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THE IMPACT OF LOW FREQUENCY NOISE ON HUMAN MENTAL PERFORMANCE

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Abstract
Objectives: There is a growing body of data showing that low frequency noise (LFN), defined as broadband noise with dominant content of low frequencies (10–250 Hz) differs in its nature from other environmental noises at comparable levels. The aim of the study was to investigate whether exposure to LFN at levels normally occurring in the industrial control rooms can influence human mental performance (e.g., visual functions, concentration, continuous and selective attention) and subjective well-being. **Materials and Methods:** The study included 96 female and male volunteers, aged 19–27 years, categorized in terms of sensitivity to LFN. They worked with four standardized psychological tests (Signal Detection, Stroop Color-Word, Comparing of Names, and Continuous Attention) during exposure to LFN or broadband noise without dominant low frequency content (reference noise) at a level of 50 dB(A). Each subject was studied only once at randomly-assigned exposure conditions. **Results:** In the Comparing of Names Test, the subjects, regardless of the LFN sensitivity, showed tendency to make more errors during exposure to LFN than in the reference noise, and in the Signal Detection Test, they generally reacted faster (had shorter median detection time). In those noise conditions, however, the high-sensitive to LFN subjects, showed tendency to work less precisely (achieved lower number of correct responses in the Signal Detection Test) compared with the low-sensitive ones, while in the reference noise there was no difference related to noise sensitivity. The subjects categorized as high-sensitive to LFN also showed poorer performance than others during exposure to LFN in the Stroop Color-Word Test (a significant interaction between noise and noise sensitivity in case of reading interference index) and in the Continuous Attention Test (a tendency to more erroneous reactions). **Conclusions:** These findings suggest that LFN at moderate levels might adversely affect visual functions, concentration, continuous and selective attention, especially in the high-sensitive to LFN subjects.

Key words:
Low frequency noise, Human mental performance, Annoyance, Noise sensitivity

INTRODUCTION

Although the international definition of low frequency noise (LFN) has not as yet been conclusively formulated, LFN is usually defined as a broadband noise with the dominant content of frequencies from 10 (20) to 250 Hz. There is a growing body of data showing that LFN differs in its nature from other environmental noises at comparable levels, which are not dominated by low frequency components [1–4].

Low frequency noise is not only ubiquitous in the general, but also in the occupational environments, especially in industrial control rooms and office-like areas. Ventilation systems, pumps, compressors, diesel engines, gas turbine power stations or means of transport may be quoted as

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some examples of the common sources of LFN. Its prevalence in offices and control rooms is mainly due to indoor network installations, ventilation, heating and air conditioning systems, but also due to outdoor sources of noise and poor attenuation of low frequency components by the walls, floors, and ceilings [2,5].

The new working conditions of personnel in control rooms and offices have led to changes in job demands, involving a high element of unpredictability, requiring selective attention, processing of a high load of information, and to a large extent paced by computers. Knowledge of mechanisms by which LFN affects performance in these types of work situations is rather sparse. Although over the years, a great deal of research has been carried out to evaluate adverse effects of different kinds of noise on human performance, it mostly concerns noise at rather high levels, whereas studies of noise at moderate levels, including moderate levels of low frequency noise are rather scanty. Moreover, their results are rather inconsistent, probably due to considerable differences in the individual sensitivity to noise [6,7].

A few previous studies generally indicated that LFN at levels that could occur in the occupational environment might reduce the human performance [8–10]. Whereas recent investigations show that LFN at relatively low A-weighted sound pressure levels (about 40–45 dB) can be perceived as annoying and adversely affecting the performance, particularly when executing more demanding tasks. Moreover, persons classified as sensitive to LFN may be at a higher risk [11–13]. Therefore, potential adverse effects of LFN seem to be important at work posts, which require increased mental processing and selective attention, especially those located in control rooms and office-like areas.

The aim of the study was to investigate whether exposure to LFN at levels normally occurring in the industrial control rooms can influence human mental performance and lead to work impairment. In particular, it has been attempted to answer the question on whether LFN can negatively affect visual functions, concentration, continuous and selective attention or subjective well-being. A further objective was to analyze the relationship between LFN effects and individual sensitivity to this type of noise.

MATERIALS AND METHODS

Study design

The pre-selected subjects, categorized in terms of individual sensitivity to LFN, performed a series of standardized psychological tests during exposure to LFN or reference noise at the same equivalent-continuous A-weighted sound pressure level (SPL) of approx. 50 dB. Each subject carried out tasks once at randomly-assigned exposure conditions. After the test session, they were asked to complete a questionnaire, which sought among others information concerning:

- subjective rating of annoyance and effort put into performing tasks; and
- symptoms experienced during the tests conditions such as headache, feeling of pressure on the eardrum, nausea, dizziness or concentration difficulties.

