Ten załącznik 4a_cz2 zawiera kopie powiązanych tematycznie artykułów naukowych A4-A6 (3 spośród 6) wchodzących w skład cyklu stanowiącego osiągniecie naukowe:

A4   Młyński R., Kozłowski E. Selection of level-dependent hearing protectors for use in an indoor shooting range. International Journal of Environmental Research and Public Health, 2019, 16(13), 2266, DOI:10.3390/ijerph16132266

A5   Młyński R., Kozłowski E. Noise reduction at the shooting range by means of level-dependent hearing protectors. Medycyna Pracy, 2019, 70(3), 265-273, DOI:10.13075/mp.5893.00730

A6   Młyński R., Kozłowski E. Localization of vehicle back-up alarms by users of level-dependent hearing protectors under industrial noise conditions generated at a forge. International Journal of Environmental Research and Public Health, 2019, 16(3), 394, DOI:10.3390/ijerph16030394

Kopie pozostałych artykułów wchodzących w skład tego cyklu, oznaczonych jako A1-A3, zamieszczono w osobnym załączniku 4a_cz1.

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Selection of Level-Dependent Hearing Protectors for Use in An Indoor Shooting Range

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Abstract: The high sound pressure level generated by impulse noise produced in an indoor shooting range makes it necessary to protect the hearing of the people it affects. Due to the need for verbal communication during training at a shooting range, level-dependent hearing protectors are useful. The objective of this study was to answer the question of whether it is possible to properly protect the hearing of a shooting instructor using level-dependent hearing protectors. The noise parameters were measured in the places where the instructor was present at the shooting range. The division of a specific group of trained shooters into subgroups consisting of three or six simultaneously shooting individuals did not significantly affect the exposure of the shooting instructor to the noise. An assessment of noise reduction was carried out for eight models of earmuffs and two variants of earplugs, using computational methods for the selection of hearing protectors. Among the noise parameters, both the A-weighted equivalent sound pressure level and the C-weighted peak sound pressure level were taken into account. Depending on the assessment criterion adopted, a sufficient reduction in impulse noise was provided by either four or six out of the 10 hearing protectors included in the study.

1. Introduction

Impulse noise is particularly dangerous for hearing due to its fast-changing nature. A single exposure to noise produced from an artillery shot can lead to a temporary hearing loss, while repeated exposure to noise associated with gunfire can result in permanent noise-induced hearing loss [1]. Auditory dysfunction after the blast results from the loss of outer hair cells and decreased spiral ganglion neurons and afferent nerve synapses [2]. Studies also showed that exposure to impulse noise caused a loss about 30% of inner hair cell synaptic ribbons in rat cochleae and the loss of about 10% of outer hair cells [3]. The occurrence of impulse noise is very often associated with the inability to apply engineering measures or administrative methods to reduce noise, which is especially true for people who are inside shooting ranges, where the sound source is in close proximity to the people. In contrast to sources of impulse noise in industry, there is no possibility to replace people with devices on a shooting range. The only known technical method of reducing the noise produced by firearms is the use of firearm suppressors [4]. It has been found that the effectiveness of suppressors can significantly exceed the noise reduction of hearing protectors [5]. However, this effectiveness, at a level of 20–28 dB, was also determined as not always sufficient [4]. In one of the reported studies, it was found that, despite the fact that suppressors significantly lower the peak sound pressure level (SPL) produced during shots—e.g., from AR-15 rifles—in most cases, its value exceeds 140 dB [6]. Due to the fact that the values of parameters of noise generated by shots most often exceed those that may be harmful to

hearing, it becomes necessary to apply the latter possible solution, namely hearing protectors. The need to use hearing protectors is highlighted by the negative effects of the lack of such protection during the exposure of military personnel to noise from rifle shots [7]. The average threshold shift of soldiers exposed to noise produced by rifle shots was over 21 dB [7]. A recommendation for the use of hearing protectors was also formulated in light of conclusions from studies carried out among military personnel which suggested that even exposure to noise levels lower than the exposure limit value may lead to acoustic trauma [8]. Recommendations were also made that firearm users should always wear hearing protectors when shooting or hunting, since the use of firearm suppressors may not be sufficiently effective [4]. Re-educating people about the importance of proper hearing protection was also a result of research which found, among other things, that the risk of high-frequency hearing loss, e.g., in men involved in hunting, increased by 7% for every 5 years of participation in this type of activities [9].

The need for communication in the presence of noise, in terms of the use of hearing protectors, is becoming increasingly common in many workplaces [10]. For noise with an SPL that changes over time, it is advisable to use level-dependent hearing protectors. The level-dependent function is carried out by means of electronic circuits. In moments of relative silence, this function supports verbal communication and the possible hearing of other non-speech sounds. This does not require the removal of hearing protectors, which is beneficial on the one hand, and protects against randomly occurring sounds on the other. This functionality is particularly valuable at shooting ranges, because a person who wears hearing protectors at the shooting range is not exposed to the accidental acoustic impulse created by firing a firearm.

Regardless of the aforementioned functionality of level-dependent hearing protectors in terms of support in the perception of ambient sounds, these protectors should limit exposure to noise in such a way that the hearing of their users is safe. Therefore, it is necessary to properly select hearing protectors on the basis of the noise parameters present in the location of the user of the hearing protectors. The selection of hearing protectors can be carried out using computational methods. It is then necessary to determine both the noise parameters present in the workplace and information about the sound attenuation of the hearing protector in question. The selection of hearing protectors is not often discussed and, for example, is limited to presenting the basic principles of such a selection or discussing the main problems involved [10,11]. It is also mentioned that one of the problems in the assessment of the effectiveness of using hearing protectors is when noise is impulsive [11].

It is not difficult to obtain information about the sound attenuation of hearing protectors used in computational selection methods for continuous noise. This attenuation is one of the parameters measured during the conformity assessment process for the EU regulation [12], and its values are included in the user instructions for the hearing protectors. Some difficulties are related to the assessment of impulse noise parameters. The selection of hearing protectors requires precise data on the noise parameters, and the information that the exposure limit values of these parameters have been exceeded is inadequate. Due to the high SPL values of impulse noise exceeding the upper limits of the measurement range of standard sound level meters, measurements of noise parameters must be carried out with the use of appropriate equipment. The experience of research personnel is also crucial to properly determine representative cycles of tasks when determining noise parameters, as required by the test methodology [13].

The objective of this study was to answer the question of whether it is possible to properly protect the hearing of a shooting instructor at an indoor shooting range, using level-dependent hearing protectors. The study includes a large number (10) of level-dependent hearing protectors. In addition, the assessment of impulse noise reduction was carried out not in the presence of laboratory-produced acoustic impulses, as in the method described in ANSI/ASA S12.42-2010 (The American National Standards Institute, Inc./The Acoustical Society of America) [14], but instead measurements of noise parameters were carried out in a real acoustic environment at an indoor shooting range. During the tests, a full program of shooting was carried out using various types of weapons and ammunition.

The only known example of a study referring to the possibility of reducing the exposure to noise at an instructor's location is a study which concerned the use of suppressors rather than hearing protectors [4].

2. Materials and Methods

2.1. Hearing Protectors Included in the Assessment

Level-dependent hearing protectors were included in the assessment of the protection of the hearing of a shooting instructor. There were eight different models of earmuffs and two variants of earplugs with two types of eartips made of polyurethane and silicone, respectively. The use of the two types of eartips is associated with different sound attenuation values. Therefore, in this study, both variants of eartips are considered as two separate hearing protectors. In Table 1, the sound attenuation data provided in the user instructions for individual hearing protectors are presented, which are determined in accordance with the principles set out in EN ISO 4869-1 [15]. Symbols HP1 to HP7 and HP10 (HP—hearing protector; designations adopted in this study) denote level-dependent earmuffs. Symbols HP8 and HP9 apply to earplugs. Data from Table 1 were used in the selection of the hearing protectors.

Table 1. Sound attenuation data of level-dependent hearing protectors. m_f—mean attenuation [1], s_f—standard deviation, H—high-frequency attenuation value [2], M—medium-frequency attenuation value, L—low-frequency attenuation value, SNR—single number rating, HP1 to HP10—hearing protectors 1 to 10.

Designation	m_f/s_f [dB]	Frequency [Hz]							H [dB]	M [dB]	L [dB]	SNR [dB]
		125	250	500	1000	2000	4000	8000				
HP1	m_f	11.5	17.9	27.8	30.0	32.1	36.2	40.3	31 [3]	25	16	28
	s_f	2.5	2.7	1.8	2.3	3.0	2.0	3.1				
HP2	m_f	13.8	21.5	30.9	36.6	35.9	35.5	39.0	32	29	20	31
	s_f	1.8	0.9	1.3	1.5	5.5	3.1	2.3				
HP3	m_f	21.1	17.9	27.0	26.8	30.5	38.3	36.4	29	23	16	26
	s_f	4.3	3.1	3.8	3.0	3.0	3.7	5.4				
HP4	m_f	17.0	24.0	29.5	36.9	37.3	39.3	35.4	34	29	22	32
	s_f	3.2	2.0	2.6	3.3	4.9	3.2	3.9				
HP5	m_f	13.3	17.4	22.3	28	30.8	37.6	37.0	29	23	17	26
	s_f	3.2	1.8	2.3	3.2	3.4	2.8	4.8				
HP6	m_f	13.5	15.5	23.7	24.1	30.4	36.6	38.6	28	21	16	25
	s_f	3.2	1.9	3.9	2.7	3.2	4.4	4.2				
HP7	m_f	18.4	21.1	27.7	36.9	36.1	42.1	38.8	34	27	20	30
	s_f	4.5	4.2	3.5	4.0	3.6	3.5	5.4				
HP8	m_f	34.5	31.5	36.2	33.4	34.8	34.9	38.8	31	30	29	32
	s_f	6.0	5.4	5.6	4.3	3.8	5.0	4.0				
HP9	m_f	37.8	36.0	40.5	41.2	41.3	39.6	46.1	37	36	34	38
	s_f	4.3	5.5	4.2	4.7	3.2	4.3	3.6				
HP10	m_f	15.7	19.1	22.9	27.0	22.4	38.4	40.9	24	22	18	25
	s_f	3.0	3.1	2.9	2.3	3.3	3.0	3.4				

[1] Definitions of m_f and s_f are given in EN ISO 4869-1 [15]; [2] definitions of H, M, L and SNR are given in EN ISO 4869-2 [16] and have since been slightly modified in the current version of this standard [17]; [3] values of H, M, L and SNR are rounded to the nearest integer [16,17].

2.2. Locations of Noise Parameter Measurements

Measurements of noise parameters were carried out during shooting exercises at the acoustically treated indoor shooting range, the dimensions of which were 35 m in length, 8.5 m in width and 2.6 m in height. As the possibility of protecting the shooting instructor's hearing was being assessed, noise measurements were carried out in the places where the shooting instructor was present during the training, with the instructor at three different distances from the shooters: 1.1 m, 2.8 m, and 16.5 m (Figure 1).
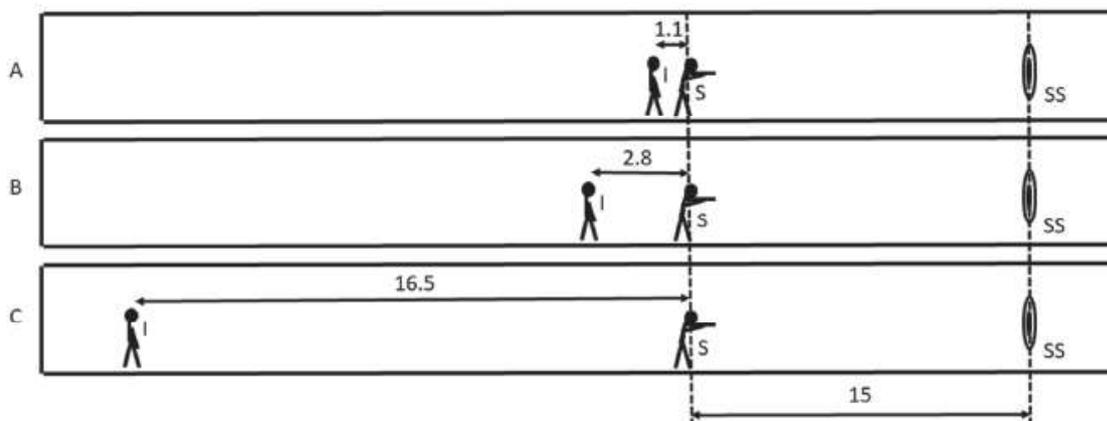
Figure 1. The three measuring situations (A, B, C) included in the measurement of noise parameters carried out at the indoor shooting range: I—shooting instructor, S—shooters, and SS—shooting target. Distances are expressed in meters.

2.3. Type of Weapon/Ammunition

The measurements were carried out during training, which consisted of four types of shooting cycles, during which shots were fired with the following weapon/ammunition combinations:

- Glock 17 pistol (9 × 19 mm Parabellum calibre) and Walther P99 (9 × 19 mm Parabellum calibre), hereinafter referred to as the 'pistols';
- PM-98 Glauberyt submachine gun (9 × 19 mm Parabellum calibre), hereinafter referred to as the 'submachine gun';
- Mossberg 590 smooth-bore shotgun (12/70 calibre: flash-bang ammunition and rubber ammunition), hereafter referred to as 'shotgun 1';
- Mossberg 590 smooth-bore shotgun (12/70 calibre: slug load ammunition and buckshot ammunition), hereafter referred to as 'shotgun 2'.

2.4. Measurement Method

The measurements included a total of 53 shooting cycles, of which 17 cycles were shot from pistols, 16 cycles were related to shots from a submachine gun, 10 cycles were shot from (smooth-bore) shotgun 1 and 10 next cycles were shot from (smooth-bore) shotgun 2.

The training took place with two variants of the number of shooters simultaneously shooting during the shooting cycle: three or six shooters. The duration of one shooting cycle was 300 s (three shooters) or 420 s (six shooters). The duration of one shooting cycle means a full representative cycle of the task, determined in accordance with the principles for noise measurements at the workplace specified in the standard EN ISO 9612 [13]. The cycle at the shooting range included actions preceding shooting—i.e., giving instructions, loading weapons and other preparatory activities; shooting; and actions after shooting related to unloading weapons, checking their condition, etc.

The following noise parameters were determined as necessary for the assessment of noise reduction by hearing protectors:

- SPL in octave bands with center frequencies: 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz.
- A-weighted equivalent SPL (L_{Aeq}),
- C-weighted equivalent SPL (L_{Ceq}),
- C-weighted peak SPL (L_{Cpeak}).

Due to the fact that, in the assessment of noise exposure at the workplace, both the parameter related to the impulse nature of noise, L_{Cpeak}, and the parameter reflecting the energy properties

of noise, i.e., the A-weighted noise exposure level normalized to an 8-h working day (otherwise also expressed as daily noise exposure level ($L_{EX,8h}$) [18,19]), are taken into account, both of these parameters were considered in this study. The determination of $L_{EX,8h}$ is based on L_{Aeq}, taking into account the time of exposure to noise T_e (expressed in seconds), according to Equation (1) from the standard EN ISO 9612 [13].

$$L_{EX,8h} = L_{Aeq} + 10 \times \log_{10}\left(\frac{T_e}{8 \times 60 \times 60}\right) \tag{1}$$

2.5. Criteria for Assessing Exposure to Noise at the Workplace

Noise is classified as dangerous to hearing when an exposure limit value of one of the parameters, i.e., L_{Cpeak} or $L_{EX,8h}$, is exceeded. For the L_{Cpeak} parameter, Directive 2003/10/EC [18] sets the exposure limit value at 140 dB. In Polish regulations, 135 dB [19] was adopted as the limit value for exposure. Similarly, the value of the $L_{EX,8h}$ parameter, in accordance with the provisions of the Directive [18], should not exceed 87 dB, while 85 dB was adopted in national regulations [19]. There are also data according to which the A-weighted SPL, which guarantees no impact of noise on hearing even after long-term exposure, is 80 dB [20]. At the same time, $L_{EX,8h}$ at 89 dB can be supplemented since one of the papers concluded that, in the case of impulse noise [21], this was considered a safe value to protect 95% of the population in 95% of cases.

2.6. Measuring Equipment

In this study, a G.R.A.S. 67SB (GRAS Sound & Vibration A/S, Holte, Denmark) transducer was used for measuring noise parameters, which is designed for impulse noise parameter measurement [14]. The upper limit of the measuring range of this transducer is 174 dB. The electrical signal from the transducer was fed to a G.R.A.S. 12AK power supply module and then to a Brüel & Kjær 3052-A-030 input module (Brüel & Kjær, Nærum, Denmark). A picture of the measuring equipment is shown in Figure 2.

Figure 2. Measuring equipment: G.R.A.S. 67SB transducer on a tripod, bottom left, measuring the cassette of the Brüel & Kjær 3052-A-030 input module (with battery and Wi-Fi modules) and the G.R.A.S. 12AK power module.

