Chapter 16

Speech perception by level-dependent hearing protectors users in impulse noise conditions

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Abstract
The aim of this study was to check the functionality of level-dependent hearing protectors in impulse noise conditions in terms of speech perception by their users. Measurements were conducted in semi-anechoic chamber under acoustic conditions that reflect the situation present at shooting range. Impulse noise previously recorded in real conditions and 20-word lists were emitted from loudspeaker sets. The study included nine different level-dependent hearing protectors, including eight earmuffs and one earplug. Each hearing protector was tested by 25 people in both passive and level-dependent mode. Two out of nine models of hearing protectors provide better speech intelligibility in level-dependent than in passive mode, on average by nearly 10 percentage points. The changes between operating modes were not statistically significant for the remaining seven hearing protectors. In level-dependent mode, there is little differentiation in speech intelligibility values between hearing protectors. In passive mode, the speech intelligibility values are more differentiated. Higher attenuation is associated with poorer speech intelligibility. The use of level-dependent hearing protectors is not restricted by any significant impairment of speech intelligibility in the presence of impulse noise. Among hearing protectors operating in level-dependent mode there are those that do not impair speech intelligibility in the presence of acoustic impulses, compared to passive protection, but also those that improve it.

Keywords: noise, hearing protectors, impulse noise, earplugs, earmuffs

1. Introduction

Due to the insufficient effectiveness of technical means and organisational solutions to reduce impulse noise [1], the only way to protect against this type of noise is usually to use hearing protectors. These devices reduce the noise reaching an employee's ears, but at the same time they may affect the perception of sounds, which carry important information for the employee. The most common reactions of employees are those that indicate that the use of hearing protectors worsens this perception. However, research shows that the deterioration in sound perception during the use of hearing protectors is not obvious and occurs on a case-by-case basis. Moreover, some available literature indicates that the use of hearing protectors even improves speech intelligibility in certain conditions. Examples of works in this field are discussed below.

One of the OSHA (Occupational Safety and Health Administration) studies [2] points out that hearing protectors may interfere with the process of verbal communication by staff. This study indicated that the problem is particularly important in the case of many elderly people working for many years in noisy conditions, who have an hearing loss and might have problems with understanding verbal instructions or auditory danger signals, which may even lead to an accident. Other study [3] already indicated that even though hearing protectors had no significant effect on speech intelligibility for people with good hearing, in the case of people with hearing loss they had a negative effect on the quality of communication. Authors of next study [4] also showed that hearing protectors with low attenuation can have very little effect on speech intelligibility in noise. Further research has shown that hearing protectors can even improve speech intelligibility. For example Howell and Martin [5] found that hearing protectors do not degrade speech intelligibility for the listener and may even effect a slight improvement. Dastpaak et al. [6] have determined that in the presence of noise, earplugs increase the speech intelligibility. This increase is greater with 25 NRR (noise reduction rating – parameter expressing the noise reduction of hearing protectors with a single number) than with 32 NRR earplugs. Other studies, apart from confirming that the use of certain types of hearing protectors affects speech intelligibility, also point to sound level as a factor affecting speech intelligibility. For example, Hashimoto et al. [7] have shown that the use of hearing protector with little low-frequency attenuation has resulted in a lower deterioration of speech intelligibility presented at A-weighted sound pressure level of 65 dB compared to two hearing protectors with higher attenuation. On the other hand, when speech was presented at an A-weighted sound pressure level of 85 dB, there was no such effect. Fernandes [8] has showed that in the presence of pink noise at the sound pressure level of 60 and 70 dB, hearing protectors reduced speech intelligibility compared to tests without hearing protectors, while for higher sound pressure levels of noise (80 and 90 dB), hearing protectors improved intelligibility. In addition, this study found that the earplugs provide better speech intelligibility than earmuffs. The authors conclude that the overall effect of hearing protectors on speech intelligibility is directly related to their frequency response.