A 100-score graphical rating scale was used for the annoyance and effort assessment. Subjective sensitivity to LFN was rated prior to the experiment, during selection of candidates.

The subjects received financial compensation for their participation in the experiment. The local Ethics Committee approved the study design.

Study Population

The study comprised 49 male and 47 female pre-selected volunteers, aged 19–27 years, high school or university graduates.

Candidates were selected from 402 persons, recruited by advertising, based on their scores on the Weinstein noise-sensitivity evaluation questionnaire [14]. This questionnaire was used in earlier studies to evaluate individual sensitivity to noise in general [12,15,16]. Only the subjects whose noise-sensitivity scores fell within either the top or bottom 30% of the initial group were eligible for the study. Additionally, each person underwent the hearing test and only those with normal hearing (<25 dB HL) were allowed to participate.

To assess sensitivity to LFN, the subjects were asked to answer the questionnaire including the following statements:

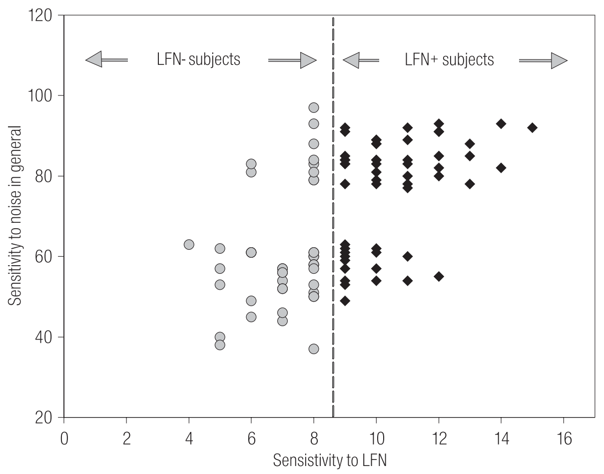

Fig. 1. Subjective sensitivity to noise in general and to LFN in the study group (scores on questionnaires).

- "I am not sensitive to noise with bass (low tones)",
- "I think that even low, monotonous humming (e.g., from a transformer) is unpleasant",
- "I like listening to music when bass are turned on".

All items had five response alternatives ranging from "do not agree at all" to "agree completely", graded from 1 to 5. However, the first and third items were scored in reverse direction before responses were summed.

Subjects were categorized as highly sensitive (high-sensitive) or less sensitive (low-sensitive) to LFN on the basis of their questionnaire scores. The higher the result, the higher the sensitivity to noise. Thus, persons who obtained at least median score (≥ 9 points) were classified as highly sensitive (high-sensitive) to low frequency noise (LFN+). The others were categorized as low-sensitive to low frequency noise (LFN–).

In the study group, 54 subjects were recognized as higher sensitive to LFN and 47 – as higher sensitive to noise in general, but the two sensitivity distributions were not identical (Fig. 1). This means that higher sensitivity to LFN was not necessarily connected with higher sensitivity to noise in general.

Table 1 shows the characteristics of the study group. The sub-groups performing tests in various noise conditions did not differ in age, education and sensitivity to noise (UMann Whitney test, $p < 0.05$).

Table 1. Characteristics of the study group

Subjects	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
Number of subjects	96	48	48
Male	49	26	22
Female	47	23	25
Low-sensitive to LFN	42	20	22
High-sensitive to LFN	54	28	26
		Mean ± SD	
Age (years)	21.7 ± 1.7	21.9 ± 1.8	21.6 ± 1.7
Sensitivity to noise in general*	70.0 ± 16.1	70.8 ± 15.3	69.2 ± 17.0
Sensitivity to LFN*	9.0 ± 2.2	9.0 ± 2.4	8.9 ± 2.1

* Score on the questionnaire; SD – standard deviation; LFN – low frequency noise.

Exposure conditions

The experiment was performed in a special chamber for psychological tests (6.8 m² area) furnished as an office environment. The noise was generated by a set of loudspeakers placed in the corners of the room.