In accordance with the recommendations of EN ISO 9612 [13], the measuring transducer was placed on a tripod at the height of the ear of the shooting instructor. The measurement path was checked using a G.R.A.S. 42AP (GRAS Sound & Vibration A/S, Holte, Denmark) pistonphone. Brüel & Kjær Pulse Reflex (Brüel & Kjær, Nærum, Denmark) software was used to analyze the measurement data.

2.7. Methods for the Selection of Hearing Protectors

The assessment of noise reduction by the hearing protectors included in the analysis was carried out by the so-called selection of hearing protectors. The selection consists of calculating the A-weighted SPL L'_A and the C-weighted peak SPL L'_{Cpeak} under the hearing protectors. For the L'_A parameter, the selection methods presented in EN 458 [22] were used: the octave band method, the HML method and the SNR method. The results of the octave band method were considered as the reference, because this method is considered to be the most accurate [22]. The other two methods (HML and SNR) were used for comparative purposes. In the case of the L'_{Cpeak} parameter, the methodology for assessing impulse noise reduction is included in informative Annex B of the mentioned standard [22] and is entitled "method for assessing the sound attenuation of the hearing protector for impulse noise". In view of the fact that impulse noise is generated at the shooting range, level-dependent hearing protectors are then considered as if they were used in passive mode, because the electronic circuits of such protectors block the transmission of sound in the presence of an acoustic impulse.

Calculations with the octave band method are made using sound attenuation data (Table 1) in seven frequency bands ranging from 125 Hz to 8000 Hz. The HML method is based on a smaller number of data and three parameters are used, i.e., H, M and L (introduced in Table 1). The SNR method uses only one parameter (SNR—Table 1), which characterizes the properties of the hearing protector.

In the case of exposure to impulse noise, the assessment of noise reduction by hearing protectors is more complicated, because the instructions for the use of the hearing protector do not contain data related directly to impulse noise. Therefore, appropriately adjusted hearing protector data should be used; i.e., the previously mentioned H or M or L parameters. Due to the fact that a specific hearing protector limits the acoustic impulses generated by various sources to various degrees, these sources are divided into three groups (so-called types of noise), and the method of calculation depends on which type of source is considered. The assignment of the noise source to the noise type is related to the frequency range in which the dominant spectral components of the signal energy generated by the considered source are located. The impulse noise produced during shots from a pistol or a submachine gun is classified as type 3 noise. Then, the value of the L'_{Cpeak} parameter with the hearing protector is calculated from Equation (2). In turn, shots from a smooth-bore shotgun are a source of noise classified as type 2 noise, and then Equation (3) is used. L_{Cpeak} in Equations (2) and (3) is the C-weighted peak SPL measured at the workplace.

$$L'_{Cpeak} = L_{Cpeak} - H \tag{2}$$

$$L'_{Cpeak} = L_{Cpeak} - (M - 5) \tag{3}$$

2.8. Criteria for the Assessment of Hearing Protectors

The assessment of hearing protectors for their user's hearing protection is based on a comparison of the calculated values L'_A and L'_{Cpeak} with the relevant national regulation level, which is specified in the standard for the selection of hearing protectors [22]. Therefore, according to Polish regulations [19], which are more restrictive than the requirements set out in the Directive [18], the L'_{Cpeak} parameter may not exceed the exposure limit value of 135 dB. However, for the selection of hearing protectors in accordance with the L'_A parameter, the value should be 80 dB. This is a lower exposure action value than that established in Polish regulations and at the same time in Directive 2003/10/EC [18], after which hearing protectors must be provided to an employee. In addition, this is a value that, according to the previously mentioned ISO standard [20], does not result in hearing loss even after long-term exposure to noise. Ultimately, the hearing protector can be considered suitable for hearing protection against noise if the two conditions are met simultaneously; i.e., the L'_{Cpeak} value should not exceed 135 dB, and at the same time, the L'_A value should not exceed 80 dB.

2.9. Statistical Analysis

Statistical analysis of the obtained measurement data was carried out in order to assess whether there were significant differences in exposure to noise resulting from the two variants of the number of shooters simultaneously participating in the exercises and to assess the impact of distance on the values of noise parameters. Data were analyzed using MATLAB R2017b (version 9.3) software with the Statistics and Machine Learning Toolbox (MathWorks Inc., Natick, MA, USA). The analysis used the Wilcoxon test, equivalent to the Mann-Whitney U test.

3. Results

3.1. Firearm-Related Noise

Figure 3 shows the noise spectra, i.e., SPL in octave bands values, measured at a distance of 1.1 m from the shooters. Spectral components generally assume values ranging from 84 dB to 100 dB, and the spectrum of the four considered weapon/ammunition combinations as a function of frequency is uneven. The dominant components of acoustic energy associated with pistols are in the 1 kHz band. In the case of the submachine gun, the maximum in the noise spectrum is in the 2 kHz band. Shots from shotgun 1 lead to the spectrum of noise with the highest signal energy in the low-frequency range out of the four weapon/ammunition combinations considered. In the case of shotgun 2, the SPL values in the two lowest frequency bands are 4 dB to 6 dB lower than in the previously mentioned situation (shotgun 1), but still exceed the values measured for pistols and the submachine gun.
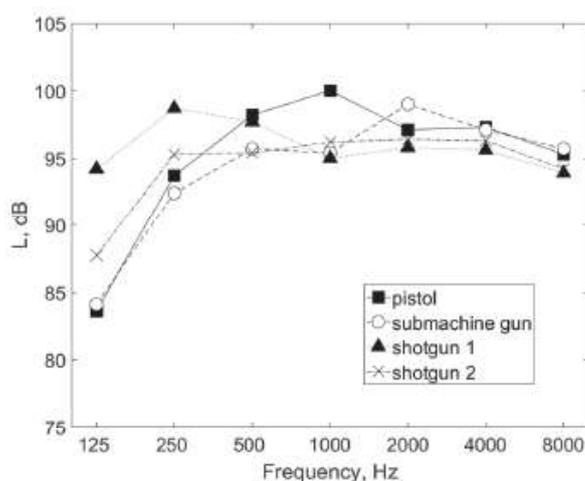

Figure 3. Sound pressure level (SPL) in octave bands representative of one shooting cycle, measured at the shooting instructor's location at a distance of 1.1 m from six shooters simultaneously taking part in the exercises. The values were determined on the basis of all data obtained during the tests at the shooting range.

Figure 4 shows the L_{Aeq} values measured for both variants of the number of shooters simultaneously shooting, with three different distances between the shooting instructor and the shooters. The highest L_{Aeq} values occur during pistol shots, and the lowest during shotgun 1 shots. The results of the measurements indicate a noticeable decrease in the L_{Aeq} value, associated with the increase in the distance of the instructor from the shooters. The decrease is about 3 dB if the distance is changed from 1.1 m to 2.8 m, and another 8 dB if the distance is increased to 16.5 m. However, the L_{Aeq} values shown in Figure 4 do not fit perfectly in straight lines with a slope of −3 dB per doubling the distance, which is the theoretical slope for free field conditions. This is due to the fact that exercises were held at an indoor shooting range, which is associated with the occurrence of reflections of acoustic waves from the walls and ceiling, which has an impact on the noise parameters. However, it should be

noted that the deviations of results from the theoretical line are relatively small, which results from the use of acoustic treatment at the shooting range.
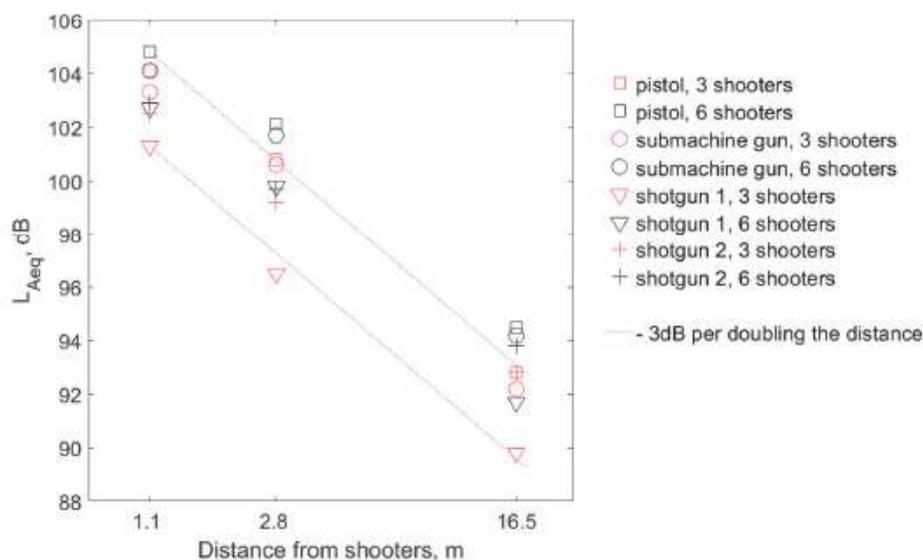

Figure 4. A-weighted equivalent SPL measured at the shooting instructor's locations, representative of one shooting cycle for both variants of the number of shooters (three or six) simultaneously firing at three different distances between the shooting instructor and the shooters. The values were determined as a result of averaging of all data obtained during the tests at the shooting range under the determined conditions. A logarithmic (base 10) scale is used for the X-axis. Dotted line—a line with a slope of −3 dB per doubling the distance.

In the case of the L_{Cpeak} parameter (Figure 5), fewer shooters are not always associated with a smaller value of this parameter, as was the case for the L_{Aeq} parameter. However, if at some distance of the shooting instructor from the shooters, a certain type of weapon/ammunition combination was associated with a higher value of L_{Cpeak} than the other weapon/ammunition combinations, it was also similar at other distances. It should also be emphasized that the highest L_{Cpeak} values are related to shots from shotgun 1, and the smallest are related to shots from the submachine gun, which is different from the situation regarding the L_{Aeq} parameter. This may be due to differences in the noise spectrum produced by different sources and the filtering of low-frequency components when calculating the L_{Aeq} value.

Similar to the L_{Aeq} parameter, increasing the distance from the shooters was associated with a decrease in the L_{Cpeak} value at the shooting instructor's location, which does not fit perfectly in straight lines representing the theoretical changes in free field conditions (−6 dB per doubling the distance); however, the deviations of results from the theoretical line are also relatively small (as in the case of L_{Aeq} parameter).
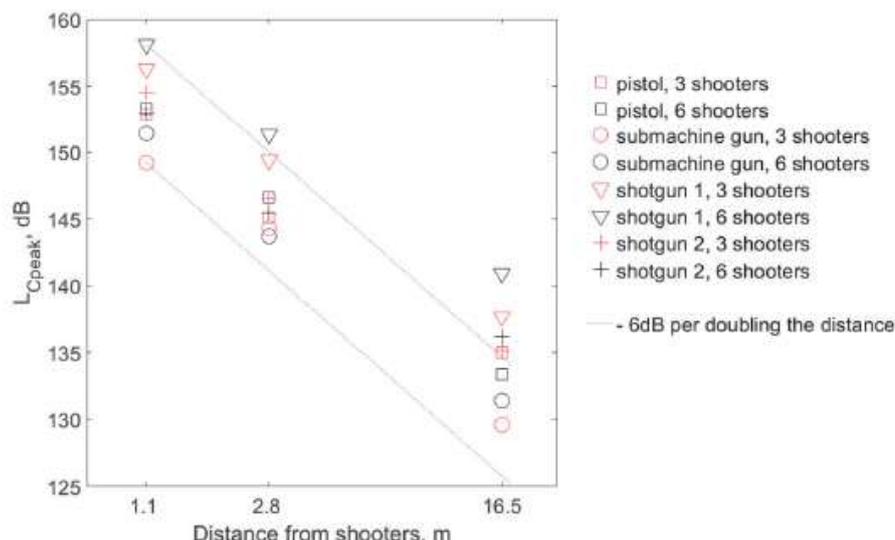
Figure 5. C-weighted peak SPL measured at the shooting instructor's locations, representative of one shooting cycle for both variants of the number of shooters (three or six) simultaneously firing with three different distances between the shooting instructor and the shooters. The values were determined as a result of averaging all data obtained during the tests at the shooting range under the determined conditions. A logarithmic (base 10) scale is used for the X-axis. Dotted line—a line with a slope of -6 dB per doubling the distance.

3.2. Impact of the Number of Shooters

The influence of two different, practically applicable scenarios of conducting shooting exercises on the exposure of a shooting instructor to noise was analyzed. Usually, the task of the instructor is to carry out training with a group of 18 shooters in one day. The training may be conducted with a group divided into six three-person subgroups or three six-person subgroups, within which the shooters shoot simultaneously. In the case of three-person teams, the total time of exposure of the instructor to the noise is 1800 s (6×300 s), or 1260 s for six-person teams (3×420 s). In Figure 6, the $L_{EX,8h}$ values are determined using Equation (1), taking into account the calculated time of exposure to noise, in the case of both variants of the division of shooters into teams. L_{Cpeak} values measured in analogous situations are also included.
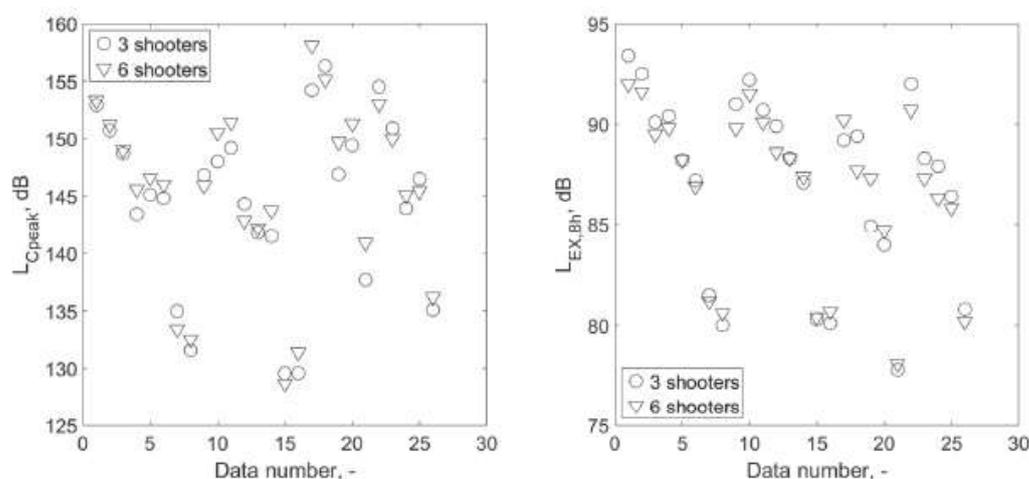

Figure 6. A comparison of L_{Cpeak} and $L_{EX,8h}$ parameter pairs, where each pair of results includes a variant of simultaneous shooting by three and by six shooters, under the same measurement conditions, i.e., at a specified distance from shooters, using a specific weapon/ammunition combination.

In the case of $L_{EX,8h}$, the variation of the value of this parameter related to a different number of shooters is not significant, and the average difference between the situation of three shooters firing in six subgroups and the situation of six shooters in three subgroups is 0.3 dB. It is worth noting that in most cases (16 out of 26), $L_{EX,8h}$ had a higher value for three-person teams than for teams of six people. The reverse situation concerned eight out of 26 cases. The value of L_{Cpeak} associated with the simultaneous firing of shots by three shooters in six subgroups in relation to the situation in which shooting takes place in three subgroups of six shooters, which is more negative than positive (18 and 8 cases out of 26 situations, respectively). On average, the difference in the L_{Cpeak} value between the two variants (three and six shooters) of the number of shooting teams is −0.8 dB.

On the basis of the results of the statistical analysis, it can be concluded that, both in the case of L_{Cpeak} and $L_{EX,8h}$, there are no statistically significant differences between the results obtained with 3-person teams, compared to the results for 6-person teams ($p = 0.65$ and $p = 0.67$ for L_{Cpeak} and $L_{EX,8h}$ parameters, respectively, Wilcoxon test). The conclusion which follows from the described analyses is that a different number of people simultaneously shooting (three or six) does not significantly affect the shooting instructor's exposure to noise.