Level-dependent hearing protectors are increasingly being used, both in industrial workplaces and in situations where acoustic impulses are produced by firearms. Such hearing protectors are equipped with an electronic system that transmit the sound to the ear of the user ,which is present outside the protector, after its modification. The use of level-dependent functionality has an influence on the sound pressure level of the sound reaching the hearing, which in the absence of noise improves the perception

of useful sounds (speech, warning signals), but in the presence of noise it is not so obvious. According to OSHA studies [2] in certain situations, using level-dependent hearing protectors (fitted with electronic system) may improve the capability of workers to communicate verbally. Electronic system carries sounds at frequencies within the speech band from the environment to the ears of hearing protectors' user. Another study indicated that the use of level-dependent earmuffs in a noisy environment was an improvement as compared to no use of hearing protectors [9]. Speech intelligibility was improved in the case of level-dependent earmuffs compared to non-electronic earmuffs and was also better than in the case of no use of earmuffs [4, 10]. There are also studies that have shown that the use of level-dependent hearing protectors has little or no effect on speech intelligibility [11-13]. However, Abel et al. [14] and Bockstael et al. [15] showed that the amplification of sounds in level-dependent mode even had a negative effect on the recognition of words in noise. The occurrence of difficulties in communication is probably related to the distortion of the signal spectrum and the lack of sufficient preserve of temporal variations by the electronic system. In the other study, depending on the type of solution realizing level-dependent functionality, the lack of change or even deterioration of speech intelligibility after the use of earplugs was shown [16]. All the above mentioned works concern the situation when speech intelligibility was tested in the presence of steady noise. There is no knowledge of the influence of hearing protectors on speech intelligibility in situations of impulse noise, what was included in the scope of this work.

The aim of this work was to check the functioning of level-dependent hearing protectors in the situation of impulse noise. The effect of these hearing protectors on speech intelligibility was tested when they operate in level-dependent mode in relation to passive mode. In addition, it was determined whether the use of different models of hearing protectors in both level-dependent and passive modes affected speech intelligibility.

2. Methods

2.1. Subjects

The studies were conducted with 50 people (24 women and 26 men). The age of subjects ranged from 18 to 42 years old (mean age was 26.4). The subjects hearing met the requirements of EN ISO 4869-1:2018 [17] regarding a subjective method for the measurement of sound attenuation of hearing

protectors. This means that the subjects hearing threshold was not greater than 15 dB for frequencies up to 2000 Hz and no more than 25 dB for frequencies above 2000 Hz.

2.2. Hearing Protectors

In the study nine models of level-dependent hearing protectors were taken into account, including eight models of earmuffs and one model of earplugs. The earmuffs studied included: M1÷M8 (designation introduced for the purpose of this study). The M1 and M6 earmuffs were designed for military applications; M2, M5 and M7 earmuffs designed for industrial applications; M3, M4 and M8 earmuffs designed for hunting or sport shooting. The P1 earplugs were designed for industrial applications with polymer tips. Two different sizes of tips of earplugs were provided for subjects. The tests were performed in two hearing protector operation mode: with the level-dependent mode switched off (passive mode) and with the level-dependent mode switched on (with maximum amplification in the sound transmission path).

2.3. Test signals

Two types of sound signals were used in the study. One of them was impulse noise, previously recorded in real conditions, produced during shooting with a Glauberyt machine gun (caliber 9 x 19 mm Parabellum) on an indoor shooting range. To record this signal, the Brüel & Kjær PULSE measurement system (based on Brüel & Kjær 3052-A-030 measurement unit) with G.R.A.A.S. 67SB blast probe and G.R.A.S. 12AK power supply module was used. Each time the impulse noise consisted of two sequential shots. The time interval between shots was 160 ms. Due to the need to ensure safe conditions for conducting the experiment, the C-weighted peak sound pressure level in the place of the subject (during subject's absence from the test stand) did not exceed 120 dB. The exposure limit value for this parameter is 135 dB [18], so that the signal played on the test stand was safe for the subject, even if that person does not wear hearing protectors.

The second of the test signals was a word test [19, 20], part of the polish numerical and verbal test for hearing and auditory training, commonly used to evaluate speech intelligibility. The test consists of 10 lists of 20 phonetically balanced monosyllabic words each. The amplification in the speech path is set so that the A-weighted equivalent sound pressure level measured at the head position of the subject is 66 dB. This corresponds to the voice raised according to the speech level classification in the assessment of speech communication standard [21].

