with lower percentages were considered less important.

The first principal component quantified the general sound quality toward which all six included aspects contribute, with slight emphasis on *clear* and *distinct*. The second principal component was dominated by the aspects *loud* and *pleasant* and the third by *treble* and *pleasant*.

Computing the principal components per hearing protector type showed that the foam earplug differs from all musician earplugs [Figure 8], as its general sound quality (PC1) was clearly rated lower than average. For the components *loud-pleasant* (PC2) and *treble-pleasant* (PC3), ratings appeared to vary less depending on the hearing protector. PCA also suggests that the participants did not judge the sound quality of the musician earplugs differently.

OAE variation per earplug type

Systematic variation in OAE amplitude before and after noise exposure

As expected, OAE responses obtained before and after noise exposure varied. For DPOAE shifts, half of the observations were found between -2.0 dB and 1.5 dB (the first and third quartile, respectively), and for TEOAE shifts, between -0.9 dB and 1.1 dB (the first and third quartile, respectively).

In Figure 9, average DPOAE [Figure 9a] and TEOAE [Figure 9b] post/preexposure shifts are shown for the different types of hearing protector. For both DPOAE and TEOAE, the observed average changes are relatively small compared to

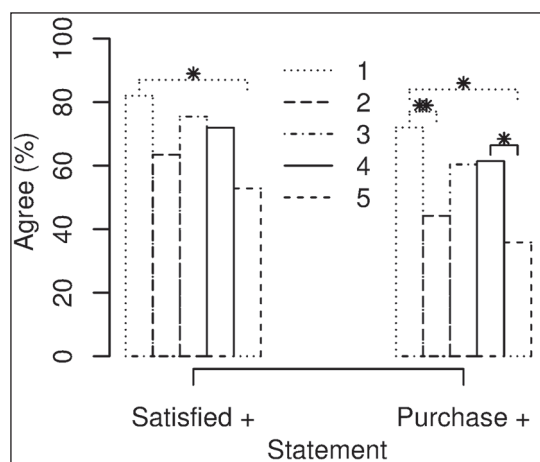


Figure 7: Percentage of participants agreeing with the statement that they are generally satisfied (satisfied +) with their protector and that they would purchase the protector (purchase +) per hearing protector type (1 to 5). Significant pairwise contrasts are indicated by * for $P < 0.05$ and ** for $P < 0.01$

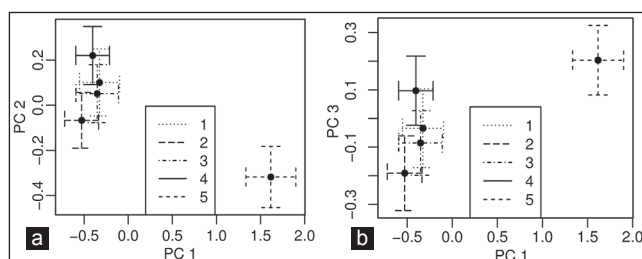


Figure 8: Principal component per type of hearing protector (1 to 5): Mean and standard error. (a) PCA 1 and PCA 2 (b) PCA 1 and PCA 3

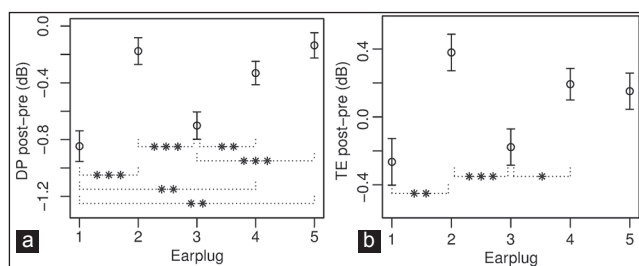


Figure 9: Comparison of post-preexposure OAE shift between earplug types (1 to 5) for DPOAE (a) and TEOAE (b) Per earplug device, the mean shift is shown with error bars spanning the mean ± 1 standard error. Between the earplug types, significant Tukey's *post hoc* comparisons are indicated by *** for $P < 0.001$, ** for $P < 0.01$, and * for $P < 0.05$ (a) DPOAE shift per earplug type (b) TEOAE shifts per earplug type

clinically relevant variations.^[22] This suggests that for none of the earplug types were strong effects of music exposure on cochlear status seen. In addition, the preexposure OAE amplitudes were stable over different test days, confirming that the observed shifts were temporary. Nevertheless, Figure 9 also reveals that the small shifts seem to differ systematically depending on the type of hearing protector.