3.3. Impact of Changing the Distance from Shooters

The positive effect of increasing the distance of the instructor from the shooters in order to reduce the exposure to noise is basically obvious. However, a verification was made to determine whether, considering the plan of exercises carried out at the shooting range, including the four weapons/ammunition combinations considered, the effects of increasing the distance of the instructor from the shooters should be treated as statistically significant. This verification was carried out with consideration of the parameters used in the noise exposure assessment criteria at the workplace. Figure 7 presents the results for the L_{Cpeak} and $L_{EX,8h}$ parameters, divided into three variants of the instructor's distance from the shooters. Determined p-values for comparisons of the L_{Cpeak} and $L_{EX,8h}$ values corresponding to different distances of the shooting instructor from the shooters; i.e., for the comparison of results measured at 1.1 m and 2.8 m, at distances of 2.8 m, 16.5 m, 1.1 m and 16.5 m, were many times smaller than 0.05 in every situation compared. The results of measurements of noise parameters at different distances were therefore significantly different for individual distances. It has been confirmed, therefore, that the change in distance significantly affects the exposure of the shooting instructor to noise, due to both the L_{Cpeak} and the $L_{EX,8h}$ parameters.
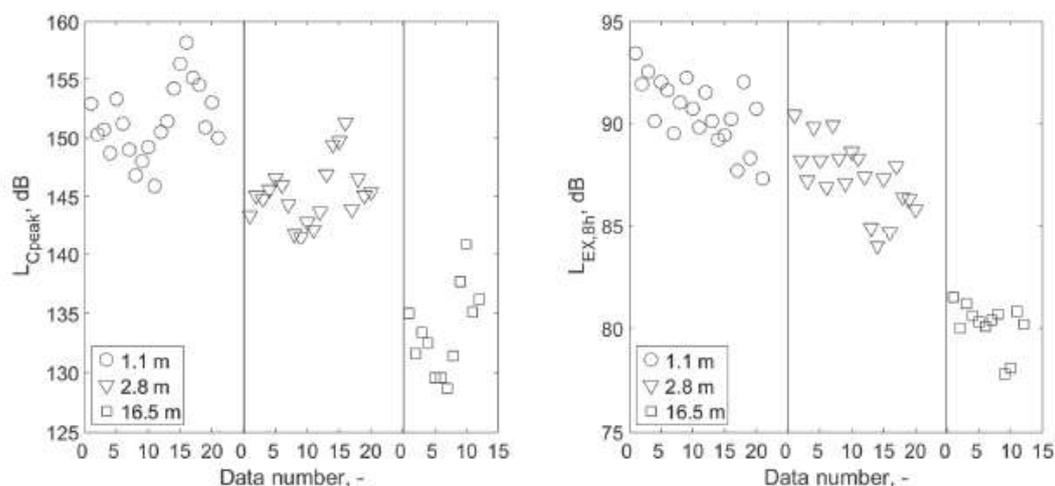

Figure 7. Values of L_{Cpeak} and $L_{EX,8h}$ parameters measured at the shooting instructor's locations, divided into three variants of the instructor's distance from the shooters, covering all the types of weapon/ammunition combinations included in the training plan on the shooting range.

3.4. Assessment of Hearing Protectors

The results of the selection of hearing protectors with respect to the noise parameter associated with its impulse character, i.e., L'_{Cpeak}, are shown in Figure 8. It can be observed that all level-dependent hearing protectors included in the tests make it possible to limit the L'_{Cpeak} value below the criterion value of 135 dB for shots from pistols or a submachine gun. However, for shots from the Mossberg shotgun, the use of some hearing protectors does not result in a sufficient reduction of the L'_{Cpeak} value. For shotgun 2, the L'_{Cpeak} value under four out of 10 hearing protectors exceeds 135 dB, while in the case of shotgun 1, this occurs under six out of 10 protectors. It can also be noted that in the case of the 140 dB criterion, this criterion is exceeded only for shots from shotgun 1, and this takes place for four out of 10 hearing protectors.
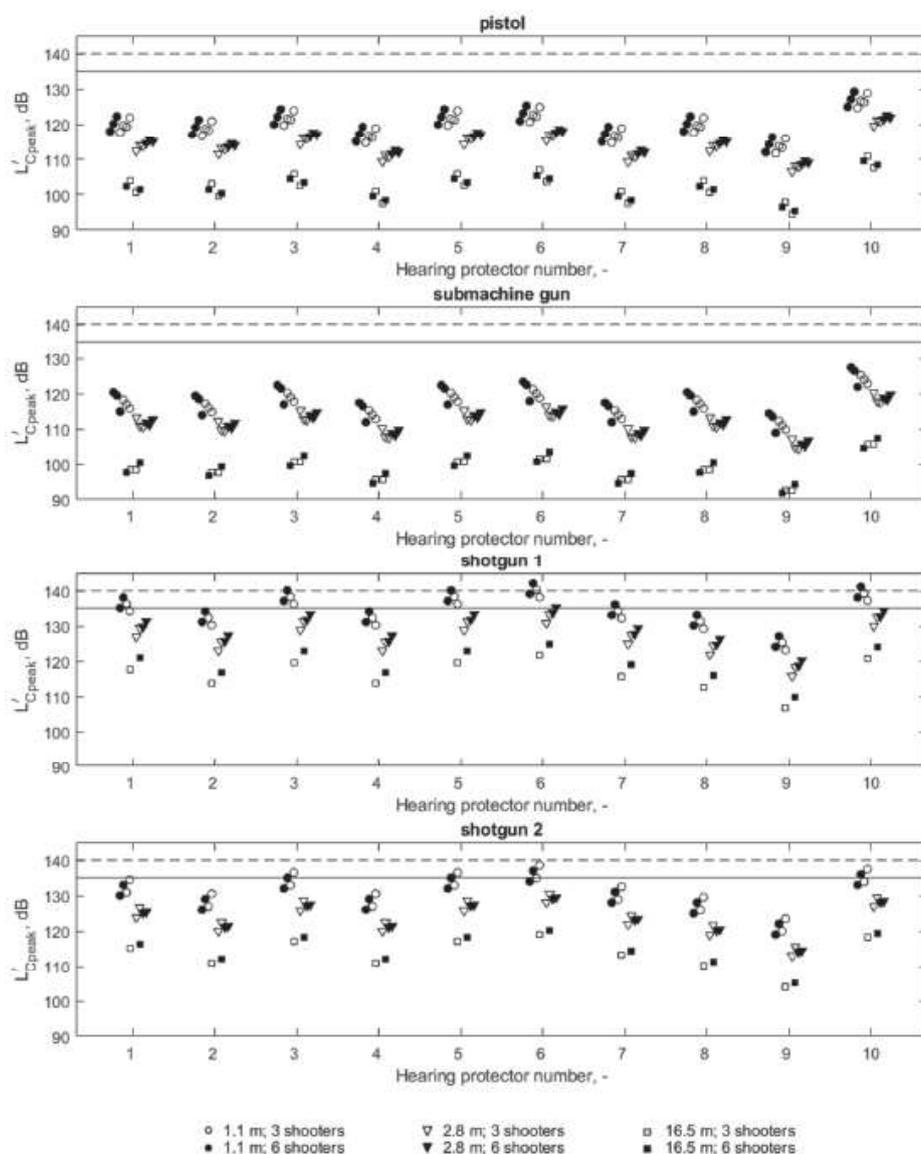

Figure 8. L'_{Cpeak} values (under hearing protectors) for four weapon/ammunition combinations. The horizontal continuous line indicates the criterion value of 135 dB, while the dotted line represents a criterion value of 140 dB.

The selection of hearing protectors by the octave band method results in the obtained L'_A values, as shown in Figure 9. The calculations demonstrate that for each of the four weapon/ammunition

dr inż. Rafał Młyński

Załącznik 4a_cz2 Kopie powiązanych tematycznie artykułów naukowych A4-A6 wchodzących w skład cyklu stanowiącego osiągniecie naukowe

combinations, not all of the hearing protectors in question resulted in a sufficient reduction of the L'_A value. Hearing protector number 10 did not fulfil its task in relation to all four weapon/ammunition combinations, while hearing protector number 6 sufficiently limited the L'_A value only in the case of the submachine gun.
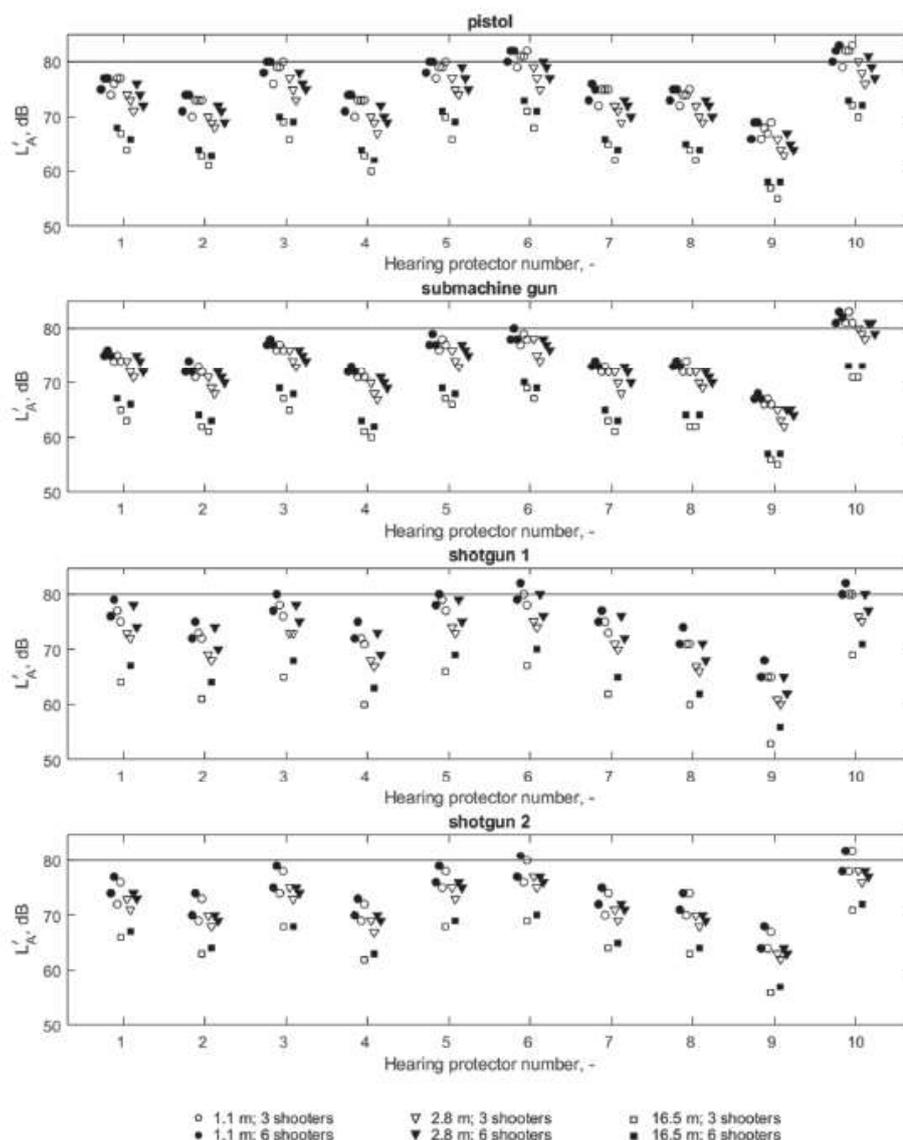

Figure 9. L'_A values (under hearing protectors) for four weapon/ammunition combinations. A horizontal solid line indicates a criterion value of 80 dB.

The highest absolute values of difference between the calculations of the L'_A value using the octave band method and the HML method were 2 dB, while between the octave band and the SNR method, the difference reached 4 dB. The results of the comparison with the criterion value of L'_A, calculated using the SNR method and the octave band method, were not consistent in individual measurement situations; however, the SNR method ultimately ruled out the same two protectors from the group of appropriate hearing protectors with the octave band method. The result is slightly different when comparing the results of using the HML method and the octave band method, where the HML method excluded four hearing protectors (marked as 3, 5, 6 and 10), while according to the results of the octave band method, an inadequate reduction of L'_A values took place in the case of two hearing protectors (6 and 10). The results obtained indicate, therefore, that if suitable measurement data are available,

the most accurate selection method should be used: i.e., the octave band method. The use of other methods for calculating the L'_A value may result in different conclusions from the octave band method, which is considered as the reference method.

The highest values of L'_{Cpeak} and L'_A determined from all the measuring situations included in the study are shown in Table 2.

Table 2. The highest values of noise parameters under hearing protectors determined from all the measuring situations included in the study (53 shooting cycles).

Hearing Protector Number	1	2	3	4	5	6	7	8	9	10
L'_{Cpeak}, dB	138.1	134.1	140.1	134.1	140.1	142.1	136.1	133.1	127.1	141.1
L'_A, dB	79	75	80	75	80	82 [1]	77	75	69	83

[1] Results exceeding the relevant criterion value are provided in bold. Criteria values: L'_A = 80 dB, L'_{Cpeak} = 135 dB.

4. Discussion

The research conducted indicated that the noise produced in individual training situations at the shooting range was different in terms of the content of acoustic energy components in individual frequency bands (Figure 3). Taking this fact into account, and taking into consideration that the characteristics of the sound attenuation of hearing protectors as a function of frequency are uneven (Table 1), it should be stated that the assessment of the reduction of the noise produced at a shooting range by individual hearing protectors requires appropriate calculations in each situation considered.

The measurements of the impulse noise parameters generated in the places where the shooting instructor was located indicated relatively high SPL values produced by the firearms, which is in line with the results of other studies on shots from firearms. Measurements conducted in this study showed that the instructor, when standing at a distance of 1.1 m behind the shooters, was exposed to acoustic impulses whose L_{Cpeak}, depending on the variant of weapon/ammunition combination and the shooting scenario, assumed values ranging from 145.9 dB to 158.1 dB. There are, however, no data that could be directly compared with the data obtained in this study at the indoor shooting range for the instructor's locations. Published results usually characterize noise close to the shooter's ear (although not always), or there is no precise information about the measurement location and C-weighted peak SPL or unweighted peak SPL (L_{peak}) being considered; moreover, measurements are usually carried out on military fields. For example, in [1], there is general information that the peak SPL produced by small-caliber rifles, shotguns and large-caliber handguns ranged from 132 dB up to more than 172 dB for high-powered firearms. In the study in which the measurements were carried out in field conditions, a few meters away from the shooter, the L_{peak} associated with C7 rifle shots was 148.3 dB, while at the distance of 30 cm from the shooter, it was 154.7 dB [23]. For shots from a 9 mm caliber pistol, values of 148.4 dB and 155.6 dB were obtained, respectively [23]. Subsequent data [24] indicated that for L_{peak} determined on the basis of waveforms associated with a 5.56 mm caliber C7 rifle shot, recorded at a distance of 4 m from the muzzle at 90° and 6.4 m at 39°, in both cases, the value was approximately 157 dB. In one of the studies, the L_{peak} values associated with AR-15 rifle shots were 168 dB at the distance of 1.8 m, 150 dB at 4.3 m, and 132 dB at 25.7 m [25]. Despite the mentioned differences between the aforementioned studies and this study regarding the measurement conditions, the common point is that large and comparable SPLs are measured in the places where the shooting instructor is located. The exposure of the shooting instructor to the noise produced at the shooting range, which, according to the previously mentioned criteria should be classified as dangerous for hearing, requires the use of appropriately selected hearing protectors. Another conclusion is that in order to correctly determine the values of the noise parameters to obtain the necessary data for the selection of hearing protectors, the measurements could not be carried out using standard sound level meters. The upper measuring range of such devices is usually limited to approximately 145 dB. In response to the problem of measuring high SPL values related to impulse noise, hardware solutions were developed [14,26].

In one of the studies, where strategies for possible ways to reduce the negative impact of impulse noise on shooters' ears were formulated, among others, the use of outdoor or acoustic-treated indoor shooting ranges was recommended [27]. The results obtained on the shooting range included in the present study confirmed that when applying acoustic treatment, acoustic conditions similar to the free field conditions can be obtained. Although the L_{Aeq} and L_{Cpeak} values shown in Figures 4 and 5 do not fit perfectly in straight lines with the theoretical slope for free field conditions, the deviations of results from the theoretical lines are relatively small. This proves that the use of acoustic treatment on the shooting range effectively limited the impact of sound reflections. Therefore, it can be assumed that the effect of the distance of the shooting instructor from the sound source on the degree of hearing hazard is similar to the situation in free field conditions.

In the case of impulse noise, it is not possible to characterize the reduction of this kind of noise by a specific hearing protector using one value only. This is due to the fact that the parameters of acoustic impulses produced by different sources differ from one another [22], and the reduction of the impulse noise strongly depends on the source of this noise [25]. According to the methodology for hearing protector assessment referring to the L_{Cpeak} parameter, in this paper, for each hearing protector, two attenuation values were distinguished: one for shots from pistols and a submachine gun, and the second for shots from smooth-bore shotguns (shotgun 1 and shotgun 2). The different values of noise parameters produced by each weapon/ammunition combination and the different values of the acoustic parameters of individual hearing protectors resulted in different noise values determined under the hearing protectors. For example, the highest L'_{Cpeak} values (Figure 8) under the HP1 hearing protector were 122.3 dB (pistols), 120.4 dB (submachine gun), 138.1 dB (shotgun 1) and 134.5 dB (shotgun 2). The range of these values is therefore 17.7 dB. Similarly, the range of the L'_{Cpeak} values among the four weapon/ammunition combinations, depending on the hearing protector, ranges from 12.7 to 18.7 dB for all other hearing protectors. At the same time, it should be emphasized that with a particular hearing protector, the L'_A parameter values are much less varied (from 1 dB to 3 dB—Figure 9) between different weapon/ammunition combinations than they are in the case of the L'_{Cpeak} parameter. Therefore, for impulse noise, the parameter reflecting the energy properties of noise (L'_A) differentiates individual noise sources to a much lesser extent than the parameter referring to the instantaneous values characterizing impulses (L'_{Cpeak}). It is therefore confirmed that for exposure to impulse noise, the assessment of hearing protectors is insufficient due to the value of the L'_A parameter, as is the case for continuous noise. It is necessary to take into account the L'_{Cpeak} parameter, which of course is primarily due to the fact that the L_{Cpeak} value of noise is exceeded.