Both signals were reproduced in such a way that there was a coincidence in time between the acoustic impulses and the words to be recognized.

2.4. Experimental setup

The experimental setup was located in a semi-anechoic chamber in the Tech-Safe-Bio Laboratory in Central Institute for Labour Protection – National Research Institute (Warsaw, Poland). The configuration of the experimental setup was designed to reflect an example of the situation that may occur at the shooting range. The main components of the experimental setup were loudspeaker sets designed to reproduce sound signals. The JBL SR4722A loudspeaker set was used to reproduce impulse noise (shots). It was positioned on the right side of the subject, 1.5 m away from centre and at the height of the subject's head. The location of this loudspeaker set on the side of a subject reflected the situation of the impulses generated at shooting range by other shooters. The JBL SR4722A loudspeaker set was powered by the Crown Macro-tech 2400 power amplifiers. The impulse noise shaping assembly, in addition to these power amplifiers, consisted of a Yamaha YDG 2030 graphic equalizer and a JBL DSC 260 limiter.

The speech (word test) was played with the M-Audio BX5 D2 loudspeaker set. The loudspeaker set was located 1.8 m away from the centre and at the height of the subject's head. The loudspeaker set was positioned at the rear right hand side in diagonal direction (angle of 45°). This location of the loudspeaker set was to reflect the real situation consisting in the perception of speech sounds spoken by a shooting instructor. A picture showing the location of the loudspeakers on the test stand is presented in Figure 1.

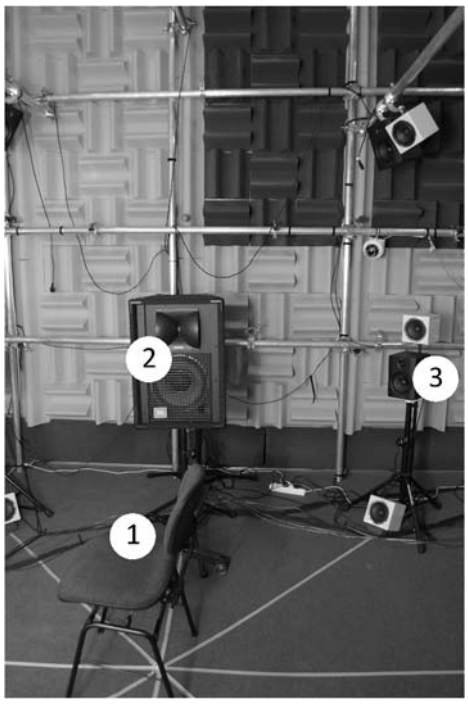

Figure 1. The view of experimental setup: 1 –seat for the subject, 2 – loudspeaker set used to reproduce impulse noise, 3 – loudspeaker set used to reproduce speech

The electrical signal to the inputs of the loudspeaker sets was provided by the MOTU 24I/O audio interface. This interface is controlled by a computer with the MOTU PCI-424 card installed. A sampling frequency of 44100 Hz was used when signals were reproduced. The reproduction of individual sound files during the test was controlled by a computer through DAW (digital audio workstation) application.

2.5. Test Method

The study was based on the word recognition by hearing protectors users. Hearing protectors were divided into two groups of 5 and 4 models. Hearing protectors from both groups were independently used by two equal groups of 25 people. Hearing protectors were worn by individuals in a different (fixed) order. Each time, the hearing protectors were used in two modes: passive and level-dependent. Thus, in each elementary measurement situation (one hearing protector in one of the two modes) tests were conducted using a single 20-word list. Subjects wrote down the content of understood words on forms prepared for this purpose. Then the number of correctly understood words was counted and speech intelligibility was determined. Speech intelligibility was defined as the ratio of the number of correctly understood words in a given elementary measurement situation to the total number of words reproduced in that situation. Before the proper tests, each person underwent a training session during which 20 numbers from a single list were recognized. The other conditions of the training session were identical to those of the appropriate tests.

The conditions for sound reproduction were determined during the preliminary tests so that the measured speech intelligibility values oscillated around 50%. The conditions determined in such a way that the individual results of each subject are not limited by extreme situations, i.e. the possibility of achieving full (100%) speech intelligibility or inability to recognize words (0%). Both of these extreme situations would make it impossible to differentiate between hearing protectors, assuming there are differences between them.

