Sound Attenuation of the Indoor/Outdoor Range E-A-R Plug

Guarantor: Sharon. M. Abel, PhD
Contributors: Sharon. M. Abel, PhD; Quan Lam

The sound attenuation provided by the AOSafety Indoor/Outdoor Range E-A-R Plug was examined. This device, currently used in military operations in several countries, is comprised of two plugs that provide conventional ("indoor" plug) and level-dependent sound reduction (the "outdoor" plug), respectively. The effects of the user's gender and repeated fittings were explored. Eight men and eight women were tested on two separate occasions. Unoccluded and protected hearing thresholds were measured for each of nine one-third octave noise bands centered at 0.125 to 8 kHz. Attenuation was calculated as the difference between these two measures. The indoor plug provided 21 to 40 dB of sound reduction across the frequencies tested, closely matching the manufacturer's specification. The outdoor plug provided 5 to 22 dB of conventional attenuation, suggesting that it might serve as a safe means of conventional and level-dependant attenuation in hearing-impaired users. No differences were found in relation to gender or repeated fittings.

Introduction

Personal hearing protection devices (HPDs) are a proven, easily implemented, and cost-effective means of controlling the level of sound reaching the ear. As such, they have the capability of minimizing the development of noise-induced hearing loss.[1-3] HPDs are available in plug and muff styles. Plugs are made in a wide range of materials (e.g., formable polyurethane foam, moldable wax, and premolded silicone rubber), shapes, and sizes.[4] There are two main types of hearing protectors, conventional and level dependent.[5] Conventional devices reduce sounds by the same amount, regardless of their level. However, the sound attenuation is frequency dependent. Typically, the attenuation provided by muffs increases linearly from approximately 10 dB at 0.25 kHz to 35 dB at 1 kHz and then remains fairly constant. Plugs may provide more low frequency attenuation but are comparable to muffs above 1 kHz.[6]

By comparison, level-dependent HPDs do not impede sound at low to moderate sound intensities but do provide protection against exposure to high-level impulse noise.[5] Passive nonelectronic types include precision orifices in an acoustical duct to improve transmission of low-level sounds.[7] High-level impulses greater than a predetermined criterion (e.g., 120 dB, depending on the product) create turbulent air flow in these orifices that restrict their passage. There are two electronic types. The first provides limited amplification of as much as 10 dB at noninjurious sound levels and conventional attenuation in the range considered injurious to human hearing.[8] The second type provides active noise reduction. An electronic circuit housed within the muff inverts the incoming waveform and adds it out of phase to the original.[9] Components of the two waveforms that are out of phase will cancel, thereby reducing the overall level. Active noise reduction is limited to frequencies below 1 kHz.

The focus of interest for the present investigation was the real-world attenuation provided by the AOSafety Indoor/Outdoor Range E-A-R Plug. According to the manufacturer, this device is currently used by the military in several countries. It is comprised of two premolded, flexible plugs made of a thermoplastic elastomer, each with three flanges. The plugs are attached to each other stem to stem and are available in one size (Fig. 1). Based on the manufacturer's specifications, one of the plugs, denoted the "indoor" plug, provides conventional sound attenuation of approximately 22 dB. The other plug, denoted the "outdoor" plug, contains a sharp-edged orifice. If the ear receives a shock wave (e.g., a weapon's discharge), turbulence created in the orifice opening impedes the transmission of sound. The question of interest for the present study was the degree of attenuation provided by each of these plugs in the absence of a shock wave and the degree of similarity of real-world attenuation of the indoor plug to the manufacturer's specification over a broad range of frequencies. It is known that lower values of attenuation accrue from real-world fits.[10] A related question is the degree to which observed values differ across repeated fittings by the same subject.

It has previously been demonstrated that differences exist in the attenuation levels obtained by men and women even when the same brand of earplug is used. In one study, for example, it was found that with earplugs that were available in only one size, women obtained significantly lower levels of sound attenuation than men.[11] This was shown to be because of the fact that women typically had smaller ear canals than men, resulting in a poorer seal of the plug to the ear.[12] The observed attenuation was significantly correlated with the cross-sectional diameter of the ear canal. Because the Indoor/Outdoor Range E-A-R Plug was available in only one size, it was deemed important to examine the effect of gender on attenuation.