There are no published data on the reduction of impulse noise by individual hearing protectors, which could have been directly compared with the results presented in this paper. For example, data are available for the insertion loss of impulses generated during shots from an AR-15 rifle with a L_{peak} of 150 dB [25]. These data were measured using an acoustical test fixture for earmuffs with similar properties to the hearing protector designated in this paper as HP2. The earmuff from the aforementioned study [25] reduced the L_{peak} to 108.8 dB. In similar measurement conditions in the next study, data were obtained that indicated that another earmuff reduced L_{peak} to 118 dB [28]. In this study, in the most similar situations to the two mentioned studies, the average L_{Cpeak} value with the HP2 protector at distances from the shooter equal to 1.1 m and 2.8 m was 113.3 dB for submachine gun shots and 125.0 dB for shotgun 2 shots. Examples of published data can be supplemented with the result of 132 dB concerning the L_{peak} parameter measured using an acoustical test fixture with an earmuff, in the presence of an impulse produced during a shot from a 12.7 mm machine gun [29]. The impulses produced by this source were characterized by a L_{peak} value of 152 dB. The studies in the referenced papers [25,28,29] and this paper differ in the type of weapon, noise parameter analyzed, hearing protector model, distance from the shooter and measurement method used; however, independently obtained values of noise parameters potentially reaching the user of the hearing protector exceed 100 dB and are below the exposure limit values. It can be observed that in all the studies discussed, the reduction of impulse noise by hearing protectors was measured using a head and torso simulator; i.e.,

an acoustical test fixture. This is different from this particular study, in which a calculation method was employed in which sound attenuation data of hearing protectors was used, which are determined with the participation of subjects.

Since a hearing protector can only be considered suitable for protecting hearing against noise when its use obtains correspondingly reduced parameter $L'_{C_{peak}}$ and L'_A values at the same time. On the basis of the data in Table 2, it can be stated that, according to the adopted criteria for the assessment of hearing protectors, L'_A = 80 dB and $L'_{C_{peak}}$ = 135 dB, an appropriate hearing protection for the shooting instructor will be possible when using hearing protectors 2, 4, 8 and 9. Two of the earmuffs (hearing protectors 2 and 4) and earplugs in two variants of eartips (hearing protectors 8 and 9) were found to be appropriate.

At the same time, it can be noted that by changing the criterion for $L'_{C_{peak}}$ to less severe, i.e., $L'_{C_{peak}}$ = 140 dB, as used in many countries and defined in the Directive [18], an adequate protection of hearing would also be guaranteed by hearing protectors 1 and 7.

The results obtained indicated that the parameter associated with the instantaneous value of the signal, i.e., $L_{C_{peak}}$, is crucial in the process of assessing hearing protectors in terms of their ability to reduce the impulse noise produced on a shooting range. In both situations in which the parameter L'_A value was exceeded, the criterion value referring to the parameter $L'_{C_{peak}}$ was also exceeded. At the same time, in four consecutive situations of exceeding the criterion value of the $L'_{C_{peak}}$ parameter, these situations did not involve exceeding the L'_A parameter. It is therefore important that, for impulse noise, the selection of hearing protectors cannot be limited to taking into account the L'_A parameter, as in the case of continuous noise, where there is no problem in exceeding the exposure limit values of $L_{C_{peak}}$.

At the same time, it should be noted that hearing protection requires not only properly selected hearing protectors, but that they must be used and set up correctly, and other sources of noise exposure, often unrelated to professional work, should be avoided. For example, practical instances of the improper use of earplugs were observed, and the reason behind this was a lack of training or that it was deliberately done to better hear messages spoken by the Range Safety Officer [23]. In turn, in one of the papers investigating the hearing condition of 20 policemen after 10 years of service, a deterioration of hearing was found despite the use of double hearing protection [30].

5. Conclusions

The results of the study indicate that impulse noise produced on the shooting range should be assessed as dangerous for hearing. The exposition of the shooting instructor to this noise requires the use of appropriately selected hearing protectors. The results of the analysis of noise parameters measured at different distances of the shooting instructor from the shooters confirmed that increasing this distance, if possible, is a good method for reducing the exposure of the instructor to noise. It also appeared that with a certain number of shooters who are to be trained, their division into subgroups consisting of three or six people at the same time does not significantly affect the shooting instructor's exposure to noise.

The results of the assessment of level-dependent hearing protectors demonstrated that it is possible to adequately protect the hearing of a shooting instructor who is at an indoor shooting range when using protectors of this type. It is possible to choose hearing protectors, both earmuffs and earplugs, that will sufficiently reduce the impulse noise to which the instructor is exposed.

It appears that, taking into account the program of exercises at the shooting range at which shooting was carried out with pistols, a submachine gun and smooth-bore shotguns, the assessment of hearing protectors with a more restrictive criterion (L'_A = 80 dB, $L'_{C_{peak}}$ = 135 dB) showed that only four out of the 10 level-dependent hearing protectors included in the analysis sufficiently reduced the noise. Assuming a less restrictive criterion regarding the C-weighted peak SPL, i.e., $L'_{C_{peak}}$ = 140 dB, six out of 10 hearing protectors would be appropriate. Therefore, regardless of which criterion for the assessment of earmuffs is used, only some of the hearing protectors will be a potentially suitable means of protecting the shooting instructor's hearing, and the correct selection of hearing protectors

is necessary. However, in the case of impulse noise, this selection must be based not only on the standardized selection methods related to the continuous noise but must also take into account the parameter associated with the instantaneous value of the signal level; i.e., the C-weighted peak SPL.

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NOISE REDUCTION AT THE SHOOTING RANGE BY MEANS OF LEVEL-DEPENDENT HEARING PROTECTORS

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ABSTRACT

Background: The aim of the tests was to establish the possibilities of reducing impulse noise by using level-dependent hearing protectors at a shooting range. The tests included 9 models of level-dependent earmuffs and 2 models of level-dependent earplugs. They were conducted in the presence of impulse noise generated by 7 types of firearms (pistols, a submachine gun, rifles, a shotgun). **Material and Methods:** The tests were conducted at an outdoor shooting range, using an acoustic test fixture that meets the requirements of the ANSI/ASA S12.42-2010 standard. Noise parameters were established for the noise reaching the microphones installed in the ear simulators of the acoustic test fixture: uncovered and protected by the tested hearing protectors. **Results:** All 11 tested level-dependent hearing protectors allow to satisfactorily (below the exposure limit values) reduce the C-weighted peak sound pressure level and A-weighted maximum sound pressure level parameters of noise produced during shots from the 7 types of firearms included in the study. Moreover, in the most unfavorable case, the permissible number of impulses due to the value of the A-weighted noise exposure level normalized to an 8-h working day parameter exceeds 5000 per day. **Conclusions:** Level-dependent hearing protectors constitute the appropriate means to protect the hearing of people at a shooting range, while maintaining the functionality of these protection devices to transmit speech signals. Med Pr. 2019;70(3):265–73

Key words: impulse noise, earplugs, attenuation, earmuffs, noise reduction, level-dependent hearing protectors

INTRODUCTION

Level-dependent hearing protectors are increasingly used, not only at industrial workplaces, but also in the areas of exposure to acoustic impulses generated by firearms. It should be noted that the use of hearing protectors in the presence of firearms being fired is a necessity resulting from the insufficient effectiveness of other technical means of reducing impulse noise, such as noise suppressors [1].

Level-dependent hearing protectors affect the sound that reaches their users. This is performed by an electronic system, equipped with microphones mounted outside the hearing protector and speakers that reproduce the sound under the hearing protector. This system improves the reception of useful sounds (speech,

auditory danger signals) in the absence of noise. There is also the potential danger that, with a large amplification in the acoustic signal reproduction system, the sound reaching the person may cause increased noise exposure. The use of hearing protectors must adequately protect the hearing of their users [2].

In order to be able to determine if the hearing protector provides adequate noise reduction, the parameters of the noise heard at the person's location as well as the noise reduction effectiveness of the hearing protector must be known. The methods for determining the reduction (attenuation) of noise by hearing protectors are divided into 2 categories: subjective (using the response of a person) and objective (measured using a microphone). Due to the relatively high values of the peak sound pressure level and the rapidly chang-

ing nature of impulse noise, the authors could not use the subjective real-ear attenuation at threshold (REAT) test method [3–5] to assess the effectiveness of noise reduction by hearing protectors for impulse noise [6]. The technical possibility of measuring impulse noise attenuation is provided by objective methods, based on sound pressure level measurements by using a miniature microphone placed in the ear, under the hearing protector (microphone in real ear – MIRE method) [7] or by using acoustic test fixtures [8].

However, conducting impulse noise attenuation tests on hearing protection requires the use of test signals which are inherently dangerous to hearing. In spite of the use of hearing protectors, exposure to impulse noise may be dangerous to hearing [9]. Therefore, a better and safer solution is the use of devices which reproduce human characteristics, which eliminates the need for human participation in the tests [10,11]. These devices are called acoustic test fixtures. They are frequently used in tests where impulse noise with a high peak sound pressure level is present [12–14].

So far, only a few studies have been conducted on the reduction of impulse noise by level-dependent hearing protectors [15–17], therefore we have no test results to compare the properties of different hearing protector models used for this purpose. The aim of the tests presented in this paper was to establish the possibilities of reducing the impulse noise using 11 models of level-dependent hearing protectors at an outdoor shooting range (9 earmuffs and 2 earplugs).

MATERIAL AND METHODS

Hearing protectors included in the tests

The tests included 11 different models of level-dependent hearing protectors. Nine of them were earmuffs, while the remaining 2 were earplugs. The list of hearing protectors included in the tests is presented in Table 1. This table also contains the letter designation assigned to each hearing protector for the purpose of this study (used henceforth when test results are presented on charts).

Impulse noise source

The tests of shooting range noise reduction by hearing protectors were conducted at an outdoor shooting range, in the presence of acoustic impulses generated by 7 types of firearms, popular among law enforcement services, sporting enthusiasts and hunters. A list of the firearms included in the tests and the designations of

Table 1. Level-dependent hearing protectors included in the tests and the designations of individual hearing protectors

Hearing protector	Designation	Type
3M Peltor ComTac XP	A	earmuffs
3M Peltor Tactical XP	B	earmuffs
3M Peltor Sportac	C	earmuffs
3M Peltor ProTac Shooter	D	earmuffs
3M Peltor ProTac Hunter	E	earmuffs
MSA left/RIGHT CutOff	F	earmuffs
MSA Supreme	G	earmuffs
Hellberg Active Secure 2H	I	earmuffs
Realhunter Active pro	J	earmuffs
3M Peltor LEP-100 EU	L	earplugs
Etymotic GunSport Pro GSP-15	M	earplugs

Table 2. Firearms included in the shooting range tests and the designations of individual firearms

Firearm	Designation	Type
Walther P99	firearm 1	pistol
Glock 17	firearm 2	pistol
PM-98 Glauberyt	firearm 3	submachine gun
Remington 700	firearm 4	rifle
Mossberg MMR	firearm 5	tactical rifle
Mossberg 500	firearm 6	shotgun
AKM	firearm 7	rifle

the firearms used for this study (for presenting its results) are presented in Table 2.

The impulses generated during shots from individual types of firearms included in the tests differ in C-weighted peak sound pressure level (L_{Cpeak}) and duration. These differences may be the reason for the varying degree of attenuation of noise generated by individual firearm types by the hearing protectors [12]. In the case of acoustic impulses generated during shots from firearms at a shooting range, the C duration is the most representative for determining impulse duration, due to the waveform of this noise type; this particular waveform comprises a series of significant increases and decreases of sound pressure. The definition of C duration [18] specifies that this is the total time the waveform of the analyzed signal exceeds a value of −10 dB in relation to the peak value. Moreover, the peak value is calculated using the absolute value of the analyzed signal. All of the weapons in question generate impuls-

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es which should be considered potentially harmful to hearing. The determined C-weighted peak sound pressure level values and the duration of the sample impulses selected from each firearm type are presented in the *Results* section.

Experimental set-up

An acoustic test fixture ("artificial head") was used for conducting noise reduction tests by means of level-dependent hearing protectors at the shooting range, establishing the values of noise parameters potentially reaching the hearing protector user. An image of the measurement system used is shown in Figure 1.

In the foreground: left – a GRAS 67SB transducer used for measuring the properties of acoustic impulses, right – a GRAS 45CB acoustic test fixture to measure the acoustic properties of hearing protectors, with level-dependent earmuffs (test object). The impulse noise is generated by discharging the firearm operated by a shooter (not shown in the photograph).

Figure 1. The measuring system for testing acoustic impulse reduction by level-dependent hearing protectors used during tests at a shooting range

Currently, the most advanced design which enables the modeling of a person's features for the purpose of testing the acoustic properties of hearing protectors is the GRAS 45CB acoustic test fixture (GRAS Sound & Vibration A/S, Denmark) [19]. This test fixture meets the requirements of the standard on the measurement of the acoustic properties of hearing protectors [20]. The acoustic test fixture models the anatomical shape of the head and ear. Ear simulators and GRAS 40BP microphones were installed in the fixture. Moreover, the fixture elements which could potentially come into contact with the test earplugs or earmuffs were covered with materials with a Shore hardness of 55 (Shore 00), in

order to reflect the characteristics of human skin. During the tests, in each measurement situation, a heating system was used in order to maintain the acoustic test fixture at a temperature corresponding to human body temperature. This ensured that the test conditions provided were as close as possible to the conditions in which hearing protectors are used by humans. This is important due to the impact of temperature on the properties of materials used in the manufacture of hearing protectors.

The acoustic impulse parameters were measured using a GRAS 67SB transducer with a GRAS 40DP microphone. Electrical signals from this transducer and from the acoustic test fixture were transmitted to a Brüel & Kjær 3052-A-030 measurement unit (Brüel & Kjær, Denmark). For the analysis of measurement data, Brüel & Kjær PULSE Reflex software was used.

Test performance method

During the performance of the tests, conditions were achieved in which each of the tested level-dependent hearing protectors was placed on the acoustic test fixture in a manner corresponding to its use by a person. It was therefore attempted to obtain tight adherence between the earmuff cushions and the side surfaces of the test fixture's head, and between the earplugs and the walls of the ear simulator couplers. As it was difficult to obtain the tight adherence of the hearing protectors to the acoustic test fixture surface (requiring considerable experience on the part of the operator), in particular in field conditions, a quality check of the placement of the hearing protector was performed. After each placement of the earmuffs on the acoustic test fixture head or of the earplugs in the test fixture ears, a shot from a starter pistol was fired, while the indications of the measuring instruments were observed. If necessary, the action of placing the hearing protectors was repeated until a satisfactory result was obtained. Adherence checks based on the degree of starter pistol noise transmission under the hearing protector did not guarantee its perfect adherence. For this reason, it was assumed that the tests would be conducted in such a way as to obtain 6 elementary measurement results under a specified hearing protector in every measurement situation.

The elementary measurement situation was understood as measurement conducted during a shot from the specified firearm when the specified hearing protector was placed on the acoustic test fixture. Carrying out 6 measurements enabled the selection of cases in which it was assumed that the adherence of the hearing protector to the acoustic test fixture surface was correct.

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Finally, 3 measurement results of parameters of impulse noise under the specific level-dependent hearing protector were selected (out of 6 measurement results). Thus, the final measurement result under a specific hearing protector for a particular type of firearm was obtained on the basis of measurements carried out in the presence of 3 shots from this firearm. Similarly, 3 shots from the individual type of firearm were taken into consideration when determining parameters of the impulse noise generated by this type of firearm when every hearing protector was tested. Each of the mentioned 3 selected measurement results were averaged. The mean value calculated from the data was expressed in a linear scale i.e., following the conversion of the values expressed in decibels to Pascals.

The tests resulted in obtaining insertion loss representing the noise attenuation by the hearing protector in question. The insertion loss measured using the acoustic test fixture corresponds to sound attenuation measured with human participation [3].