2.6. Statistical Analysis

A statistical analysis of the obtained data were completed to determine which results of speech intelligibility measurements obtained in particular situations should be considered significant. Depending on properties of obtained data, a t-test or Wilcoxon test (equivalent to the Mann-Whitney U test) were used. The calculations were performed using MATLAB R2019a (version 9.6) with the Statistics and Machine Learning Toolbox (MathWorks Inc., Natick, MA, USA).

3. Results and discussion

3.1. Speech intelligibility

The speech intelligibility values determined with participation of subjects using hearing protectors in both passive and level-dependent mode are shown in Figure 2. Each point shown in the graphs in Fig. 2 is the result of a measurement carried out using one of the word lists consisting of 20 words. Analysing the speech intelligibility values presented in Figure 2, it is not possible to determine whether the groups of results related to the passive and the level-dependent mode of hearing protectors are separable.

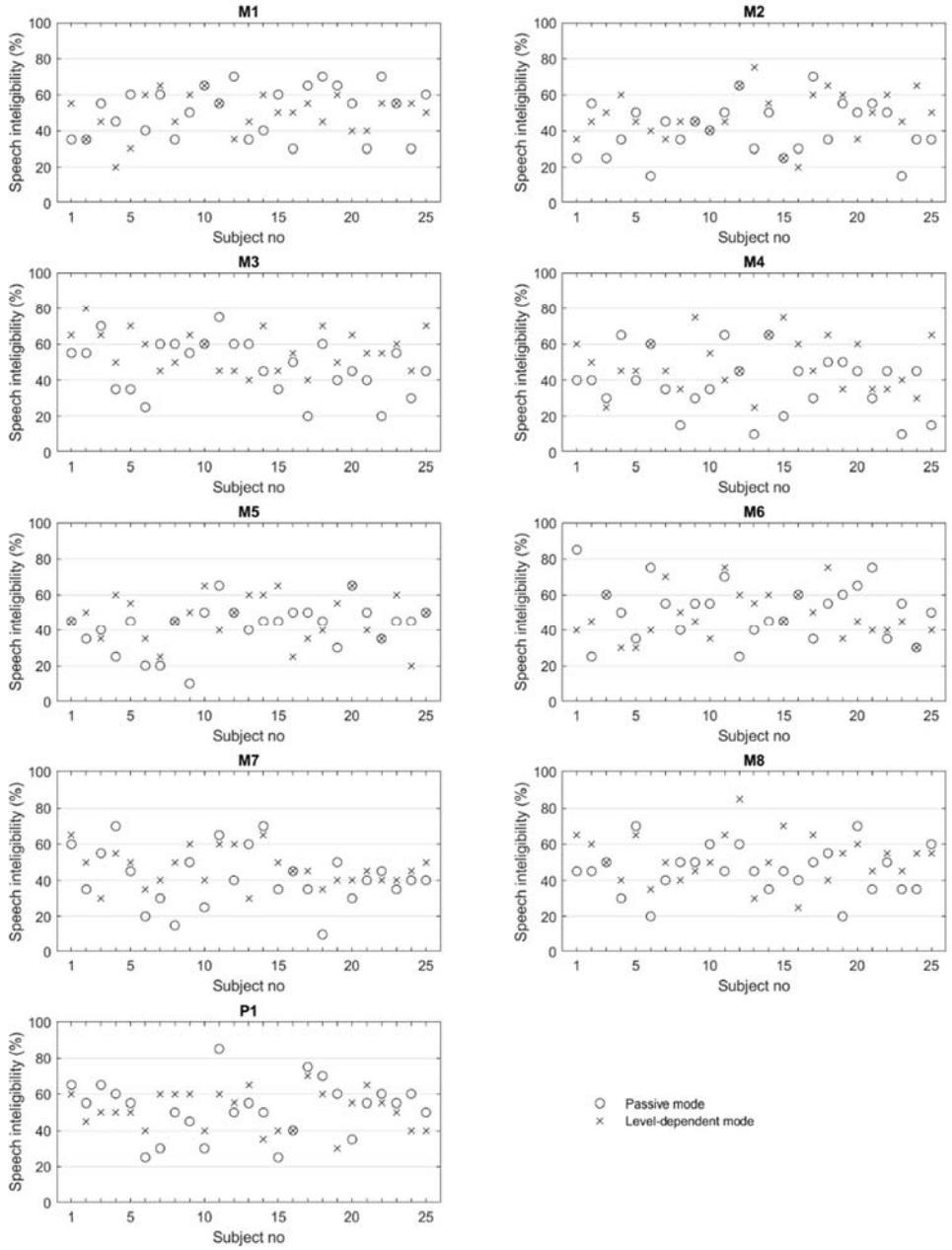

Figure 2. Speech intelligibility values obtained by subjects during the use of the hearing protectors

The outcome of the verification of the hypothesis that data for a specific hearing protector in a specific mode of use has a normal distribution (Lilliefors test) has led to the result that this hypothesis should be discarded in the following four cases: M1 earmuff in both level-dependent and passive mode, M5 earmuff in passive mode, M6 earmuff in level-dependent mode.