The specific objective of the current study was to measure the attenuation of the Indoor/Outdoor Range E-A-R Plug in human subjects. The effect of these plugs on high-level impulse noise was beyond the scope of the present study. The questions of interest were whether the two earplugs (indoor and outdoor) would provide substantially different attenuation levels at a given frequency, how closely the levels of attenuation obtained by participants would match the levels specified by the manufacturer, whether the earplugs would have differential attenuating effects as a function of a participant's gender, and whether there would be significant differences in the attenuation achieved on repeated fittings.

Communications Group, Human Factors Research and Engineering, Defence Research and Development Canada-Toronto, 1133 Sheppard Avenue, West Toronto, Ontario, Canada M3M 3B9.

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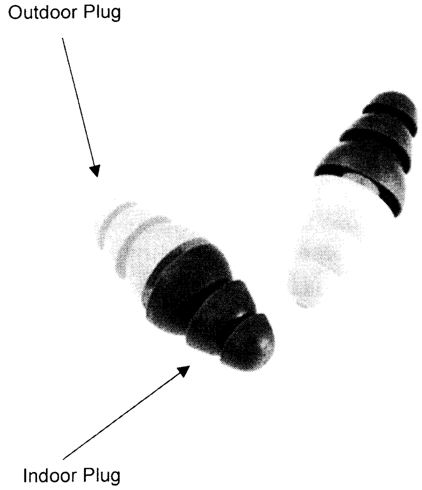

Fig. 1. The Indoor/Outdoor Range E-A-R Plugs manufactured by the Aearo Company.

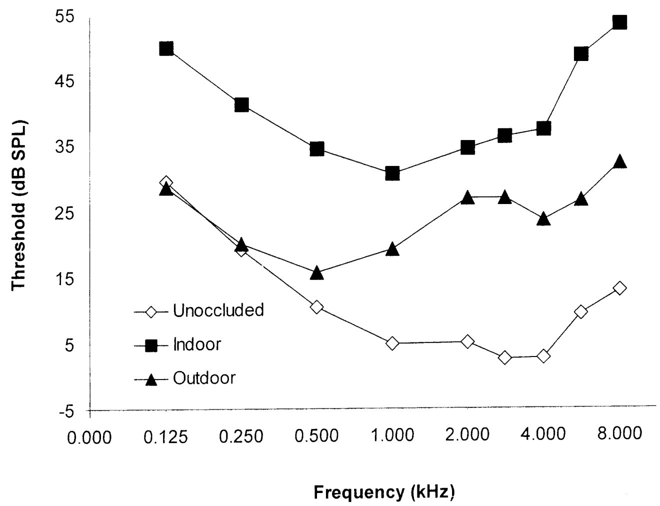

Fig. 2. Unoccluded and protected hearing thresholds as a function of frequency.

Materials and Methods

Experimental Design

One group of 16 working age adults (21–53 years) participated in the study. An equal number of men and women were tested to allow for an assessment of the effect of gender on achieved attenuation levels. Because the attenuation achieved is the same regardless of hearing status,[5] hearing was not a screening factor for subject selection. However, hearing loss is an important consideration in the evaluation of protected speech understanding and the detection of warning signals in noise.[4] Volunteers who had a history of middle ear disease and/or abnormal build up of wax in the ears, conditions that might be further aggravated by the insertion of an earplug, were not accepted.

Within each of two 1-hour sessions separated by 1 week, participants hearing thresholds were measured with the ears unoccluded and they were then subsequently fitted with the two plugs in a quiet background. The attenuation provided by each of the two plugs was derived by subtracting the unoccluded hearing threshold from the protected threshold. The two replications allowed an assessment of the magnitude of differences in achieved attenuation from inconsistencies within the subjects in fitting the earplugs. For the protected conditions, participants were provided verbally with the manufacturer's instructions for inserting the earplugs before doing so themselves. The fits were checked by the tester to ensure that the plugs were well seated in the ear canal. This protocol is a variation of Method A (Experimenter-Supervised Fit) described in ANSI Standard S12.6-1997[10] for measuring the real-ear attenuation of hearing protectors. Subjects were asked to wash their hands before the fitting to minimize any risk of infection. The order of testing the two types of plug (indoor and outdoor) was counterbalanced across subjects to equalize practice effects. Within subject, the order of the plugs was the same for both sessions.