The C-weighted peak sound pressure level parameter, i.e., L_{Cpeak} was considered to be the most important parameter concerning impulse noise exposure. Moreover, the remaining 2 noise parameters used in the occupational noise exposure assessment were taken into account: L_{Amax} (A-weighted maximum sound pressure level) and $L_{EX,8h}$ (A-weighted noise exposure level normalized to an 8-h working day; otherwise also expressed as daily noise exposure level) [21]. The effectiveness of impulse noise reduction by the hearing protector, due to the $L_{EX,8h}$ value may be assessed by establishing the permissible number of impulses against which the employee using the specified hearing protector will be protected. Therefore, this study has established the permissible number of impulses (PNI) (a single impulse is the result of a single firearm shot), to which the hearing protector user could be exposed, with the assumption of a simultaneous reduction of the L_{Cpeak} and L_{Amax} parameters below the exposure limit values. The permissible number of impulses was determined on the basis of the formula (1) which takes into account the permissible value of the $L_{EX,8h}$ parameter of 85 dB [21]:

$$PNI = \frac{10^{\frac{85}{10}}}{10^{\frac{L_{EX,8h}}{10}}}$$

(1)

where:

PNI – permissible number of impulses,

$L_{EX,8h}$ – A-weighted noise exposure level normalized to an 8-h working day.

It was assumed that the values of the $L_{EX,8h}$ parameter in formula (1) were obtained for every single shot based on formula (2):

$$L_{EX,8h} = L_{Aeq} + 10 \lg \left[\frac{T_{imp}}{T_0} \right]$$

(2)

where:

L_{Aeq} – A-weighted equivalent sound pressure level obtained for 1 shot,

T_{imp} – shot duration (time interval used to L_{Aeq} calculation),

T_0 – reference duration 3600 s (8 h).

The aforementioned insertion loss is expressed as the difference of the value of the specified noise parameter measured by the acoustic test fixture microphone without the hearing protector and the value of this parameter measured with the hearing protector. In practice it is not possible to simultaneously both listed results, i.e., without and with a hearing protector. In this situation, it is necessary to conduct the measurement using an additional transducer, located next to the acoustic test fixture, which, using the appropriate correction, pursuant to the methodology specified in the reference standard [8], allows to obtain insertion loss values corresponding to the tested hearing protector. Such corrections were, in the past, also used for impulse noise [14,22]. Measurement data for establishing this correction were used during additional measurements, conducted simultaneously with 3 microphones (transducer located next to an acoustic test fixture and 2 microphones of the fixture in question) with no hearing protectors on the test fixture.

The results obtained by separate laboratory testing indicated that the presence of the level-dependent system in the case of earmuffs did not impact the attenuation value expressed by the L_{Cpeak} parameter, although it was important in the case of earplugs [23].

Therefore, the measurement of the properties of each of the tested earmuffs was conducted with the level-dependent system turned on (the highest amplification in the system was selected). This enabled the most adverse situation, in terms of obtaining sufficient hearing protection for the L_{Amax} and L_{Aeq} parameters, to be taken into account. In the case of the earplugs, where with the presence of acoustic impulses the role of the level-dependent system was important, the tests were conducted in different modes. The earplugs marked with the letter L: the measurements were conducted with the medium amplification in the level-dependent system (max), average amplification (med) and passive mode (pas); that is, with

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the level-dependent system turned off. In the case of the earplugs marked M, 2 possible modes were used: high amplification (max) and low amplification (min.). In the case of these earplugs, no measurement in passive mode was conducted, since the earplugs' electronic system could not be turned off.
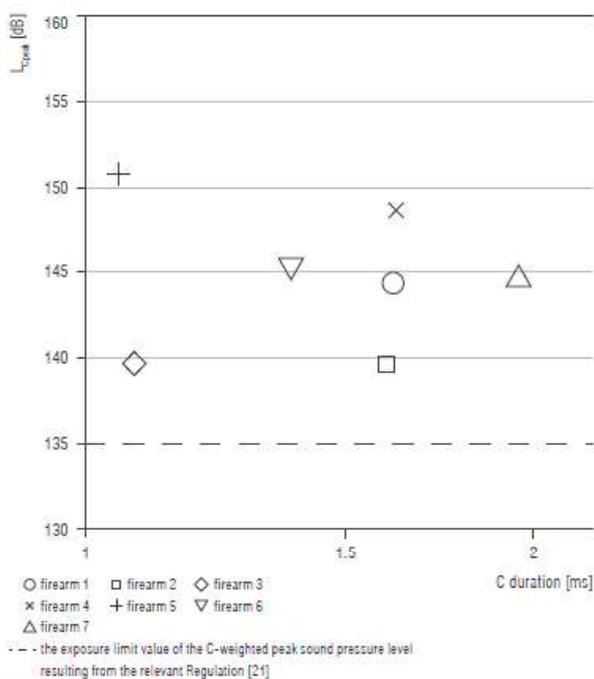
RESULTS

The determined C-weighted peak sound pressure level values and the duration of the sample impulses selected from each firearm type are listed in Figure 2. The criterion line of the exposure limit value of the C-weighted peak sound pressure level (135 dB), specified in regulations on hearing protection [21] is also shown.

The values of corrections used for obtaining insertion loss data, mentioned in the *Material and Methods* section, in the case of the L_{Cpeak} parameter, depending on the noise source (firearm type) the values of the corrections, were within the range 3.4–12.3 dB. In the case of the L_{Amax} parameter, they were 6.5–11.5 dB. In the case of the L_{Aeq} parameter, the values of the corrections also varied within the range 6.5–11.5 dB.

A list of the values of L_{Cpeak} reduction by the tested level-dependent earmuffs is provided in Figure 3, and by the earplugs in Figure 4. In general, it is plausible to state that the lowest values of the L_{Cpeak} reduction resulting from the noise attenuation by level-dependent hearing protectors were obtained for the impulses generated by firearm 2, and then firearm 1. The highest degree of noise attenuation applies to impulses generated by firearm 5. The difference between the listed highest and lowest L_{Cpeak} reduction values, i.e., between the L_{Cpeak} reduction established for impulses generated by firearm 2 and impulses generated by firearm 5 are statistically significant. The Wilcoxon test showed p = 0.0004 (calculated with the use of Matlab R2017a [version 9.2] with Statistics and Machine Learning Toolbox [MathWorks, Inc., USA]).

The obtained L_{Cpeak} reduction values representing the attenuation of noise generated by level-dependent hearing protectors at shooting ranges was used for establishing the range of L_{Cpeak} values under the hearing

○ firearm 1   □ firearm 2   ◇ firearm 3
× firearm 4   + firearm 5   ▽ firearm 6
△ firearm 7
- – - the exposure limit value of the C-weighted peak sound pressure level resulting from the relevant Regulation [21]

ELV – exposure limit value.

Figure 2. A list of C duration and C-weighted peak sound pressure level (L_{Cpeak}) values that characterize impulse noise generated during shots from the various types of firearms included in the tests
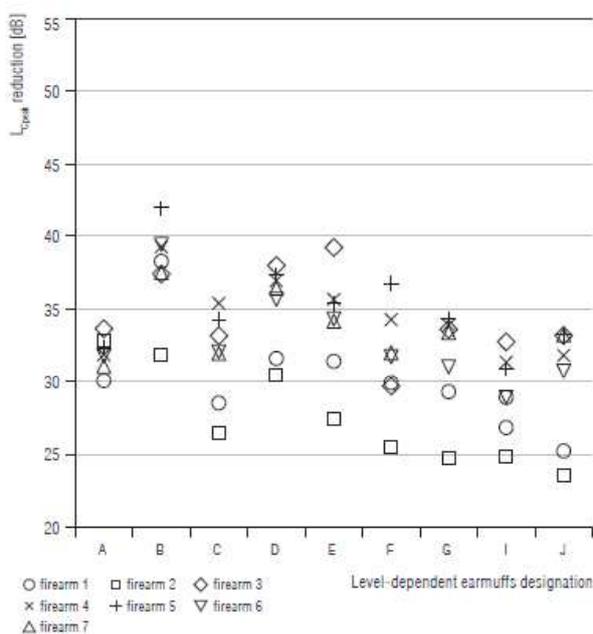
○ firearm 1   □ firearm 2   ◇ firearm 3
× firearm 4   + firearm 5   ▽ firearm 6
△ firearm 7

Each presented point on the chart was determined based on measurements carried out in the presence of 3 shots.
Hearing protector and firearm designations as in Table 1 and 2.

Figure 3. Reduction of C-weighted peak sound pressure level (L_{Cpeak}) by the tested level-dependent earmuffs
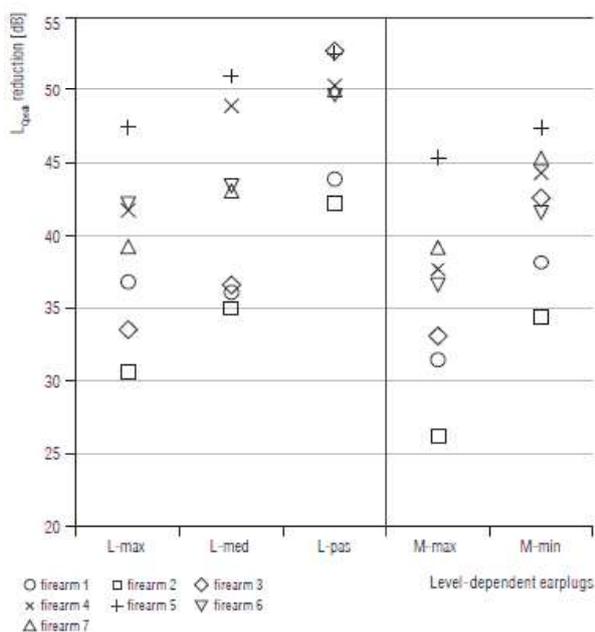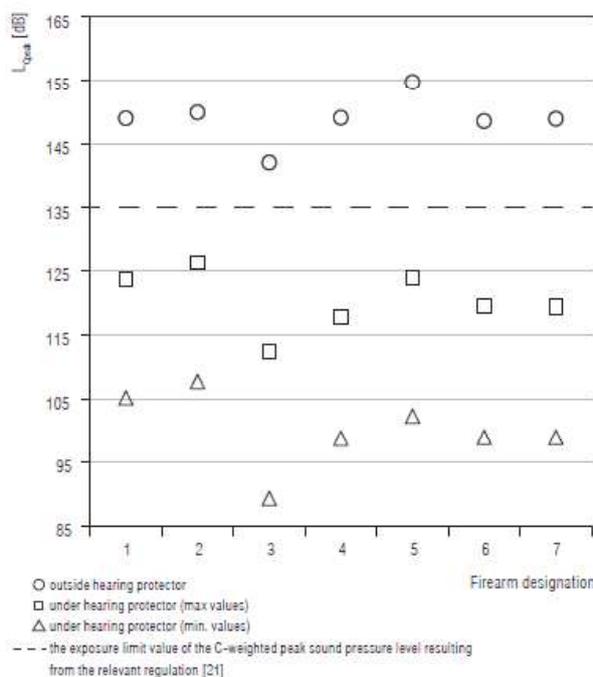
Each presented point on the chart was determined based on measurements carried out in the presence of 3 shots.

max – high amplification in the level-dependent system,

med – average amplification, min. – low amplification , pas – passive mode.

Hearing protector and firearm designations as in Table 1 and 2.

Figure 4. Reduction of C-weighted peak sound pressure level (L_{Cpeak}) by the tested level-dependent earplugs

Each presented point on the chart was determined based on measurements carried out in the presence of 3 shots.

ELV – exposure limit value.

Firearm designations as in Table 2.

Figure 5. Estimated values of the C-weighted peak sound pressure level (L_{Cpeak}) under the hearing protectors that are best and worst at reducing the impulses generated by various types of firearms

protectors. It was assumed that outside of the hearing protectors, impulses with the highest L_{Cpeak} levels were generated, and were measured during the tests at the shooting range (for each firearm type). Among the values obtained for L_{Cpeak} reduction for each of the 7 types of firearms, the lowest L_{Cpeak} reduction value and the highest L_{Cpeak} reduction value were determined (i.e., in the case of hearing protectors which reduced noise made by a specific type of firearm to the lowest degree). Subsequently, the L_{Cpeak} parameter of the noise potentially reaching under the hearing protector was calculated. The results of these activities are shown in Figure 5. It emerged that the range of the L_{Cpeak} under the hearing protectors included in the tests, regardless of the hearing protector, was below the exposure limit value. Therefore each of the tested level-dependent hearing protectors sufficiently reduces noise generated by the firearm types included in the test, with regard to the L_{Cpeak} parameter.

The highest value of the subsequent parameter: L_{Amax} measured in the sound field outside of the hearing pro-

tectors during tests at the shooting range exceeded the exposure limit values of 115 dB [21] and amounted to 118.1 dB. However, the established values of the L_{Amax} parameter reduction are high enough to ensure that in all cases under the analysis, the use of level-dependent hearing protectors resulted in the reduction of the L_{Amax} value below 115 dB. The lowest value of the L_{Amax} reduction in the case of the shooting range noise amounted to 15.7 dB, which occurred in the case of the level-dependent earplugs marked M, operating in a high amplification mode (max) in the level-dependent system. This means that the reduction of noise generated during shots from the firearms included in the study by all 11 tested level-dependent hearing protectors is sufficient to satisfactorily reduce the L_{Amax} parameter even when the generated impulses are characterized by L_{Amax} reaching 130 dB.

The calculated permissible number of impulses due to the value of the $L_{EX,8h}$ parameter is given in Figure 6. It emerged that in the most unfavorable case, this number exceeded 5000 impulses generated during shots. In
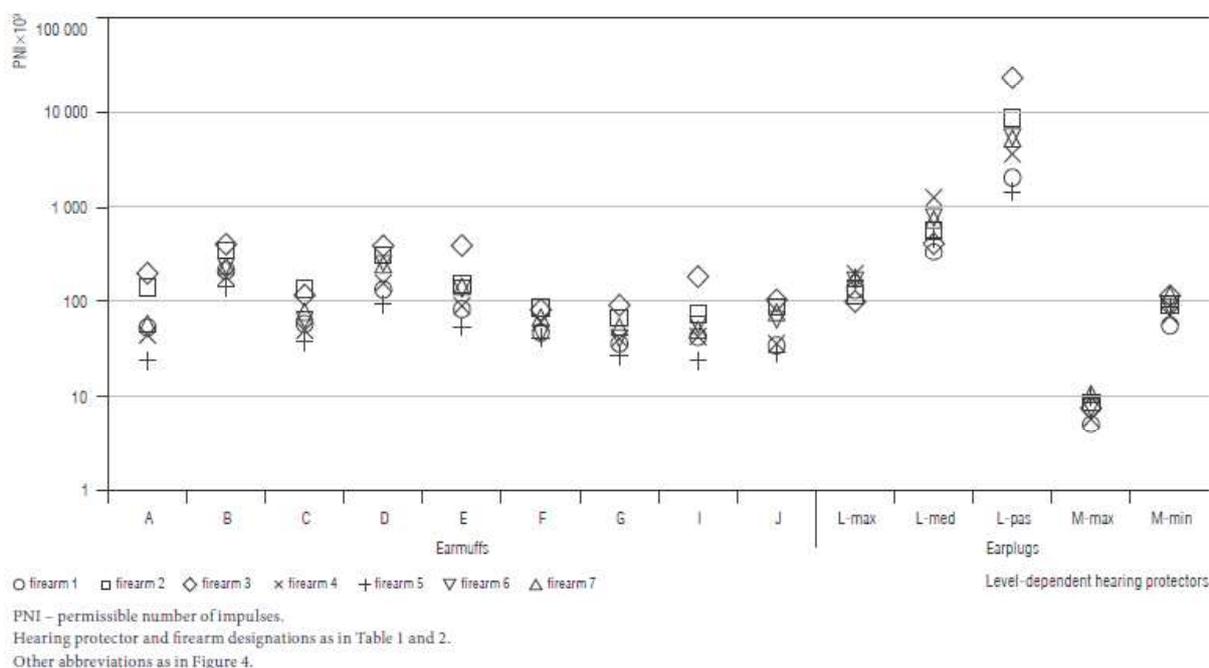
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O firearm 1 □ firearm 2 ◇ firearm 3 × firearm 4 + firearm 5 ▽ firearm 6 △ firearm 7

Level-dependent hearing protectors

PNI – permissible number of impulses.
Hearing protector and firearm designations as in Table 1 and 2.
Other abbreviations as in Figure 4.

Figure 6. The permissible number of impulses (PNI) resulting from the data on noise exposure, taking into account the use of individual types of level-dependent hearing protectors

practice, during field training exercises the shooter is not exposed to such a large number of impulses. The data specified in Figure 6 may be, however, important for firearm testing employees, where the employee is expected to discharge the weapon a significant number of times, counted in thousands.

DISCUSSION

The tests conducted during this study enabled the authors to achieve the goal specified in the introduction, which involved obtaining data on the possibilities of reducing the impulse noise at the shooting range by 11 models of level-dependent hearing protectors (9 earmuffs and 2 earplugs). The test results obtained through this study are significant since so far there have been no regular data on the reduction of impulse noise generated by level-dependent hearing protectors during shots from firearms.