Due to the fact that not all series with test results are characterized by a normal distribution and there were cases that the results contain outliers or the test results for equal variances was not positive during selected analyses, instead of parametric tests (t-test), nonparametric Wilcoxon test was used.

Figure 3 shows mean speech intelligibility values, including all subjects. The mean values were determined independently for passive and level-dependent mode. This allows to assess the effect of changing the passive on the level-dependent mode on speech intelligibility and whether the use of individual hearing protectors may affect speech intelligibility. The mean speech intelligibility values shown in Figure 3 for level-dependent hearing protectors range from 46.6% (M5 and M7 earmuffs) to 56.8% (M3 earmuff). When the hearing protectors were in passive mode, the mean speech intelligibility values ranged from 38.4% (M4 earmuff) to 52.2% (P1 earplugs).

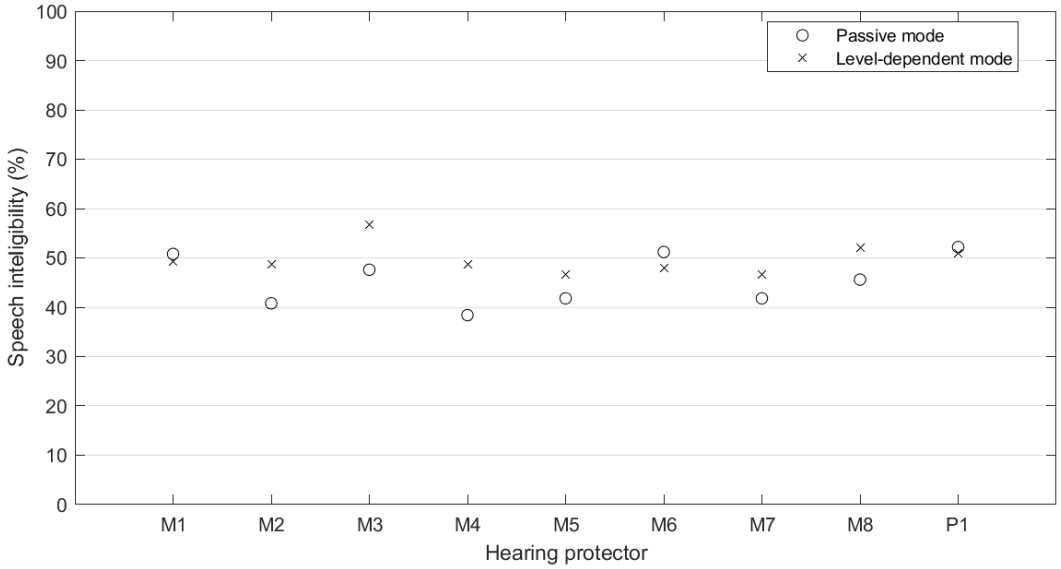

Figure 3. Mean speech intelligibility values including all subjects

3.2. Effect of the mode of use of hearing protectors

The activation of the level-dependent mode resulted in a change in the speech intelligibility values that can be considered statistically significant for two of the 9 hearing protectors included in the study. These are M3 and M4 earmuffs for which increase in speech intelligibility, resulted from changing