At the conclusion of the experiment, the subjects were asked to rate the comfort of the plugs on a 5-point scale from "very uncomfortable" to "very comfortable." They also indicated how long they would be willing to wear the plugs on a 4-point scale from "I wouldn't wear them" to "A full day."

Subjects

Eight men and eight women ranging in age from 22 to 51 years and 21 to 53 years, respectively, participated in the study. They were recruited by means of notices sent to all employees of Defense Research and Development Canada-Toronto. Each subject received compensation in accordance with guidelines established at this institution.

Apparatus

Subjects were tested individually in a double-walled, semireverberant, soundproof booth (IAC Series 1200; IAC, Bronx, NY) with inner dimensions (3.5 m long × 2.7 m wide × 2.3 m high) and ambient noise levels that met the requirements of ANSI Standard S12.6-1997.[10] A detailed description of the instrumentation and calibration methods is given in Giguère and Abel.[13] A Brüel and Kjaer Instruments (Norcross, GA) white noise generator (B&K 1405; Brüel and Kjaer Instruments) and band pass filter (B&K 1617; Brüel and Kjaer Instruments) were used to produce the one-third-octave noise band stimuli used in the experiment. The duration and envelope shape of the stimuli were set by means of a Coulbourn Instruments (Lehigh Valley, PA) modular system. The output was fed to a manual range attenuator (HP 350-D, Hewlett-Packard, Palo Alto, CA) and power amplifier (RX-V620; Yamaha, Ontario, Canada) and was presented free-field over a set of three loudspeakers (DL10; Celestion; Maidstone, Kent, UK) positioned to create a uniform sound field.

Procedure

Unoccluded and protected hearing thresholds were measured using a variation of Békésy tracking.[14] The stimulus was a train of short pulses. The duration of each pulse was 250 milliseconds including rise and fall times of 50 milliseconds. The time between pulses was 150 milliseconds. During each of the two test sessions, thresholds were measured once for each of nine one-third-octave noise bands, centered at 0.125, 0.25, 0.5, 1, 2, 3.15, 4, 6.3, and 8 kHz. The subject was given a hand-held pushbutton switch and was asked to press the button as soon as the sound was detected and to keep the button depressed

TABLE I

HEARING THRESHOLDS (DB SPL) WITH EARS UNOCCLUDED AND FITTED WITH THE INDOOR/OUTDOOR RANGE E-A-R EARPLUGS

			Frequency (kHz)								
Ear Condition	Gender	Replications	0.125	0.25	0.5	1	2	3.15	4	6.3	8
Unoccluded	M	1	30.4 (4.2)[a]	19.4 (4.8)	10.6 (4.6)	5.5 (2.9)	5.4 (5.4)	3.9 (3.3)	4.3 (2.6)	10.6 (4.6)	14.6 (6.6)
		2	28.3 (5.7)	18.3 (3.6)	9.5 (5.3)	3.9 (3.6)	4.3 (4.2)	4.1 (3.9)	3.6 (3.0)	10.3 (5.0)	13.5 (5.4)
	F	1	30.9 (1.5)	19.0 (2.9)	10.9 (4.7)	4.1 (5.7)	4.8 (2.8)	1.1 (2.4)	1.1 (6.7)	7.8 (5.7)	11.3 (3.8)
		2	30.8 (2.6)	20.3 (6.3)	10.3 (4.5)	5.4 (6.4)	5.4 (2.8)	1.0 (3.2)	2.0 (6.7)	9.0 (5.1)	12.3 (3.3)
Indoor plug	M	1	48.9 (4.9)[b]	42.5 (6.6)	32.4 (6.5)	30.3 (9.4)	36.6 (6.3)	38.9 (6.2)	40.3 (7.1)	48.9 (7.0)	55.6 (4.5)
		2	50.1 (8.5)[b]	41.3 (9.7)	34.9 (10.0)	31.3 (7.1)	33.1 (9.1)	34.5 (8.9)	37.0 (10.8)	51.9 (9.5)	56.3 (4.3)
	F	1	51.8 (9.1)	40.3 (9.3)	35.0 (9.9)	29.1 (6.1)	33.6 (3.4)	35.0 (3.9)	34.3 (7.0)	45.0 (6.7)	49.4 (5.7)
		2	50.8 (6.4)	40.8 (4.2)	35.0 (5.8)	31.6 (4.8)	34.1 (5.9)	36.1 (4.5)	36.9 (6.7)	48.4 (6.3)	51.5 (5.0)
Outdoor plug	M	1	28.1 (6.0)	20.9 (4.8)	16.1 (5.2)	19.0 (3.1)	28.3 (6.5)	28.1 (3.8)	23.1 (3.6)	27.5 (4.3)	33.9 (2.9)
		2	27.8 (6.0)	18.6 (4.7)	14.1 (6.4)	16.6 (5.2)	25.4 (6.1)	25.3 (6.4)	22.8 (4.7)	26.5 (7.3)	32.8 (5.4)
	F	1	31.5 (3.7)	20.0 (6.2)	17.1 (6.5)	21.5 (6.3)	27.0 (3.0)	27.4 (4.2)	24.5 (8.1)	25.3 (6.9)	31.1 (6.3)
		2	29.6 (4.1)	20.6 (5.3)	15.3 (5.8)	19.1 (5.8)	27.0 (2.5)	26.5 (3.9)	23.6 (8.0)	26.4 (5.4)	30.9 (4.9)