There is no possibility of a direct comparison of the test results for impulse noise reduction by level-dependent hearing protectors with the results in published studies. Only a study by an American team [17] presents the results of attenuation of noise generated during shots from rifles by 3M Peltor TacticalPro level-dependent earmuffs. These earmuffs are most similar in their design to the 3M Peltor Tactical XP earmuffs included in the tests in this study. The authors of the study in question [17] have specified that the earmuffs they have tested reduce the peak sound pressure level (L_{peak}) generated during a AR-15 rifle shot by the value of 41.2 dB for impulses with L_{peak} of 150 dB. As part of this study, it was tested that the use of 3M Peltor Tactical XP earmuffs resulted in the reduction of the L_{Cpeak} value by 37.5 dB with impulses with a L_{Cpeak} of 146.1 dB, generated by an AKMS 7.62×39 rifle (firearm 7). Considering the various hearing protector models, types of rifles, peak sound pressure level of the generated impulses and the noise parameter, the result obtained in this study should be seen as consistent with the result presented in the aforementioned study [17].

The efficiency of impulse noise reduction was also assessed using an acoustic test fixture by Buck [15]. The work considered the reduction of impulse noise by level-dependent hearing protectors, however only as an example [15]. It stated that the level-dependent hearing protectors might be treated as passive devices in situations where the sound pressure level value exceeds the level of signal transmission through the electronic system. Whereas in a reverse situation (sound pressure

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level does not exceed the signal transmission level) the hearing protectors may be considered to be devices which transmit sound directly. Therefore, the study did not provide numerical data on noise reduction by level-dependent hearing protectors.

Neither did another study, in which tests were conducted on the reduction of impulse noise by 2 level-dependent hearing protectors [16] provide any data, either, which could be directly compared to the results of this study. This was due to different noise sources and different hearing protector models, as well as differences in established noise parameters.

As shown in the presentation of the results, the lowest values of the reduction of L_{Cpeak} resulting from the noise attenuation by level-dependent hearing protectors occur for impulses generated by firearm 2, and then firearm 1. The highest degree of noise attenuation applies to impulses generated by firearm 5. The C duration is not a universal method of reflecting the time properties of the impulse (due to the waveform's complexity), therefore there is no complete coincidence of the relationship between the example C durations of the individual weapon types (Figure 2) and the degree of reduction of the noise generated by the individual weapon types, expressed by the L_{Cpeak} parameter (Figures 3 and 4). It may be noted that the C duration of the impulse generated by firearm 5 (reduced most significantly) is the shortest whereas the C duration of the impulses generated by firearm 1 and firearm 2 (reduced least significantly) is longer than in the case of firearm 5. This observation is consistent with the conclusions of one of the studies published earlier [12], in which it was established that the reduction of impulses by passive hearing protectors was stronger the shorter an impulse was.

Among the hearing protectors included in these studies there are 2 similar models of level-dependent earmuffs, however with different earmuff cup dimensions. These were 3M Peltor ProTac Shooter (D) and 3M Peltor ProTac Hunter (E) earmuffs. The first of these 2 earmuffs was characterized by deeper cups. In the case of impulse noise generated by 6 of the 7 types of firearms, the L_{Cpeak} reduction in the case of earmuffs D (deeper cup) exceeded the values measured in the case of earmuffs E by 0.2–3 dB (depending on the firearm type). The only exception was a situation observed during impulses generated during shots from firearm 3, where the L_{Cpeak} reduction in the case of 3M Peltor ProTac Shooter (D) was lower by an average of 1.2 dB compared to the second of the listed earmuffs. In general, it should be stated that the greater depth of the earmuff cups (and thus the higher mass of earmuffs) favors more significant reduction of the impulse noise generated during firearm shots.

CONCLUSIONS

This study assessed the effectiveness of impulse noise reduction by level-dependent hearing protectors. The assessment was conducted for 9 earmuffs and 2 earplugs. The tests used the impulse noise generated during shots from 7 types of firearms. The following observations can be formulated based on the tests performed:

1. The range of the C-weighted peak sound pressure level under the hearing protectors included in the tests, regardless of the hearing protector, is below the exposure limit value. Therefore, each of the tested level-dependent hearing protectors sufficiently reduces noise in terms of the L_{Cpeak} parameter.

2. All 11 tested level-dependent hearing protectors allow to satisfactorily reduce the L_{Amax} parameter of noise produced during shots from the 7 types of firearms included in the study even when the generated impulses are characterized by L_{Amax} reaching 130 dB.

3. In the most unfavorable case, the permissible number of impulses against which the hearing protectors provide sufficient protection exceeds 5000. In typical shooting range training conditions, it is not possible for a shooter to discharge as many shots.

In summary, the user of properly worn tested level-dependent hearing protectors, both earmuffs and earplugs, will be sufficiently protected against noise generated at a shooting range during the shots from the 7 types of firearms included in this study. This protection will be provided regardless of the hearing protector mode (level-dependent system or passive hearing protector operation mode).

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Article

Localization of Vehicle Back-Up Alarms by Users of Level-Dependent Hearing Protectors under Industrial Noise Conditions Generated at a Forge

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Abstract: The use of hearing protectors in various noisy workplaces is often necessary. For safety reasons, auditory information may be required to correctly localize the direction of an auditory danger signal. The purpose of this study was to verify if the selection of a specific level-dependent hearing protector may be important for the ability to localize a vehicle back-up alarm signal. The laboratory conditions reflected industrial conditions, under which an impulse noise was emitted against a background of continuous noise. A passive mode and a level-dependent mode (maximum and incomplete amplification) were considered. Four different models of level-dependent earmuffs and one model of level-dependent earplugs were included in the tests. The tests enabled differentiation between the individual hearing protectors. The use of earplugs in level-dependent mode did not significantly affect the ability to correctly localize the back-up alarm signal. For the earmuffs, the global assessment of the impact of a mode change revealed that, depending on the model of the earmuffs, the impact may be insignificant, but may also result in considerable impairment of the ability to localize the back-up alarm signal.

Keywords: sound localization; level-dependent hearing protectors; back-up alarm; directivity of hearing; impulse noise; earmuffs; earplugs; auditory danger signal; warning signal; safety at work

1. Introduction

Noise is a physical factor that affects the hearing of people who have to be in places where it is emitted. Impulse noise is a particularly dangerous type of noise due to the sudden nature of its impact [1]. This type of noise may be present during military field exercises and in industrial conditions. Under industrial conditions, impulse noise occurs most often against a background of continuous noise. Noise reduction possibilities using technical means are limited [2]. Certain activities, such as metalworking, require manual handling close to the noise source so that physically separating a person's workplace from the noise source is impossible. The final solution, albeit the only one available, is the use of hearing protectors. Level-dependent hearing protectors are gaining in popularity and are being used more frequently. Their advantage over typical passive hearing protectors is that they do not reduce the relatively quiet sounds as much as sounds with a high sound pressure level [3]. This enables the perception of low pressure level sounds that are relevant for those using hearing protectors [4].

Level-dependent hearing protectors can be defined as a system consisting of a barrier that passively reduces the transmission of sound under these hearing protectors and from the sound transmission path in certain situations. The sound transmission path is created by means of an electronic system that reproduces the sound present in the user's environment through a speaker

placed under a hearing protector. The electronic system must be designed so that the amplification in the sound transmission path decreases as the sound pressure level of the signal present outside the hearing protector increases. The sound under the hearing protectors must be transmitted so as to ensure safe noise conditions for the user of these devices. In this respect, hearing protectors should meet the requirements set out in relevant standards, which apply to both earmuffs [5] and earplugs [6].

Some studies have been conducted on the possibility of reducing impulse noise by means of level-dependent hearing protectors [7–9]. It was observed that, for hearing protectors with electronic systems used in military conditions, the provision of adequate hearing protection should not be considered the only problem. Detection, recognition, identification, localization, and communication were also found to play significant sound-related roles [10]. Thus, when using hearing protectors under industrial conditions, in addition to the protective properties of hearing protectors, using the information contained in auditory danger signals is also crucially important. The presence of an electronic system used to transmit the sound under the hearing protector affects the formation of the sound reaching the users of these devices. The use of these hearing protectors may impair the ability to localize sound, i.e., recognize the direction of the source of the sound [11–13]. For safety reasons, under industrial conditions, it is vital to be able to correctly localize the noise source, which particularly applies to vehicle back-up alarm signals. Localization enables the user to take action to avoid being hit by a vehicle. The problem with the perception of back-up alarm signals was deemed serious enough that a dedicated electronic system for earmuffs was designed and introduced. The system functions to support the detection of such signals during the use of earmuffs in noisy environments [14]. The ability to perceive back-up alarm signals when using hearing protectors was also assessed [15]. The results of the study cited showed, with some exceptions, that the ability of normal-hearing people to locate a vehicle's back-up alarm signal in the presence of pink noise did not improve when using level-dependent hearing protectors (one model of level-dependent earplugs and earmuffs) in comparison to using passive hearing protectors. In a different study [16], the authors checked the possibility of locating a back-up alarm signal in the presence of noise simulating quarry conditions using one specific model of hearing protector. The localization of the back-up alarm signal was found to be slightly worse when the protector was used in passive mode in comparison to when it was not used, and did not improve after the electronic system was switched on. Vaillancourt et al. [17] compared the effects of different types of signals used as a vehicle back-up alarm signal and concluded that, despite the specific advantages of a signal with broad frequency content, the use of passive hearing protectors more severely affected the detection thresholds when compared to a tonal alarm. Unfortunately, the study did not consider level-dependent hearing protectors.

The purpose of this study was to verify whether the selection of a specific level-dependent hearing protector could be important for the ability to localize the auditory danger signal, represented by a back-up alarm signal, under industrial conditions where impulse noise is generated against a background of continuous noise. We also aimed to examine the impact of changes in the amplification of the electronic system of level-dependent hearing protectors. The tests were carried out in the presence of ambient noise recorded under industrial conditions containing impulse components, which is in contrast to the previous study [11,13–15,17].

2. Materials and Methods

2.1. Ethics and Bioethics Commission

Prior to the commencement of this research, an application for the study was submitted to the Ethics and Bioethics Commission of the Cardinal Stefan Wyszyński University in Warsaw. The commission issued a positive review (No KEiB-22/2017) of the study, providing consent for the implementation and publication of the research results.

2.2. Hearing Protectors Included in the Tests

We considered commercially available level-dependent hearing protectors produced by different manufacturers including four models of earmuffs and one model of earplugs. The hearing protectors studied included: N1 (designation introduced for the purpose of this study and to retain the anonymity of the manufacturer), which were earmuffs designed for military applications, digitally controlled; N2, earmuffs designed for industrial applications, digitally controlled; N3, earmuffs designed for industrial applications, analogically controlled; N4, earmuffs designed for hunting, analogically controlled; and W, earplugs designed for industrial applications with polymer tips, digitally controlled. In the case of the earplugs, the subjects were provided two different sizes of tips. All hearing protectors carried the CE mark (means that specified European Union requirements relating to hearing protectors have been fulfilled), which is a mandatory requirement for a product to be considered as a personal protective device. The hearing protectors included in the study varied in terms of price. The most expensive was more than 11 times more expensive than the cheapest.

The tests were performed in three hearing protector operation modes: passive mode, with the level-dependent system switched off (labelled PASS); level-dependent mode, with maximum amplification in the sound transmission path (labelled LD-MAX); and level-dependent mode with the amplification set to incomplete (approximately half and labelled LD-MID).

2.3. Subjects

The test group consisted of 50 people. The group included an equal proportion of women and men. The age of the subjects ranged from 18 to 42 years old. The subjects qualified for the trial based on the condition of their hearing, which had to meet the requirements of EN 24869-1:1992 [18] regarding a subjective method for the measurement of sound attenuation. This standard requires that the hearing threshold should not be greater than 15 dB for frequencies up to 2000 Hz and no more than 25 dB for frequencies above 2000 Hz.

2.4. Back-Up Alarm

Vehicles used in Polish industrial plants are most often equipped with acoustic signaling devices to warn others about reverse driving, and they generate a tonal signal. Two types of signaling devices can be distinguished that differ in the location of the dominant spectral components of the signal generated. These can be in the 1/3-octave band with a center frequency of 1250 Hz or 3150 Hz. The dominant spectral components in the first type are within the range of 500 to 1500 Hz, as specified in ISO 7731:2003 [19], in reference to one of the conditions to be met by an auditory danger signal. In the tests, we used a vehicle's back-up alarm signal that met the required standards.

The system designed to reproduce the back-up alarm signal was based on eight M-Audio Bx5 D2 loudspeaker sets (inMusic Brands, Cumberland, RI, USA) that were placed at the height of a sitting person's head. The M-Audio loudspeaker sets were evenly distributed in eight directions, every 45°, where the first loudspeaker set was placed directly in front of the subject's face. This direction was marked as 0°. Figure 1 provides a graphic representation of the directions from which the back-up alarm signal was reproduced. The distance between the loudspeaker sets and the point determined by the center of the person's head was 1.8 m. The electrical signal was fed to the inputs of the M-Audio loudspeaker sets from a MOTU 24I/O audio interface (MOTU, Cambridge, MA, USA). The sampling frequency was 44,100 Hz. For the purpose of testing the perception of back-up alarm signals, 15 different sequences of these signals were prepared. The order of signal reproduction from individual directions was randomly determined. The test of each elementary measurement situation was performed based on a sequence of 24 instances of a back-up alarm signal, as this signal was reproduced from eight directions, and the measurement was repeated three times in each of the directions.
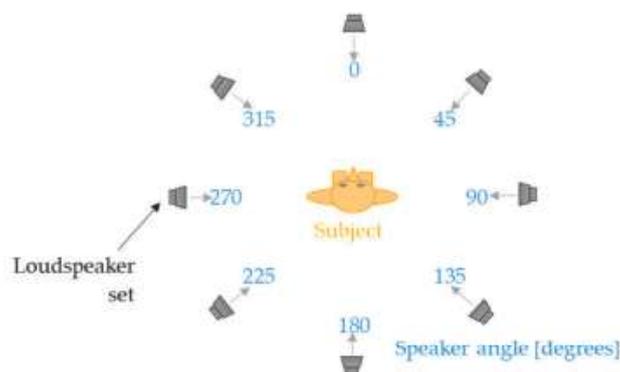
dr inż. Rafał Młyński

Załącznik 4a_cz2 Kopie powiązanych tematycznie artykułów naukowych
A4-A6 wchodzących w skład cyklu stanowiącego osiągniecie naukowe

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Figure 1. The directions from which the back-up alarm signal was reproduced and the location of the subject in the experimental setup.

2.5. Acquisition of the Direction Indications Provided by Subjects

The subjects indicated the directions from which a back-up alarm signal was received by pressing a button on a panel of eight push buttons arranged in a circle, reflecting the possible locations of the sound source. The response panel has been described in detail in a previous study [20].

2.6. Reflecting Industrial Noise Conditions

To reflect the presence of noise generated in industrial situations under laboratory conditions, a virtual acoustic environment using ambisonic technology was developed. The experimental setup was located in an acoustic chamber in the Tech-Safe-Bio CIOP-PIB Laboratory (Central Institute for Labour Protection—National Research Institute, Warsaw, Poland) [21]. The ambient noise obtained was reproduced in the experimental setup based on the recording of noise generated during metal processing at a forge. The ambient noise consisted of acoustic impulses generated by drop-forging hammers against a background of continuous noise. The recording was performed with the use of a Sennheiser AMBEO VR Mic ambisonic microphone (Sennheiser Electronic GmbH & CO KG, Wennebostel, Germany) connected to a Tascam DR-680 MkII recorder (TEAC Corporation, Tokyo, Japan).

A total of 17 Avantone MixCube loudspeakers (Avantone Pro, Tallman, NY, USA) were placed in the test room to reproduce ambient noise. The loudspeakers were located in a sphere with a 2-m radius in relation to the center of the seated person's (the subject's) head. Eight loudspeakers were placed circumferentially directly above the M-Audio BX5 D2 loudspeaker sets (inMusic Brands). Another four Avantone MixCube loudspeakers (Avantone Pro) were placed on the floor, and another four above the test subject (45 degrees upward in relation to the level of the subject's head). The 17th loudspeaker was placed directly above the subject's head. The sound reproduction system was supplemented with two sets of Nexo LS600/PS8 subwoofers (Nexo, Plailly, France). A photograph of the experimental setup during the tests is shown in Figure 2. The ambient noise was reproduced using a Rapture 3D Ambisonic Player (Blue Ripple Sound Limited, London, UK) at a sampling frequency of 48 kHz.

The A-weighted equivalent sound pressure level of the ambient noise reproduced on the experimental setup was 84.8 dB. The C-weighted peak sound pressure level was 111.8 dB. The values of the noise parameters were monitored before the beginning of each measurement session. The measurements were recorded at the location of the subject's head while the subject was absent by using a SVAN 979 Class 1 sound level meter (SVANTEK Sp. z o.o., Warsaw, Poland).

Figure 2. The experimental setup during the back-up alarm signal localization tests, performed with the participation of a subject wearing a level-dependent hearing protector.

2.7. Test Method

Before commencing the tests, each subject completed a training session. Each subject participated in the measurements for all five hearing protectors (listed in Section 2.2) in each of the three operation modes.