operation mode to level-dependent was about 10 percentage points. The results of M2 are close to the criterion value (p=0.05), but the *p*-Value is greater than 0.05 and the change in speech intelligibility is not considered statistically significant. The difference between the hearing protectors M3, M4 and the other hearing protectors cannot be easily pointed out, although it is known that each manufacturer uses its own solutions for the construction of the electronic circuit. In one of the works cited earlier [15], it was suggested that both the distortion of the signal spectrum and the lack of sufficient preserve of temporal variations by the electronic system may have a decisive influence on the perception of speech sounds.

As indicated in the introduction, this paper deals with the use of hearing protectors in the presence of impulse noise, which is different from other published papers. The possibilities of direct comparison of the results obtained are therefore limited. It was also not possible to compare the situation in which hearing protectors were used in relation to their non-use, as this was impossible due to tests carried out in the presence of impulse noise (regardless of the fact that formal noise parameters did not indicate that the exposure limit values for the working environment were exceeded). However, an important element of the work was the comparison between the modes of use of hearing protectors, i.e. passive and level-dependent.

The difference between passive and level-dependent mode was indicated in one of the study on speech perception in noise [4]. The authors of mentioned study stated that the use of level-dependent mode may lead to improve intelligibility in relations to passive mode. In one of the papers, the results indicated that the improvement in speech intelligibility associated with the change in the operating mode of earmuffs may reach as much as 50 percent points [10]. In our study statistically important increasing of speech intelligibility after activation of level-dependent mode was also observed in some of the hearing protectors and was no higher than 11 percentage points. No statistically significant deterioration in speech intelligibility was found for the other hearing protectors. However, this is different from the results presented in one of the papers [14], where it was stated that the use of level-dependent mode caused the deterioration of word recognition in noise.

3.3. Level-dependent mode

Table 1 summarizes the differences between the mean values of speech intelligibility when using different hearing protectors in level-dependent mode, calculated on the basis of the values presented in Figure 3. The results of the comparison among hearing protectors can be read from Tab. 1 according to

the "each with each" key. This means that the result for a pair of any two hearing protectors included in the test should be read at the intersection of one of the columns and one of the rows. From the values in Tab. 1, it can be concluded that there are cases where there is no difference between the speech intelligibility values of the hearing protectors (M2 and M4 earmuffs; M5 and M7 earmuffs) and there are significant differences of more than 10 pp (M3 and M5 earmuffs; M3 and M7 earmuffs).

Table 1. Differences in speech intelligibility between situations where different hearing protectors are used in level-dependent mode. The values are expressed in percentage points

		Hearing protector							
		M2	M3	M4	M5	M6	M7	M8	P1
Hearing protector	M1	-0.6	7.6*	-0.6	-2.6	-1.2	-2.6	2.8	1.8
	M2		8.2*	0.0	-2.0	-0.6	-2.0	3.4	2.4
	M3			-8.2*	-10.2*	-8.8*	-10.2*	-4.8	-5.8
	M4				-2.0	-0.6	-2.0	3.4	2.4
	M5					1.4	0.0	5.4	4.4
	M6						-1.4	4.0	3.0
	M7							5.4	4.4
	M8								-1.0

* – statistically significant value

In 6 out of 36 situations where hearing protectors were compared with each other, i.e. 17%, the differences in the measured speech intelligibility values were statistically significant. Mean speech intelligibility values that distinguish the use of individual hearing protectors in statistically significant situations ranged from 7.6 to 10.2 percentage points. It should also be noted that all situations where differences in mean speech intelligibility values are statistically significant relate to M3 earmuff. This means that only with this earmuff can speech intelligibility values be expected to be higher than with other hearing protectors, for which the mean speech intelligibility value is approximately 50%. Even less differentiation between the models of level-dependent hearing protectors was found in a work that included 4 devices [12]. Speech intelligibility between different level-dependent hearing protectors differed by 3-5 percentage points.