This finding warrants further analysis. An overview of the subsequent analysis steps is given in Table 1.

To assess the possible effects of the type of earplug on OAE post/preexposure shift, two baseline mixed linear regression models were built: One for DPOAE shifts and one for TEOAE shifts. Both models account for variables, other than the type of earplug, that are known to influence OAE outcome. In the baseline model, either DPOAE or TEOAE post/preexposure shift was modeled as a function of four independent variables: *Participant*, *ear*, *gender*, and *frequency*. The variable *participant* (random factor) was included to account for the fact that each participant was repeatedly tested with different types of earplugs. The variables *ear* (left or right), *gender* (male or female), and *frequency* were added as fixed factors because they are known confounding factors for OAE amplitude.^[23] The variable *frequency* was centered around 4000 Hz and quadrated to account for the fact that the greatest effect of noise exposure is expected in this frequency region.^[15]

To the two baseline models, one for DPOAE one for TEOAE, the variable *music exposure* (LAeq) was added, as higher exposure levels affect OAEs more strongly. For both DPOAE and TEOAE, higher exposure levels introduce, as expected, a more pronounced negative shift in OAE amplitude after noise exposure (regression coefficient $-7.7e-2$ and $-4.4e-2$ for DPOAE and TEOAE, respectively). Table 1 confirms that, especially for DPOAE response [Table 1a], music exposure has a significant effect on DPOAE shift. This is seen from the significant difference between the AIC (Akaike information criterion) value for the baseline model alone and the AIC value for the baseline model with *music exposure* ($P < 0.001$). For TEOAE [Table 1b], the added value of *music exposure* compared to the baseline model alone appeared statistically less strong, but the AIC still showed a tendency to decrease ($0.05 < P < 0.1$).

When the variable *earplug* was then added to the regression model, it was immediately clear [Table 1] that the type of earplug has a strong, statistically significant effect on the OAE shift before and after noise exposure, for both DPOAE ($P < 0.0001$) and TEOAE ($P < 0.001$) results.

Tukey's *post hoc* tests were carried out to compare the observed OAE shifts pairwise between the different types of earplugs. For DPOAE, Figure 9a shows that musician Earplugs 1 and 3 have a systematically more pronounced shift compared to the musician Earplugs 2 and 4, and the standard Earplug 5. For TEOAE, the pairwise differences were less statistically strong [Figure 9b], but the observed differences are consistent with the DPOAE results. Earplug 3 in particular has a more pronounced shift compared to Earplug 2 and Earplug 4. In addition, Earplug 1 shows significantly more negative variation than Earplug 2.

Table 1: Overview of regression models for (a) DPOAE and (b) TEOAE shifts. The model “Base” models the OAE shift as a function of ear, gender, and frequency; the variables music exposure (LAeq), earplug type (HPD), and the music exposure corrected with the earplugs’ APV (LAeqA) were added subsequently to this baseline model. For each of the added variables, the AIC values of the new model and the baseline model were compared (Comp) using chi-square statistics and the associated chi-square value (Chisq), degrees of freedom (Chi df), and *P* value were tabulated per comparison

No.	Model	AIC	Comp	Chisq	Chi Df	<i>P</i> value
(0)	Base	51438				
(1)	(0) + LAeq	51427	(0) vs (1)	13.426	1	0.0002
(2a)	(1) + HPD	51388	(1) vs (2a)	46.916	4	1.587e-9
(2b)	(0) + LAeqA	51430	(0) vs (2b)	10.194	1	0.0014