Industrial noise conditions were reflected during the tests. The ambient noise was reproduced according to the rules defined in Section 2.6. A back-up alarm signal was reproduced against the background of this noise according to randomly defined sequences (as described in Section 2.4). The task of the subject sitting in the center of the experimental setup was to indicate the direction of the back-up alarm signal by pressing the appropriate key on the panel (as described in Section 2.5). During the tests, each subject provided 360 indications (a sequence of 24 signals in each basic measurement situation for the three operation modes of each of the hearing protectors, for five different hearing protectors).

To analyze the obtained data, we created a direction recognition index for the back-up alarm signal. This index expresses, as a percentage, the ratio of the number of correct indications of the direction (or directions) in a given measurement situation to the number of all reproductions of the back-up alarm signal from the direction (or directions) considered in this situation.

2.8. Statistical Analysis

To determine which changes in the value of the direction recognition index between particular measurement situations should be considered significant, we completed a statistical analysis of the obtained data. For this purpose, a Wilcoxon test (equivalent to the Mann-Whitney U test) was used. The calculations were performed using MATLAB R2017b (version 9.3) with the Statistics and Machine Learning Toolbox (MathWorks Inc., Natick, MA, USA).

3. Results

3.1. Distribution of Indications between Individual Directions

The first step of the back-up alarm signal perception assessment involved analyzing how the indications of the subjects changed if the signal was reproduced from a specific direction. This analysis enabled the identification of the regularity of level-dependent earmuffs (N1–N4). In situations where the danger signal was reproduced from the $0°$ and $180°$ directions, in the majority of cases, a significant

number of indications did not only reflect the direction from which the signal was played. Correct indications of the 0° direction were noted for 20–40%, 31–47%, and 25–45% of cases for earmuffs used in the PASS, LD-MAX, and LD-MID modes, respectively. Correct indications of the 180° direction were slightly more frequent and their numbers expressed as a percentage were 45–53%, 26–53%, and 26–67% for the PASS, LD-MAX, and LD-MID modes, respectively. In the case of these two back-up alarm signal reproduction directions, 0° and 180°, the most frequent errors were of the 'front–back' type. This means that the subjects had problems in determining whether the back-up alarm signal came from in front or from behind. This situation is represented by the example in Figure 3a, where, for the back-up alarm signal from the 0° direction, the indications of this direction given by all subjects accounted for 39% of all indications, whereas the indications of the 180° direction were only six percentage points lower, representing 33% of all indications. Indications for the other directions in any situation did not exceed 10% of the overall number of indications.
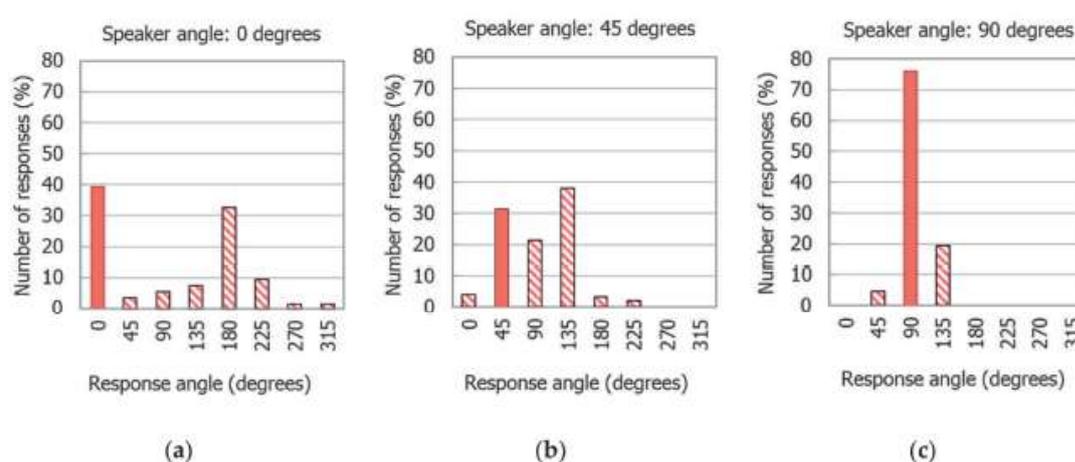

Figure 3. Distribution of the indications given by users of the N2 earmuffs in the LD-MAX mode when the back-up alarm signal was reproduced from a certain angle: (**a**) 0°, (**b**) 45°, and (**c**) 90°. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path.

An even worse situation occurred when the back-up alarm signal was reproduced from the directions at the angles of 45° and 315°. In these directions, the direction of the signal was reproduced was not the one that was indicated the most often. The subjects made errors in changing the direction from the front to the direction from the back of the person and indicated the directions of sound as adjacent to the directions from which the signal was played. An example of this situation is shown in Figure 3b, where, in the case of the back-up alarm signal coming from the 45° direction, the correct indications of this direction identified by all subjects were not the most frequent (31%). A larger number of indications, at 38%, was in the direction deviated from the axis crossing the person's ears by 45°; however, not from the front, but from beyond at 135°. Therefore, these were front–back type errors. A significant proportion of indications (21%) were in the direction adjacent (90°) to the direction from which the signal to be recognized was reproduced.

However, in the case of directions located to the side of the person, i.e., from directions at angles of 90° and 270°, the situation was different, since the majority of the indications of the subjects when the signals were reproduced from these directions were correct. Therefore, the correct indication of the 90° direction occurred in up to 81% of cases. This occurred when using the N3 earmuffs in LD-MAX mode. This was also the case for the 270° direction. In the case of these two directions (90° and 270°), the histograms were the slimmest. An example of this is shown in Figure 3c, where, in the case of the back-up alarm signal from the direction at the 90° angle (left side of the person), the correct indications of this direction given by all subjects were by far the most frequent, representing 76% of the total. For the other two directions of 45° and 135° (adjacent to direction 90°), 5% and 19% of indications were given, respectively.

The widest histogram distributions were obtained with the N4 earmuffs and indications regarding the reproduction of the back-up alarm signal from the directions at angles 0° and 180°. In such situations, the indications ranged over all eight directions. An example of this situation is shown in Figure 4a. For the earmuffs (N4), there were a significant number of front–back errors, which occurred for the back-up alarm signal reproduction directions at the angles of 45° and 315°. Then, in all operation modes of the N4 earmuffs, the majority of subjects responded that the signal came from the direction of 135° instead of 45° (as shown in Figure 4b) and similarly from the direction of 225° instead of 315°.
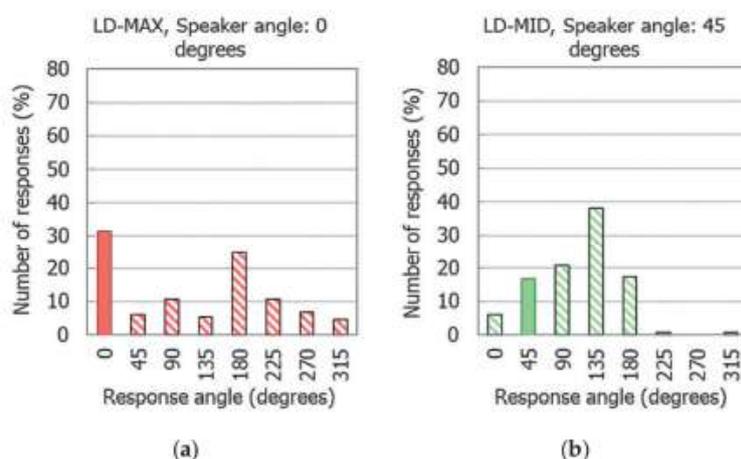

Figure 4. Distribution of the indications given by users of the N4 earmuffs, when the back-up alarm signal was reproduced from a certain angle: (a) 0° (earmuffs used in the LD-MAX mode) and (b) 45° (earmuffs used in the LD-MID mode). LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).

In the case of the W earplugs, the situation was different from the earmuffs. The direction most frequently indicated by the subject was almost always the direction from which the back-up alarm signal was reproduced. The histogram bar showing the direction from which the signal was reproduced was almost always (23 out of 24 histograms) the highest of the eight directions considered. For the directions from angles of 90° and 270° (at the side of the person), nearly 90% of the indications were correct, whereas the lowest frequency of correct direction recognition (37%) was for the angle of 0° when the earplugs were used in passive mode.

Similar direction recognition observations could be made when the signal came from the front/behind or from side of the person were also made in mean absolute error analysis. Mean absolute error was calculated as the mean angular distance between response and the direction from which signal was reproduced. The examples of error values are shown in Figure 5a,b, respectively, for N2 earmuffs and W earplugs. The greatest errors were observed for angles of 0° and 180°, regardless of the model of the level-dependent hearing protector. For angles of 90° and 270° mean error values were the smallest and they were approximately equal to the angular resolution used in the experiment (45°).
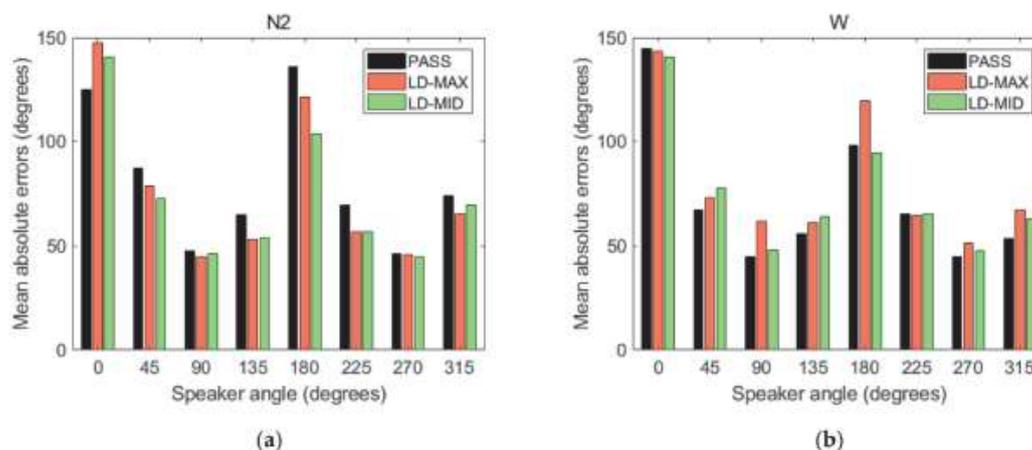
Figure 5. Mean absolute errors calculated for the indications given by users of the N2 earmuffs (**a**); and W earplugs (**b**). PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).

3.2. Direction Recognition Index

3.2.1. Global Index Values

During the tests, all subjects provided a total of 18,000 indications; 8181 of which were correct, meaning the directions of the back-up alarm signal were correctly identified. Therefore, the global direction recognition index of the back-up alarm (as defined in Section 2.7) was 45.5%. For each of the hearing protectors, the subjects provided 3600 indications. The values of the direction recognition index determined for all results obtained for each hearing protector were: 41.6% (N1), 45.0% (N2), 45.9% (N3), 38.6% (N4), and 56.1% (W). The numbers indicate that the correct recognition of the direction of the back-up alarm signal is possible in more cases when level-dependent earplugs are used rather than level-dependent earmuffs.

3.2.2. Index Values Broken Down by the Different Modes of Using Hearing Protectors

To compare the influence of different modes of level-dependent hearing protectors on the ability to correctly recognize the direction of sound, the values of the direction recognition index were determined with a breakdown by these modes. The values obtained are shown in Figure 6. Every point in the chart was created based on the 1200 indications provided by the subjects. Overall, the use of earplugs enabled the correct localization of the back-up alarm signal in a greater number of cases than with earmuffs, regardless of the operation mode of the hearing protectors. Differences in the number of correct indications of the back-up alarm signal direction between the different operation modes of the hearing protectors was as low as 2.3 percentage points (N2 earmuffs). However, these differences could exceed 15 percentage points (N4 earmuffs).
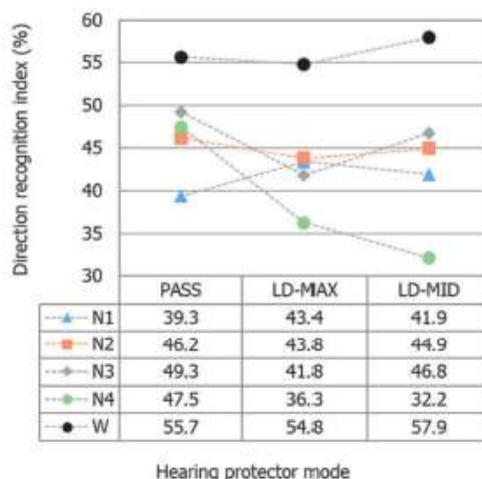
	PASS	LD-MAX	LD-MID
N1	39.3	43.4	41.9
N2	46.2	43.8	44.9
N3	49.3	41.8	46.8
N4	47.5	36.3	32.2
W	55.7	54.8	57.9

Hearing protector mode

Figure 6. Values of the direction recognition index determined for all of the measurement data obtained for each of the hearing protectors with a breakdown by the operation mode of these protectors. PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).

3.2.3. Values of the Index Determined by Breakdown by Different Directions of Back-Up Alarm Signal Reproduction

The diagrams shown in Figures 7–9 present the results obtained in each of the three operation modes of the hearing protectors with a breakdown by the individual directions of the back-up alarm signal source. The results of the analysis, indicating which changes in the values of the direction recognition index should be deemed as significant, are presented in Table 1.
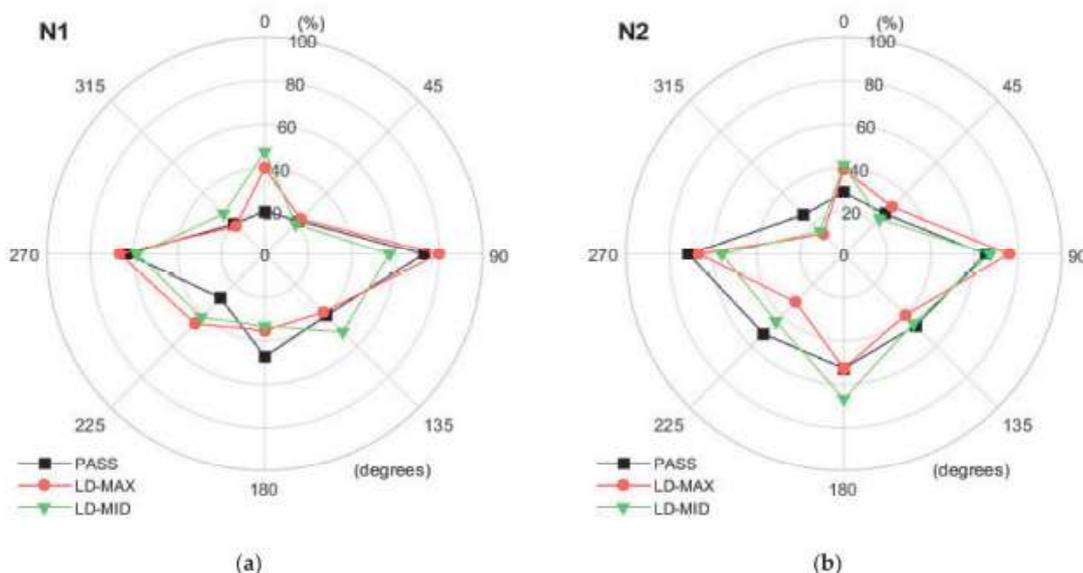

Figure 7. The values of the direction recognition index determined for different directions when using earmuffs in different modes: (a) N1 and (b) N2. PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).
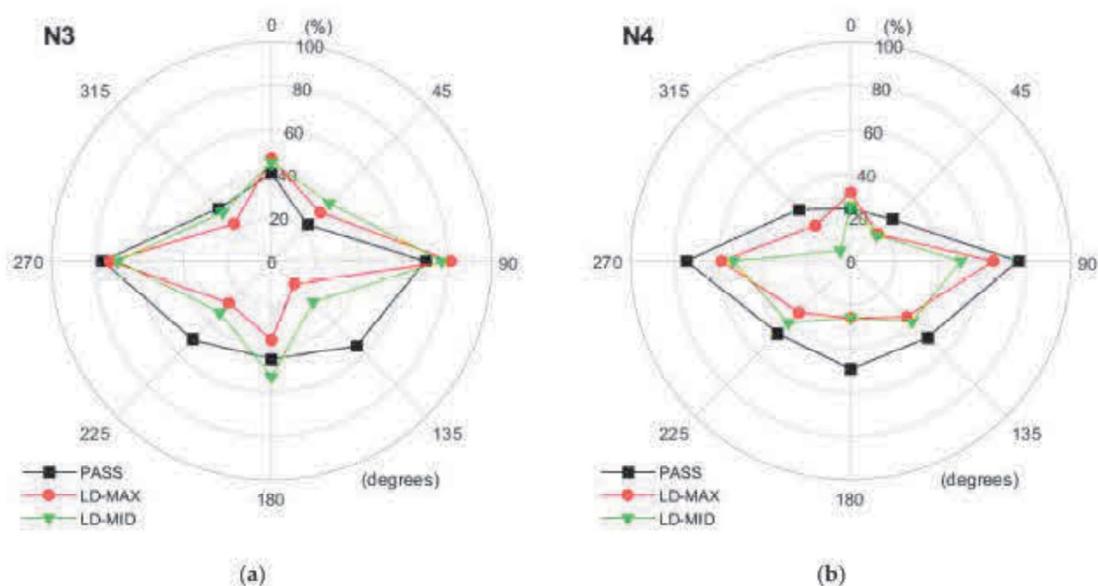
Figure 8. The values of the direction recognition index determined for different directions when using earmuffs in different modes: (**a**) N3 and (**b**) N4. PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).