Low frequency noise simulated noise occurring in the industrial control rooms (Fig. 2). The reference noise was the broadband noise of a predominantly flat frequency character, without dominant low frequency components. Both noises were at the same equivalent-continuous

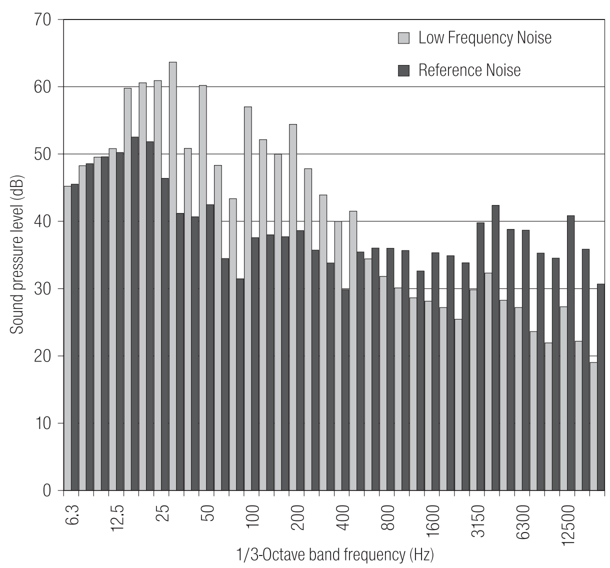

Fig. 2. 1/3-Octave band frequency spectrum of low frequency noise and reference noise used during test sessions, measured at the position of subjects' head.

Table 2. Noise exposure parameters during test sessions

Noise parameter (dB)	Exposure conditions	
	Low frequency noise	Reference noise
	Mean ± SD	
Equivalent-continuous A-weighted sound pressure level $L_{A\ eq\ T}$	49.7 ± 1.1	49.9 ±1.1
Equivalent-continuous linear (unweighted) sound pressure level $L_{LIN\ eq\ T}$	69,5 ± 0.6	59,7 ±1.0
Equivalent-continuous C-weighted sound pressure level $L_{C\ eq\ T}$	66.0 ± 0.7	53.5 ±0.7
Equivalent-continuous G-weighted sound pressure level $L_{G\ eq\ T}$	72.8 ± 0.6	64.5 ±1.4

SD – standard deviation.

A-weighted SPL of approx. 50 dB, but they differed in C- and G-weighted sound pressure levels (Table 2).

Performance tasks

In order to elucidate the influence of LFN on human mental performance, the subjects performed four standardized tests: the Signal Detection Test (test I), the Stroop Color-Word Test (test II), the Comparing of Names Test (test III), and the Continuous Attention Test (DAUF) (test IV).

Tests I, II and IV involved working with a computer, while test III – working with pen and paper. Before the test session, the subjects were informed how to perform the first two tests. Instructions concerning tests III and IV took place just before performing them. Generally, the subjects were asked to work as accurately and quickly as possible.

The Signal Detection Test is a computerized test applied to measure the ability of visual differentiation. The screen is covered with dots, then one after another, they are faded out apparently by pure chance and are substituted by new ones. Subjects are expected to detect cases when four dots represent the shape of square. The main variables include the amount of correct and delayed reactions as a measure for reliability of the detection process and the mean detection time as a measure for the speed of the detection process [17,18].

The Stroop Color-Word Test is a computerized realization of the Color-Word interference paradigm by Stroop [17,19]. It is based on the assumption that reading speed of a color-word is slower, if the word is written in a differently colored font. There is always a delay in naming the color of this word, if color and color-word do not match. This test is used for registration of the color-word interference tendency, i.e. impairment of the reading speed or color recognition due to interfering information. Therefore, it is useful in determining the individual susceptibility to stimulus disturbing mental processes.

The test consists of four parts:

- the first, in which the names of colors (RED, GREEN, YELLOW or BLUE) are exposed in gray on the screen and the subject is expected to push the button corresponding to the name – "reading in the baseline conditions";
- the second, in which color rectangles are shown and the subject is asked to press the button in the same color "naming in the baseline conditions";
- the third, in which the names of colors are presented in different colors (e.g., name "GREEN" is written in red, blue or yellow) and the subject is expected to push the button corresponding to the name "reading in the interference conditions";
- the fourth, in which names of colors are shown in similar way as in a preceding part, but the person is told to respond to the color of font "naming in the interference conditions".

The main evaluated variables are:

- the reading interference, i.e. the difference between the median reaction times of reading in the interference and baseline conditions;
- the naming interference, i.e. the difference between the median reaction times of naming in the interference and baseline conditions;
- median reaction times and the number of incorrect answers for each individual test part.

The Comparing of Names Test (test III) is a sub-test of the General Aptitude Test Battery (GATB) adapted to Polish population [20]. It consists of two columns of words (names). The respondent decides whether couples of words (names) in both columns are exactly the same. This test is designed to measure the ability to see pertinent detail in verbal material. Test results are the number of correct and incorrect answers given within 6 min.