(a) Regression models for DPOAE shift

No.	Model	AIC	Comp	Chisq	Chi Df	<i>P</i> value
(0)	Base	7361.5				
(1)	(0) + LAeq	7360.5	(0) vs (1)	3.3531	1	0.0671
(2a)	(1) + HPD	7347.3	(1) vs (2a)	20.874	4	0.0003
(2b)	(0) + LAeqA	7363.3	(0) vs (2b)	0.1306	1	0.7178

(b) Regression models for TEOAE shift

OAE differences between earplugs: Potential confounding factors

The previous section clearly shows that the type of earplug has a statistically significant effect on the observed variation in OAE amplitude after noise exposure. However, before these findings can be further interpreted in terms of earplug characteristics, the potential influence of other underlying factors has to be investigated. In this research setup, the following three variables could have (unintentionally) contributed to the observed differences between earplugs:

1. Exposure dose during the listening test as a function of earplug type,
2. OAE amplitude in the preexposure condition for different earplug types, and
3. Measurement conditions during OAE registration per earplug type.

Statistical analyses revealed that for the different earplug types no statistical differences were found for exposure duration, exposure level, or preexposure DPOAE/TEOAE amplitude ($\alpha = 0.05$). This suggests that differences in OAE shift between types of earplugs are not introduced by differences in exposure dose or preexposure OAE amplitude.

Furthermore, the ILO system and Otodynamics software register, by default, the noise level together with the OAE registration. It should be stressed that the registered noise levels were in general very low: During DPOAE registration on average -6.06 dB (standard deviation: 4.74 dB), and during TEOAE on average -5.60 dB (standard deviation: 3.54 dB). Comparing the noise levels to normative data for healthy OAE amplitudes^[24] confirms that the measurement conditions were indeed perfectly suitable for OAE registration.

Apart from the overall low noise levels, (slight) variation in noise levels for pre- and postexposure measurements could still indicate slight variation in measurement conditions, for instance with respect to background noise, physiological noise, or probe placement. Variations in noise levels are expected, but it is important to investigate whether this pattern would coincide with the OAE amplitude variation found for different earplug types. Hence, the mixed linear regression models described previously for OAE responses [Table 1] were run again, only this time post/preexposure shifts in *noise level* are used as outcome variable.

For DPOAE, the average post/prenoise level shift is below 1 dB, but the shifts do differ significantly depending on the earplug type ($P < 0.001$). Tukey’s *post hoc* testing revealed that Earplug 4 has somewhat more systematic variation compared to 1, 2, and 5 ($\alpha = 0.05$). For TEOAE, the average variation is also below 1 dB, and here no statistically significant effect of earplug type was seen ($P > 0.1$). All this strongly suggests that the more systematic decrease in OAE responses found for Earplugs 1 and 3 cannot be explained by differences in OAE measurement conditions between earplugs.

As a final check, the mixed models with earplug type described in Table 1 were subsequently rerun for reduced datasets, excluding more extreme variation in OAE amplitude. It is important to make sure that the observed trends in OAE shifts are valid for the majority of the dataset and not simply governed by (a few) more extreme observations. For DPOAEs, amplitude changes exceeding 20 dB (0.003% of the observations), 15 dB (0.009%), and 10 dB (0.031%) were subsequently excluded and for TEOAEs the same was done for 10 dB (0.002%), 5 dB (0.029%), and 3 dB (0.113%). These analyses revealed that especially the differences in OAE shift observed between Earplug 4 and Earplug 3, and between Earplug 4 and Earplug 2, remained statistically significant for the reduced datasets.

OAE differences between earplugs: Influence of nominal attenuation

The previous sections show that the systematic differences in OAE variation between earplugs is most likely a true difference between earplugs, not introduced by other (unwanted) confounding factors. Hence, intuitively, the most logical explanation for the observed differences would be variation in the nominal attenuation reported by the manufacturers as APV [Figure 2]. To test this hypothesis, the baseline models reported in Table 1 were again used as a starting point. Instead of adding unprotected LAeq values and earplug type, a new exposure variable was made by correcting the music exposure levels per earplug device with their respective octave band APV as shown in Figure 2.