Figure 9. The values of the direction recognition index determined for different directions when using the W earplugs in different modes. PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).
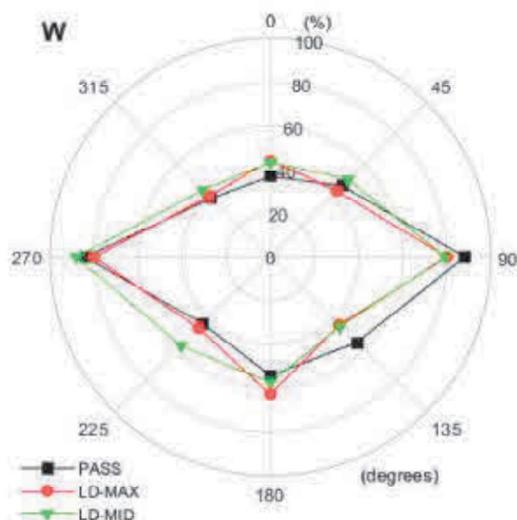
Analyzing the data in Figures 7–9, we confirmed that users of level-dependent hearing protectors have the least difficulty in correctly indicating the direction of the back-up alarm signal when the signal is reproduced from the side of the person (angles 90° and 270°). The values of the direction recognition index were lower when the sound was played behind a person and the lowest when it came from directly in front of a person.

Table 1. Determined p-values for comparisons between different modes of using level-dependent hearing protectors for individual angles. PASS—with the level-dependent system switched off. LD-MAX—level-dependent mode, with maximum amplification in the sound transmission path; LD-MID—level-dependent mode with the amplification set to incomplete (approximately half).

Angle (°)	PASS –LD-MAX	PASS –LD-MID	LD-MAX –LD-MID	PASS –LD-MAX	PASS –LD-MID	LD-MAX –LD-MID
	N1 [1]			N2		
0	**<0.01** [2]	**<0.01**	0.20	0.05	**0.02**	0.73
45	0.78	0.67	0.48	0.37	0.51	0.12
90	0.17	**<0.01**	**<0.01**	**0.04**	0.72	0.10
135	0.72	0.06	**0.03**	0.25	0.82	0.35
180	**0.04**	**0.01**	0.72	1.00	**0.01**	**0.01**
225	**<0.01**	**0.02**	0.49	**<0.01**	0.17	**0.02**
270	0.55	0.41	0.15	0.38	**0.01**	0.06
315	0.77	0.17	0.10	**0.01**	**0.02**	0.62
	N3			N4		
0	0.25	0.35	0.82	0.16	0.79	0.25
45	0.12	**0.01**	0.28	0.05	**0.04**	0.88
90	**0.02**	0.15	0.39	**0.03**	**<0.01**	**0.01**
135	**<0.01**	**<0.01**	**0.01**	**0.02**	0.08	0.55
180	0.13	0.17	**<0.01**	**<0.01**	**<0.01**	1.00
225	**<0.01**	**<0.01**	0.26	**0.02**	0.25	0.23
270	0.51	0.19	0.52	**<0.01**	**<0.01**	0.35
315	0.06	0.62	0.16	**0.04**	**<0.01**	**<0.01**
	W					
0	0.20	0.24	0.91			
45	0.56	0.49	0.20			
90	0.06	**0.04**	0.89			
135	0.05	0.07	0.91			
180	0.13	0.56	0.35			
225	0.64	**0.02**	0.05			
270	0.37	0.32	0.06			
315	0.81	0.35	0.48			

[1] Hearing protector; [2] p-Values for comparisons that are significant ($p < 0.05$) are in bold font.

When using level-dependent hearing protectors, it is important to determine whether the change in the operation mode of the protector significantly affects the user's ability to correctly localize the back-up alarm signal. The data presented in Figures 7–9 indicate that, in many situations, a change in the mode of use of a hearing protector does not affect the direction recognition index. However, this is not a rule. For example, in the case of the N1 earmuffs (Figure 7a) and the 0° direction, the change from passive (PASS) to level-dependent mode led to a 27 percentage points and 20 percentage points increase in the number of correct indications for LD-MID and LD-MAX, respectively. These increases in the direction recognition index values, according to the data from Table 1, were statistically significant. Whereas, in the case of 90°, the change from the PASS to LD-MID mode resulted in a reduction in the number of correct indications by 16 percentage points, while at the angle of 180°, both variants of using the N1 earmuffs in level-dependent mode were less advantageous than in passive mode. This case was in contrast to the one observed for the angle of 225°. Here, in contrast to passive mode, both level-dependent modes were advantageous. The increase (statistically significant) was 13 percentage points (LD-MID) and 17 percentage points (LD-MAX). The results showed that the use of level-dependent mode relative to passive mode, depending on the specific angle at which the back-up alarm signal was received, resulted in an increase or decrease in the number of correct indications of the direction. In the case of the N1 earmuffs, statistically significant changes occurred in 7 out of 16 possible cases (eight related to the LD-MAX mode and eight to the LD-MID mode). An increase in the number

of correct indications was observed in four cases and a decrease in three. A similar situation occurred in the case of the N2 earmuffs (Figure 7b), where statistically significant changes occurred in 7 out of 16 cases. In three of these cases, the number of correct indications increased, and in four cases, this number decreased. The use of the N3 earmuffs resulted in only 6 of 16 statistically significant increases (two cases) or decreases (four cases) in the number of correct indications. With the N3 earmuffs (Figure 8a), the reduction in the direction recognition index related to the operation in level-dependent mode in contrast to passive mode produced relatively high values ranging from 17 to 40 percentage points, observed for the angles of 135° and 225°. The values of the advantageous changes (increase in the value of the direction recognition index) were 14 (LD-MID, 45°) and 11 (LD-MAX, 90°) percentage points. For the N4 earmuffs (Figure 8b), a significant number of cases, 11 out of 16 possible, were identified where the impact of changing the earmuff's mode from the PASS to the LD-MAX or LD-MID was statically significant. All 11 changes were unfavorable; after activating the level-dependent mode, we observed that the number of correct indications of the back-up alarm signal direction decreased.

Results obtained during the use of W earplugs (Figure 9) indicate that a change in the mode of their use was of little significance. Statistically significant changes in the direction recognition index occurred only after the change from the PASS to LD-MID mode at the angles of 90° (decrease by 9 percentage points) and 225° (increase by 14 percentage points).

4. Discussion

The analysis of the changes in the indications of the 50 subjects between the individual eight directions shows that, for the 0° angle (straight in front of the person) and 180° (behind the person), in the majority of cases using level-dependent earmuffs, a considerable number of 'front–back' errors were observed. The people who participated in the study had problems in determining whether the back-up alarm signal came from the front or was possibly from behind. These types of errors (in addition to the indication of adjacent directions) were also frequent in the case of the directions of 45° and 315°. These situations were opposite to the cases when the back-up alarm signal was played from directions located at the sides of a person, i.e., from directions at the angles of 90° and 270°. The direction of signals reproduced from these directions was indicated correctly in the vast majority of cases.

These results provide the first significant differentiation between level-dependent earmuffs and earplugs. For the earplugs, in nearly all of the situations considered, the direction from which the signal was reproduced was indicated almost always more frequently than the remaining seven directions. For the earmuffs, this was not always true because, for the angles of 45° and 315°, the direction from which the signal to be recognized was reproduced was not indicated most frequently. The conclusions resulting from the distribution of indications for the individual directions are partly consistent with other studies, where the authors claimed that the problems in locating the sources of sound occurred particularly often on the front–back axis [22]. In addition, the back direction is indicated by the subjects less frequently when the sound comes from the front rather than the other way around [23]. In this study, the correct indications of the 180° direction were insignificantly more frequent than for the 0° direction. However, this pertained to different situations than the work mentioned above, i.e., during the use of hearing protectors.

Little data exist on sound direction recognition tests for level-dependent hearing protectors. However, the results obtained in this study can be referred, to a limited extent, to the data available. A study where the direction of sound reproduction of cocking an AK-47 (70 dB) in the presence of broadband masking noise (55 dB) was analyzed, presented the indications of 10 subjects with the reproduction of the test signal from directions 30° apart [13]. The analysis of the diagrams regarding the use of level-dependent earplugs (EB-15 earplugs and earplugs designed by the authors of the above-mentioned study) enabled the identification of a similar distribution of direction indications to the ones obtained in this paper. Despite of different test conditions, for the direction at the angle of 0°, a significant number of indications fell not only in this direction, but also at 180°. The same was true

when the sound was reproduced from the direction of 180°. In addition, for the 30° direction, Brown et al. [13] reported the occurrence of front–back errors and the indication of adjacent directions, which is similar to the situation that occurred in this study when the back-up alarm signal was reproduced from the 45° direction. We observed that the relatively smallest diversity of indications in Brown et al. [13], where the test signal was reproduced from directions of 90° and 270°, corresponded to the slimmest shapes of the graphs in the histograms obtained in this study (Figure 3c).

In this study, we determined the direction recognition index for the back-up alarm signal. The values of this index, which were determined with a breakdown by hearing protector operation modes (i.e., set globally without dividing the individual directions of the alarm signal), showed that regardless of the mode of these protectors, it is possible to correctly localize the back-up alarm signal in a much larger number of cases when level-dependent earplugs are used compared to when level-dependent earmuffs are used. The average value of the index for the earplugs (with consideration of all three modes of operation) exceeded the average value for all four earmuffs and their modes of operation by more than 13 percentage points. The range of the direction recognition index values between the different operation modes of the hearing protectors was relatively small (two to four percentage points) for the N1 and N2 earmuffs and the W earplugs. Slightly greater differences in the direction recognition index between the modes were observed for the N3 earmuffs (seven percentage points). The largest span, exceeding 15 percentage points, was observed for the N4 earmuffs.

This global analysis of the results indicated that among the hearing protectors, the operation mode for some (N1, N2 earmuffs and W earplug) has an insignificant impact on the user's ability to localize the back-up alarm signal. The mode of use of the hearing protectors may also influence, to a certain extent, the ability to recognize the direction of a sound. This was the case with the N3 earmuffs, for which the level-dependent mode resulted in a noticeable deterioration in the ability to localize the back-up alarm signal. Additionally, the type of hearing protectors may significantly influence the possibility of recognizing the direction of back-up alarm signals. Hearing protectors may include those (N4) that significantly impair the user's ability to recognize the direction of the sound when switched from passive to level-dependent mode. This deterioration occurred with both the maximum and incomplete amplification in the level-dependent system of the N4 earmuffs, and amounted to above 11 and 15 percentage points in comparison to passive mode, respectively.

The results published in Alali and Casali [15] can be compared with the values of the direction recognition index measured as part of this study. In Alali and Casali [15], the correct recognition of the direction of the signal in the presence of pink noise with an A-weighted sound pressure level of 90 dB was 47.7% for the level-dependent earmuffs and 62.2% for the level-dependent earplugs. Within the framework of this study, for earmuffs, the direction recognition index (global values) ranged from 38.6% to 45.9%, and 56.1% for the earplugs. Considering the differences in the test conditions and the test facilities themselves, the results obtained can be regarded as comparable. In another study [11] where the recognition of sound directions, including the front–back, left-right, and up-down directions, was examined, the results from 20 subjects showed that the number of correct indications for level-dependent earplugs was about 42.5% and 31.5% for level-dependent earmuffs. Again, the test conditions (eight loudspeakers that were the source of the test signal with a 230 ms burst of wideband noise) or the models of the hearing protectors differed from those in this study, but the tendency of the relationship between the earplugs and the earmuffs is similar.

The determination of the direction recognition index for the back-up alarm signal, broken down by direction, enabled repeating the previous general observation that users of level-dependent hearing protectors have the least difficulty in correctly indicating the direction of the back-up alarm signal when it is reproduced from the side of a person (angles of 90° and 270°). The values of the direction recognition index were lower when the sound was played behind a person (180°) and the lowest when the source was directly in front of the person (0°). For the number of errors falling on the directions of 0° and 180°, and 90° and 270°, a similar distribution of results was obtained in the aforementioned study [13]. The root mean square error (RMSE), defining the mean angular distance of responses from

the target angle, for the level-dependent EB-15 earplugs was about 38° and 55°, when the sound came from the front and back directions, respectively, and about 9° and 11° when the sound came from the right and left sides of a person, respectively. However, these results are not fully comparable with the results of our study as a different measure was applied to different models of test earplugs and different test conditions. Nevertheless, the ratio of the average number of incorrect indications of the front–back directions to incorrect indications of the left–right directions in both studies indicated the same trend, which was 3.1 in this study and 4.7 for the cited study [13].

Alali and Casali [15] demonstrated, with some exceptions, that the ability of normal-hearing people to locate a vehicle's back-up alarm signal in the presence of pink noise did not improve when using level-dependent hearing protectors (earplugs and earmuffs) in comparison to the use of passive hearing protectors. A similar finding was reported by Giguère et al. [16], where the situation did not improve after switching from passive mode to the electronic system mode. This conclusion was also reached in this study with regard to earplugs, where their operation mode had practically no impact on the measured values of the direction recognition index. For earmuffs, in this study and in certain cases, the change from passive mode to level-dependent mode (maximum or incomplete amplification in the level-dependent system) resulted in statically significant differences in the value of the direction recognition index. During the use of the N1 and N2 earmuffs, statistically significant changes occurred in 44% of cases; however, the number of changes resulting in increasing the direction recognition index value roughly balanced the number of changes resulting in a decrease in the index value. Using the N3 earmuffs in level-dependent mode resulted in a change in the direction recognition index in almost 38% of the cases, whereas the deterioration of the ability to recognize the direction was twice more often (four instances of decreases) than the improvement (two instances of increases) when compared to passive mode. A slightly different situation was observed for the N4 earmuffs, where there was a total of 69% of cases where the ability to correctly recognize the direction of sound was statistically significantly different from passive mode, but all of the changes were negative, meaning the changes resulted in a decrease in the value of the direction recognition index. The analysis of the use of earmuffs in level-dependent mode in comparison to passive mode, with a breakdown by different directions, demonstrated that in a certain number of cases (from 38% to 69%), the mode affected the ability of the users to localize the back-up alarm signal, which differed from the conclusion drawn in the cited study [15]. Notably, the authors [15] used different ambient noise (pink noise with A-weighted sound pressure levels of 60 dB and 90 dB), a different back-up alarm signal, and included hearing protectors (one model of a specific type of hearing protector) other than the ones used in this study.

This issue is important from the perspective of ensuring safety in a workplace. The methodology used in this study can be used to assess the ability of workers using level-dependent hearing protectors to recognize the direction of an auditory danger signal. Test results indicate that the model of a level-dependent hearing protector available to a worker will significantly affect their ability to localize the vehicle's back-up alarm signal. However, the tests carried out under laboratory conditions cannot fully replicate the conditions encountered in an industrial facility. The localization of auditory danger signals by users of level-dependent hearing protectors may be, to some degree, worse in real-life conditions than in experiments conducted in a laboratory because the attention of the subjects who participated in the experiment was entirely focused on the task of sound localization. In real industrial conditions, however, the workers are focused on their jobs.

5. Conclusions

The tests enabled the differentiation of the level-dependent hearing protectors in terms of the ability to assess the direction of an auditory danger signal, represented by a back-up alarm signal, by the user of these protectors under industrial conditions where impulse noise is generated against a background of continuous noise.

We found that the operation mode of level-dependent earplugs, i.e., passive or level-dependent, did not significantly affect the ability to correctly indicate the direction of a back-up alarm signal.

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Załącznik 4a_cz2 Kopie powiązanych tematycznie artykułów naukowych
A4-A6 wchodzących w skład cyklu stanowiącego osiągniecie naukowe

The assessment of the earmuffs was complicated. The analysis of a breakdown by the individual directions indicated that, in a significant number of cases, there was a change in the operation mode result depending on the direction of the back-up alarm signal, either by an increase or decrease in the ability to properly recognize this direction. The global assessment showed that depending on the model of the earmuffs, the impact of switching on level-dependent mode may be insignificant, but it may be clearly noticeable, or even result in a significant deterioration of the ability to recognize the direction of the back-up alarm signal.

The above conclusions on level-dependent earplugs and earmuffs mean that, in workplaces where it is important for the safety of a worker using hearing protection to correctly recognize the direction of a back-up alarm signal, the choice of a specific model of these protectors is of crucial importance.

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