[a] Mean (SD).
[b] $N = 7$.

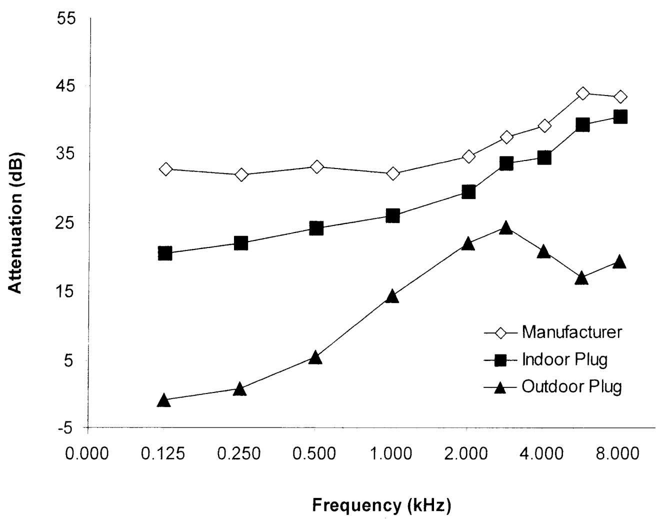

Fig. 3. A comparison of the observed attenuation with the manufacturer's specifications.

until the sound was no longer audible. The sound level of consecutive pulses increased in steps of 1 dB until the button was depressed and then decreased at the same rate of change until the button was released. The tracking trial was terminated after a minimum of eight alternating intensity excursions, with a range of 2 to 20 dB. Hearing threshold was defined as the average sound level of the eight final peaks and valleys. At the conclusion of the second session, the subject was asked to complete the questionnaire regarding the comfort of the plugs.

Results

Hearing Threshold

Mean hearing thresholds and SDs obtained for each of the nine frequencies tested are presented for combinations of ear condition, gender group, and replication in Table I. Figure 2 shows the mean thresholds as a function of stimulus frequency, averaged across gender and replication, with ear condition as the parameter. The results show that the mean hearing thresholds observed for the male and female groups were less than those specified for normal hearing in the range of 0.125 to 8 kHz.[15] There were no significant differences in relation to gender or replication. A repeated-measures analysis of variance applied to the data for the three ear conditions (unoccluded, indoor plug, and outdoor plug) indicated that there were significant effects of ear condition, frequency, and ear by frequency ($p < 0.0001$). Gender and replication were not significant. Averaged across gender, replication, and frequency, the mean hearing threshold was highest for the indoor plug (39.4 dB) and was lowest for the unoccluded condition (8.4 dB), with the outdoor plug midway between (23.8 dB). Post hoc pairwise comparisons using Fisher's least significant difference test[16] showed significant differences among all three ear conditions ($p < 0.01$ or better). There were also significant differences among the three ear conditions at every frequency ($p < 0.01$ or better) except 0.125 and 0.25 kHz, where the outdoor and unoccluded conditions were no different.