If the observed differences between earplug types are primarily due to differences in APV, one would expect that

this alternative model explains equally well the observed variance in OAE shift as the previous model with unprotected exposure LAeq and earplug type. However, the last rows in Table 1a and 1b show that for both DPOAE and TEOAE the APV-corrected exposure has clearly less added value in the model than introducing the earplug type as such. The new exposure variable is still significant for DPOAE ($P < 0.01$), but not for TEOAE ($P > 0.1$). This suggests that earplug characteristics other than APV should be considered to understand the observed differences in OAE shifts. Possible alternative explanations are discussed in the next section.

Discussion

This study evaluated subjective appreciation of and protective capacities against music exposure for five types of commercial hearing protectors commonly used during leisure-time music exposure. Four protectors were so-called “musician” earplugs: Augmented, premolded earplugs with adapted attenuation for better sound quality and the fifth was a classic/standard type of earplug frequently distributed for free at music events.

The participants in this study showed strong subjective preferences with respect to the different types of earplug. The standard earplug, Earplug 5, was generally disliked. The earplugs with the largest diameter (Earplug 2 and Earplug 5) were rated less comfortably. For appearance, the shortest earplugs (Earplug 1 and Earplug 4) had the highest scores. These two earplugs also had the best overall appreciation. Regardless of the type of earplug, female participants were systematically less satisfied with the fitting of the earplugs in the ear canal compared to male participants. A possible factor here could be sex-related differences in ear canal size.^[25]

The strong correspondence between overall appreciation and appearance suggests that the looks of the earplugs are of importance for this test group of young adults. The systematically more negative rating of the standard earplug is also of interest, because this type is often distributed for free at concerts and other music venues. It might be possible that the participants disliked all of its individual aspects separately, but a general negative feeling towards the standard earplug seems more likely. This could be due to the general appearance and packaging of the standard earplug. The researchers had not given the participants any feedback about the different types of hearing protectors, but the participants were deliberately given each earplug in its original package. Not surprisingly, the packaging of the earplugs sold for leisure-time music exposure is made much more attractive than that of the standard earplug, which was originally intended for occupational exposure.

Esthetical/commercial aspects such as looks, design, marketing, and packaging might be overlooked by health

practitioners when focusing on attenuation and prevention of NIHL. However, if a more appealing design can motivate young adults to wear their protectors consequently, then these factors cannot be neglected.

Furthermore, this test group appeared to give more diversified answers with respect to aspects such as comfort and looks than with respect to sound quality. Apart from the standard earplug being clearly rated lower on all sound quality measures, no systematic differences in various aspects of sound quality are found between the four musician earplugs. The musician earplugs do show spectral differences in attenuation, but these spectral differences were apparently not observed by the participants.

As stated in the Introduction, the sound quality of musician earplugs is of major importance for a professional population.^[5,12-14] It is plausible that sound quality is less important for the current test group of young adults who have occasional, leisure-time music exposure but are not professionally involved in music. It should also be taken into account that in this study general contemporary club music was played, so the participants were not necessarily fond of the music fragments. Even for leisure-time exposure, sound quality could be more important if people listened to music they actually liked.

In combination with the subjective evaluation, the effects of music exposure on OAE responses were investigated for the different types of earplugs. Somewhat more extreme variations in OAE responses were seen compared to normative data.^[22] This might be due to measurement environment: The current measurements were carried out in a quiet but not soundproof room. Nevertheless, analysis of the noise levels confirmed that the measurement conditions were more than acceptable for accurate OAE registration. In addition, the statistical findings hold true when analyses are redone for reduced datasets, subsequently excluding more extreme OAE shifts.

It is clear that the absolute exposure effects observed from the OAE shifts are limited. On average, the decrease in DPOAE response after exposure ranges between 0 dB and 1 dB, clearly less than what would be considered clinically relevant.^[22] In addition, the observed effects are all temporary. The limited effect is expected from the study design, with exposure levels respecting safety limits, limited exposure in time (30 min), and the compulsory use of personal hearing protectors.