3.4. Passive mode

Table 2 shows the differences in speech intelligibility between situations where different hearing protectors are used in passive mode. The arrangement of Table 2 and the way of its using is the same as Table 1. Based on the data presented in Table 2, it can be stated that in the case of passive mode, there are more cases of large differences in speech intelligibility between different hearing protectors than in the case of previously analysed level-dependent mode. There are 7 cases where the difference in speech intelligibility exceeds 10 pp. There is also one case where there is no difference in speech intelligibility values between hearing protectors (M5 and M7 earmuffs).

Table 2. Differences in speech intelligibility between situations where different hearing protectors are used in passive mode. The values are expressed in percentage points

		Hearing protector							
		M2	M3	M4	M5	M6	M7	M8	P1
Hearing protector	M1	-10.0*	-3.2	-12.4*	-9.0*	0.4	-9.0	-5.2	1.4
	M2		6.8	-2.4	1.0	10.4*	1.0	4.8	11.4*
	M3			-9.2*	-5.8	3.6	-5.8	-2.0	4.6
	M4				3.4	12.8*	3.4	7.2	13.8*
	M5					9.4*	0.0	3.8	10.4*
	M6						-9.4	-5.6	1.0
	M7							3.8	10.4*
	M8								6.6

* – statistically significant value

In passive mode, the differences in the measured speech intelligibility values were statistically significant in 12 situations in which hearing protectors were compared with each other. This is twice as much as in level-dependent mode. Mean speech intelligibility values that distinguish the use of individual hearing protectors in statistically significant situations range from 9 to 13.8 percentage points. When comparing M1 and M7 earmuffs, despite the fact that the difference in mean speech intelligibility is 9 pp, a large scattering within the group eliminated this case from the statistically significant ones. It should be noted that in contrast to level-dependent mode, three groups of hearing protectors are observed in passive mode. The first group (M1, M6 earmuffs and P1 earplugs) has speech intelligibility values exceeding 50%, the second group (M2, M4, M5 and M7 earmuffs) has speech intelligibility values close to 40%, and the third group has speech intelligibility values between 45% and 50% (M3 and M8

earmuffs). In most cases, statistically significant changes occur between the first and second mentioned group.

The highest speech intelligibility in passive mode was measured in the case of P1 earplugs. The speech intelligibility values associated with the use of P1 earplugs are significantly higher than in the case of 4 out of 8 earmuffs: M2, M4, M5 and M7. This observation is partly consistent with the results of one study, where 2 earplugs and 2 earmuffs were included [8]. In this study it was found that booth earplugs offer greater effectiveness in speech recognition than earmuffs.

3.5. Effect of hearing protector attenuation on speech intelligibility

An important practical feature of hearing protectors is the information how they reduce noise. This property is determined for example by the SNR (single number rating - parameter expressing the sound attenuation of hearing protectors with a single number, similar to the previously mentioned NRR, but used in the European Union) parameter, which is an indicator that considers seven bands with centre frequencies from 125 Hz to 8 kHz. Figure 4 compares the speech intelligibility values with the SNR values of the particular hearing protectors. The comparison includes only earmuffs. The P1 earplugs are not included because their use is different from that of earmuffs. In addition, the M8 earmuff is not included in Figure 4 because the SNR value was not included in its user manual. Figure 4 also shows a line that fits the presented data best in a least-squares sense.