Attenuation

Table II shows the mean attenuation and SD obtained for each of the nine stimulus frequencies tested for the four combinations of gender and replication for each of the indoor and outdoor plugs. Figure 3 shows the mean attenuation as a function of frequency, averaged across gender and replication, with ear plug as the parameter. In Table II and Figure 3, the observations are compared with the manufacturer's specification for the indoor plug. A repeated-measures analysis of variance applied to the data for the indoor and outdoor plugs showed significant effects of ear condition, frequency, and ear by frequency ($p < 0.0001$). As in the case of hearing thresholds, there was no effect in relation to gender or replication. The overall mean attenuation values observed for the indoor and outdoor plugs, averaged across gender, replication, and frequency were 31.07 and 15.47 dB, respectively. Post hoc pairwise comparisons using Fisher's least significant difference test showed that the differences in attenuation for the two devices were significant at all nine frequencies ($p < 0.001$ or better). The observed values for the indoor plug decreased from 12 dB less than the value specified by the manufacturer at 0.125 kHz to 6 dB less at 1 kHz, and were 3 to 5 dB less between 2 kHz and 8 kHz. The

TABLE II

ATTENUATION OBSERVED FOR THE INDOOR/OUTDOOR RANGE E-A-R EARPLUGS FOR EACH GENDER BY REPLICATION IN COMPARISON TO THE MANUFACTURER'S SPECIFICATION FOR THE INDOOR PLUG

			Frequency (kHz)								
Ear Condition	Gender	Replications	0.125	0.25	0.5	1	2	3.15	4	6.3	8
Specification	N/A	N/A	32.7 (5.9)	31.8 (6.1)	33.0 (6.5)	32.0 (5.5)	34.5 (4.1)	37.3 (5.3)	38.9 (6.1)	43.8 (6.7)	43.3 (6.9)
Indoor plug	M	1	18.2 (3.3)[a,b]	23.1 (9.1)	21.8 (6.5)	24.8 (7.9)	31.3 (6.9)	35.0 (4.7)	36.0 (4.8)	38.3 (7.2)	41.0 (4.6)
		2	23.1 (6.1)[b]	23.0 (6.8)	25.4 (7.9)	27.4 (5.5)	28.9 (7.2)	30.4 (6.1)	33.4 (9.3)	41.6 (5.9)	42.8 (2.1)
	F	1	20.9 (10.0)	21.3 (10.9)	24.1 (10.3)	25.0 (7.6)	28.9 (4.8)	33.9 (5.6)	33.1 (6.6)	37.3 (5.6)	38.1 (7.2)
		2	20.0 (8.5)	20.5 (6.1)	24.8 (5.0)	26.3 (6.1)	28.8 (5.9)	35.1 (6.4)	34.9 (7.0)	39.4 (6.5)	39.3 (5.7)
Outdoor plug	M	1	−2.3 (3.0)	1.5 (1.8)	5.5 (2.7)	13.5 (1.7)	22.9 (5.7)	24.3 (2.0)	18.9 (2.5)	16.9 (3.4)	19.3 (5.3)
		2	−0.5 (2.8)	0.4 (2.3)	4.6 (3.6)	12.8 (4.2)	21.1 (5.1)	21.1 (4.1)	19.1 (3.4)	16.3 (6.1)	19.3 (5.9)
	F	1	0.6 (2.6)	1.0 (4.8)	6.3 (4.5)	17.4 (5.9)	22.3 (4.1)	26.3 (5.0)	23.4 (6.0)	17.5 (3.4)	19.9 (4.4)
		2	−1.1 (4.1)	0.4 (2.9)	5.0 (3.5)	13.8 (3.9)	21.6 (3.7)	25.5 (4.9)	21.6 (5.2)	17.4 (3.2)	18.6 (3.8)

[a] Mean (SD).
[b] $N = 7$.

TABLE III

SUBJECTS' RESPONSES TO A QUESTIONNAIRE CONCERNING THE COMFORT OF THE INDOOR/OUTDOOR RANGE E-A-R PLUGS

	Frequency of Response		
Questions	Males	Females	Total
How comfortable were the plugs?			
a. Very uncomfortable	1	4	5
b. Uncomfortable	1	2	3
c. Okay	3	1	4
d. Comfortable	3	1	4
e. Very comfortable	0	0	0
Total	8	8	16
If you had to wear these on a regular basis, how long would you be willing to keep them in your ears?			
a. I wouldn't wear them	0	4	4
b. One hour or less	5	3	8
c. A half day	2	1	3
d. A full day	1	0	1
Total	8	8	16

observed SDs were no more than 3 dB greater than the manufacturer's specifications for all frequencies tested.