The Continuous Attention Test (DAUF) is applied to measure "long-term attention and concentration performance". According to the basic definition, attention is selection: perception and visualization are adjusted and limited to a part of stimuli acting upon the organism simultaneously. The continuous aspect emphasizes the fact that with continuous repetition it becomes more difficult to carry out attention processes. Thus, the measurement of continuous attention mainly records aspects of "general performance and/or performance readiness", which are to a large extent independent of intelligence.

For thirty minutes, rows of triangles are presented on screen under time-critical conditions; the tips of the individual triangles can point either up or down. When a previously determined amount of triangles points down, the subject has to press the reaction button. The main tested variables are: the number of correct and incorrect responses, amount of omitted stimuli, and mean reaction time [17].

The test session lasted in total about 95 min.

Statistical analysis

Covariance analyses, ANCOVA, were performed to evaluate the influence of noise exposure, sensitivity to LFN and their interaction on the different performance tests and subjective ratings. Two main effects, i.e. exposure conditions (2 noises) and LFN sensitivity (2 sensitivity sub-groups) were analyzed, taking into consideration two covariates, gender and sensitivity to noise in general (score on the Weinstein noise-sensitivity evaluation questionnaire). These covariates were introduced to the model to avoid their possible influence on test results and subjective ratings.

To evaluate the influence of exposure and noise sensitivity on answers given in the questionnaire concerning symptoms experienced during the test session, a log-lin model was applied. However, the relationships between subjective ratings and reported symptoms were analyzed using Pearson's correlation coefficient (r).

All statistical tests were done with an assumed level of significance at a value of $p < 0.05$, while p-value up to 0.10 was reported as a tendency. The statistical analysis employed SPSS software for Windows (Chicago, IL, USA).

RESULTS

Performance

The results of the Signal Detection Test are shown in Table 3. A significant main effect of noise conditions on the median reaction time was found ($p = 0.015$). Regardless of LFN sensitivity, longer median reaction times were reported during exposure to reference noise. No significant differences in other test results were noted between noise exposures. Generally, the results were not influenced by the subjective sensitivity. However, during exposure to LFN, a weak simple effect of LFN sensitivity was found in the number of correct responses ($p = 0.065$). In the LFN conditions, the subjects categorized as high-sensitive to LFN obtained poorer results than the low-sensitive subjects (Fig. 3).

The results of the Stroop Color-Word Test are given in Tables 4 and 5. There were no differences related to noise conditions. However, a significant two-way interaction between exposure conditions and LFN sensitivity was noted for the reading interference parameter ($p = 0.048$). The persons classified as high-sensitive to LFN achieved higher values of reading interference in LFN conditions compared to reference noise, whereas the reverse was seen for low-sensitive subjects (Fig. 4).

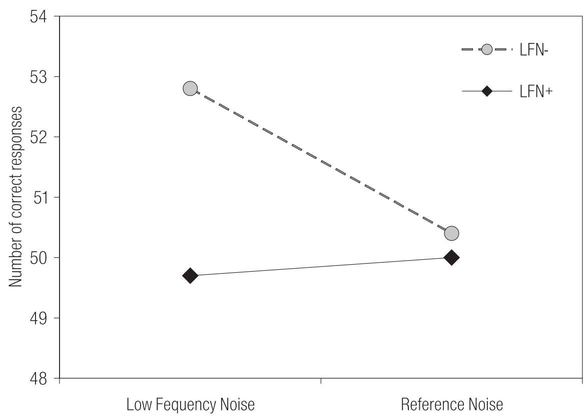

Fig. 3. Number of correct responses in the Signal Detection Test – mean values adjusted for gender and sensitivity to noise in general.