Apart from the limited absolute shift, the observed shifts do differ systematically between earplugs. The most obvious explanation for different effects of music exposure would be the nominal protection (APV) offered by the different protectors, but statistical analysis did not confirm this hypothesis. Except for the higher attenuation of the standard Earplug 5, all musician earplugs reach practically

comparable overall levels of attenuation, although spectral differences do exist.

As explained in the Introduction, not only the nominal attenuation but also the fit of the earplug in the ear canal will determine the level of protection obtained by a particular user. Here, the geometrical differences in the designs of the protectors might be of importance. One aspect is the diameter of the plug: A larger diameter might help to realize a tighter fit and more attenuation, and vice versa (see results for Earplug 3). In addition, hearing protectors have to be easy to manipulate to be inserted properly. For the premolded earplugs, the stem extending from the plug helps to hold the earplug. The results for Earplug 1 suggest that a very short stem might hamper correct insertion.

OAE results and earplugs designs can also be linked to the subjective appreciation of comfort. The earplug with the largest plug, Earplug 2, showed less systematic decrease in OAE amplitude but was also rated less comfortably, again suggesting a tighter fit. Trade-off between comfort and attenuation is a very important issue: People are in general very reluctant to wear uncomfortable devices correctly for a longer time, especially in an unsupervised context.^[26]

The current findings raise some concern with respect to the correct and consistent use of hearing protectors in an unsupervised, leisure-time context. The earplugs with the most stable OAE results were generally appreciated less positively, so it is questionable whether young adults will be motivated to actually use them. On the contrary, the most positively rated earplug is one of the earplugs showing a more pronounced shift. In general, one earplug type (Earplug 4) appears to combine subjective appreciation and postexposure OAE stability.

It goes without saying that including brands other than the earplug types tested in this study, might have led to different results. For premolded musician earplugs, the variability in styles, design, and prices currently available on the market is (mostly) covered. Only one type of standard earplug could be included because the current test protocol was already exigent. First, the duration of music listening/exposure had to be long enough for valid evaluation afterward. Second, the vast majority of the participants had to use all protectors to ensure that no individual differences, for instance in general appreciation of hearing protectors, but also in personal susceptibility to NIHL, would confound the comparison between earplug types.

Further research is certainly needed with respect to the implementation of personal hearing protectors to prevent NIHL from leisure-time music exposure. First, the finding that not all types of earplugs are positively appreciated raises concerns about the motivation to actually use them consistently in an unsupervised context. Second, the observed

exposure effects of music exposure with hearing protectors are limited, but they do occur at a very controlled exposure. The question is whether the observed differences in earplugs' protective capacity persist in real exposure conditions. To assess this, follow-up research should be carried out in a larger cohort, for longer exposure time and higher exposure levels, and with no (or very little). If feasible, a control group could be included, attenuation could be measured on an individual basis, and potential (temporary) effects on hearing could be measured with a more extensive audiometric test battery.

Conclusion

This paper addresses subjective appreciation of and protective capacities against music exposure for five types of commercial hearing protectors. The target users were young adults not professionally involved in music. Appreciation appeared to depend mainly on each earplug's looks and comfort of usage; differences in sound quality were less noticed. Additionally, OAE measurements before and after noise exposure showed that two out of five earplug types show a more systematic decrease in OAE amplitude after noise exposure, although the variation is limited in terms of clinical relevance. Nevertheless, it is important to note that one of the most appreciated earplug types also showed the largest OAE shifts, and that the earplug with more stable OAE responses was rated more negatively in terms of comfort.

These findings suggest that in leisure-time music exposure, personal hearing protection is a complex matter where very different aspects such as acoustic attenuation, correct earplug fit, and personal preferences, but also motivation and even marketing need to be optimally accounted for. Hence, well-designed hearing conservation programs are necessary. The population of occasional leisure-time music listeners should be specifically targeted, and actions need to be taken at all levels of risk control.

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