Table III shows the results of the questionnaire. For question 1, the majority of women (six of eight) rated the earplugs as uncomfortable or very uncomfortable, whereas the same number of men rated them as okay or comfortable. For question 2, almost all of the women (seven of eight) reported that they would not wear the earplugs again or would wear them for 1 hour or less. For the men, responses ranged from 1 hour or less (most chosen) up to a full day. The responses to questions 1 (comfort) and 2 (wearing times) were significantly correlated with each other ($r = 0.75$; $p > 0.001$). To determine whether comfort was related to achieved attenuation, the Pearson correlation coefficient was computed between the response to question 1 (comfort) and attenuation observed at 4 kHz for the indoor plug for all 16 subjects. The result was not statistically significant.

Discussion

The current study was undertaken to measure the real-world attenuation characteristics of the Indoor/Outdoor Range E-A-R Plug. The results showed that the attenuation provided by the indoor plug, averaged across gender and replication, increased from 21 dB at 0.125 kHz to 40 dB at 8 kHz. These values support the conclusion that this device would rank among those conventional devices on the market with the highest attenuation.[17] The presumption was that the outdoor plug would not attenuate low- to moderate-level sounds. Contrary to expectation, the results demonstrated that this device attenuated threshold levels by 5 and 14 dB at 0.5 and 1 kHz, respectively, and by 17 to 22 dB in the range of 2 to 8 kHz. A comparison of the two plugs showed that the indoor plug provided significantly more attenuation than the outdoor plug at all nine frequencies tested. Mean differences, averaged across gender and replication, ranged from a minimum of 7.5 dB at 2 kHz to a maximum 22.1 dB at 6.3 kHz. The attenuation levels obtained with the indoor plug fell short of the manufacturer's specifications at all frequencies. However, the difference was no more than 3 to 6 dB between 1 and 8 kHz, and the SDs were close to those specified by the manufacturer. The small discrepancy could be because of a difference in methodology (strict experimenter fit of the device vs. experimenter-supervised fit). Regardless, the observed outcomes suggest that the manufacturer's specifications were a good predictor of outcome.

The indoor plug elevated hearing thresholds relative to unoccluded listening at all of the frequencies tested. Hearing thresholds with the indoor plug fitted ranged from a minimum of 31 dB SPL (1 kHz) to a maximum of 53 dB SPL (8 kHz). Previous studies have demonstrated that for normal-hearing individuals, thresholds in this range will not adversely affect speech understanding in noisy surroundings. Those with preexisting mild to moderate hearing loss could experience deficits in consonant discrimination in quiet or noise of up to 30%.[4,5] Contrary to expectations, the outdoor plug also elevated thresholds significantly. The range of significant elevation was restricted to 0.5 to 8 kHz, where thresholds ranged from 16 to 32 dB SPL. Those with pre-existing hearing loss might be well served by the outdoor plug alone in situations characterized by impulse or continuous noise.

Two variables of special interest that were investigated were the gender of subjects and replication. Differences in the mean attenuation levels between replications 1 and 2 were not significantly different. This result suggests that learning to fit the plugs did not play a role in outcome. The effect of gender on attenuation was also not significant, although with the indoor plug, men obtained relatively higher attenuation levels than women at all frequencies, with the exception of 0.5 and 3.15 kHz. At most, the difference was 3 dB. The gender effect was not consistent in the case of the outdoor plug. These results are contrary to findings of previous research that have examined various brands of earplugs available in only one size. These studies found that men achieved significantly higher levels of attenuation than women.[11]

Although a gender effect was not observed, women were more likely than men to report discomfort in wearing the plugs. Six (75%) of eight women, compared with two (25%) of eight men, rated the plugs as being uncomfortable or very uncomfortable. Furthermore, only 50% of the women said that they would not wear the earplugs again, whereas all of the men said that they would use the earplug for at least 1 hour or more. The increased level of discomfort felt by women is consistent with previously findings[12] that the cross-sectional diameter of female ear canals is significantly smaller than that of males. The finding that participants' comfort levels were significantly correlated with how long they would be willing to wear the earplug is in line with earlier research.[18]

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