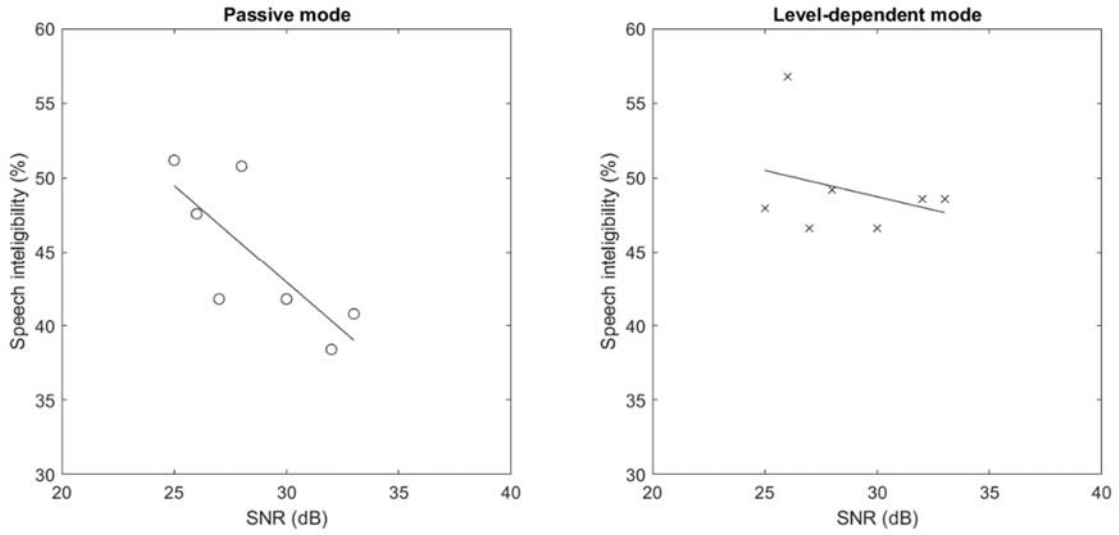

Figure 4. Comparison of the speech intelligibility values with the SNR values for M1-M7 earmuffs used in two modes: left panel – passive mode, right panel – level-dependent mode

The graphs in Figure 4 show a clearly different relationship between speech intelligibility and SNR for passive and level-dependent mode. The slope of the passive mode trend line is much higher (-1.3 %/dB) than in the case of level-dependent mode (-0.35 %/dB). When the earmuffs are used in passive mode, a higher attenuation is associated with a deterioration in the ability to understand speech. The situation is different for level-dependent mode, where speech intelligibility is almost independent of the SNR value. In passive mode, only 2 out of 7 earmuffs provide a speech intelligibility of more than 50% and, at the same time, increasing attenuation leads to increasingly lower speech intelligibility values (less than 40%). In the case of level-dependent attenuation, switching on the electronics results in higher average speech intelligibility values. As mentioned above, these values are aligned between the individual earmuffs, with the exception of the individual case with the distinctly improved speech intelligibility of the other earmuffs.

The results for the passive mode of use of hearing protectors are consistent with the conclusions of one study, where two models of earplugs with different attenuation were considered in the speech intelligibility tests [6]. Although the authors of mentioned study conducted researches in the presence of continuous rather than impulse noise, using monosyllabic words in another language (Persian), they also stated that speech intelligibility depends on the attenuation of the earplugs. The speech intelligibility was higher in the case of earplugs with NRR equalled to 25 dB than for earplugs with 32 dB NRR. The distinction between the two earplugs in the presence of noise was 11-12 percentage points. Among the earmuffs included in our study there were two earmuffs with SNR of 25 and 32 dB. Speech intelligibility between the two earmuffs (Fig. 4, left panel) differs by 12.8 percentage points.

4. Conclusions

The results did not indicate any statistically significant deterioration in speech intelligibility related to the change in the use of hearing protectors from passive to level-dependent mode in impulse noise conditions that may occur at the shooting range. This means that users of level-dependent hearing protectors who choose them for their basic functionality, i.e. the ability to transmit speech sounds at moments of relative silence under these protectors, can also use them in the presence of acoustic impulses without fear of impairing their ability to understand words (as opposed to passive hearing protectors). Furthermore, the results have shown that level-dependent hearing protectors include models that do not impair speech intelligibility (compared to passive protection), but also improve it.

Two out of nine hearing protectors provide better speech understanding used in level-dependent mode than in passive mode, on average by nearly 10 percentage points.

An analysis of the measured speech intelligibility values when using different hearing protectors in level-dependent mode in the presence of impulse noise showed that in the group of nine hearing protectors included, for one of them (M3 earmuff) the speech intelligibility values were 5-10 percentage points higher than for the other hearing protectors, for which the average speech intelligibility value was about 50%. In general, in level-dependent mode, there is little differentiation in speech intelligibility values between hearing protectors.

In passive mode there are three groups of hearing protectors differentiated in terms of speech intelligibility: more than 50%, close to 40% and between 45% and 50%. In most cases, statistically significant differences in speech intelligibility occur between the first and second group of hearing protectors.

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