Table 3. The results of the Signal Detection Test

Test parameter	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Number of correct reactions	All subjects	50.5 ± 5.2	51.0 ± 4.9 (51.2)	50.1 ± 5.4 (50.2)
	LFN-	51.8 ± 5.2 (51.6)	53.1 ± 3.9** (52.8)	50.7 ± 6.0 (50.4)
	LFN+	49.5 ± 4.9 (49.8)	49.5 ± 5.0** (49.7)	49.5 ± 4.8 (50.0)
Number of delayed reactions	All subjects	0.56 ± 0.75	0.58 ± 0.74 (0.58)	0.53 ± 0.78 (0.51)
	LFN-	0.45 ± 0.67 (0.45)	0.50 ± 0.61 (0.50)	0.41 ± 0.73 (0.40)
	LFN+	0.64 ± 0.81 (0.64)	0.64 ± 0.83 (0.66)	0.64 ± 0.81 (0.63)
Number of omitted stimuli	All subjects	8.9 ± 5.1	8.4 ± 4.9 (8.2)	9.4 ± 5.4 (9.3)
	LFN-	7.7 ± 5.1 (8.0)	6.4 ± 4.1 (6.7)	8.9 ± 5.8 (9.2)
	LFN+	9.9 ± 5.0 (9.5)	9.9 ±5.0 (9.6)	9.9 ± 5.1 (9.4)
Number of incorrect reactions	All subjects	1.63 ± 2.05	1.63 ± 1.55 (1.68)	1.64 ± 2.47 (1.61)
	LFN-	1.64 ± 1.69 (1.54)	1.85 ± 1.57 (1.76)	1.45 ± 1.82 (1.32)
	LFN+	1.62 ± 2.31 (1.74)	1.46 ± 1.55 (1.59)	1.8 ± 2.96 (1.89)
Median detection time (s)	All subjects*	0.8 ± 0.14	0.77 ± 0.10 (0.77)	0.83 ± 0.16 (0.83)
	LFN-	0.77 ± 0.15 (0.79)	0.74 ± 0.10*** (0.76)	0.8 ± 0.17*** (0.82)
	LFN+	0.82 ± 0.13 (0.81)	0.79 ± 0.09**** (0.78)	0.86 ± 0.15**** (0.83)

*A significant main effect of noise conditions (p = 0.015); ** A weak simple effect of LFN sensitivity during exposure to LFN (p = 0.065);
***A weak simple effect of noise condition in the LFN− subjects (p = 0.084); ****A weak simple effect of noise condition in the LFN+ subjects (p = 0.090);
SD – standard deviation; LFN- – subjects classified as low-sensitive to low frequency noise; LFN+ – subjects classified as high-sensitive to low frequency noise.

Regardless of the noise exposure, the influence of LFN sensitivity was found for the median reaction time (p = 0.003) and the number of errors of naming in the baseline conditions (p = 0.034) as well as in the case of the median reaction time of naming in the interference conditions (p = 0.056) (Tables 4 and 5). In particular, during exposure to reference noise, the subjects categorized as high-sensitive to LFN achieved longer median reaction times of naming in the baseline conditions compared to low-sensitive ones (p = 0.031) (Table 4). Similar relationship was observed in the LFN conditions, but the differences were less evident (p = 0.095).

Only a weak main effect of noise conditions on the number of erroneous answers was found (p = 0.066) in the

Table 4. The results of the Stroop Colour-Word Test: Part I

Test parameter (sec)	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Reading interference	All subjects*	0.099 ± 0.094	0.098 ± 0.097 (0.093)	0.099 ± 0.092 (0.101)
	LFN-	0.094 ± 0.102 (0.093)	0.070 ± 0.089**** (0.069)	0.116 ± 0.109 (0.117)
	LFN+	0.102 ± 0.088 (0.101)	0.118 ± 0.099**** (0.116)	0.085 ± 0.072 (0.086)
Naming interference	All subjects	0.063 ± 0.125	0.064 ± 0.150 (0.065)	0.062 ± 0.094 (0.063)
	LFN-	0.078 ± 0.083 (0.070)	0.072 ± 0.092 (0.065)	0.083 ± 0.076 (0.075)
	LFN+	0.051 ± 0.15 (0.058)	0.058 ± 0.183 (0.065)	0.043 ± 0.106 (0.051)
Median reaction time of reading in the baseline conditions	All subjects	0.752 ± 0.107	0.743 ± 0.098 (0.742)	0.761 ± 0.117 (0.759)
	LFN-	0.730 ± 0.091 (0.731)	0.734 ± 0.103 (0.734)	0.727 ± 0.080***** (0.727)
	LFN+	0.769 ± 0.117 (0.770)	0.750 ± 0.095 (0.749)	0.790 ± 0.137***** (0.791)
Median reaction time of naming in the baseline conditions	All subjects**	0.717 ± 0.107	0.714 ± 0.106 (0.708)	0.721 ± 0.109 (0.719)
	LFN-	0.676 ± 0.070 (0.675)	0.674 ± 0.072**** (0.673)	0.679 ± 0.07****** (0.677)
	LFN+	0.750 ± 0.121 (0.751)	0.742 ± 0.119**** (0.742)	0.758 ± 0.124****** (0.760)
Median reaction time of reading in the interference conditions	All subjects	0.851 ± 0.128	0.842 ± 0.119 (0.835)	0.860 ± 0.137 (0.860)
	LFN-	0.825 ± 0.122 (0.824)	0.805 ± 0.089 (0.804)	0.843 ± 0.146 (0.843)
	LFN+	0.871 ± 0.130 (0.872)	0.868 ± .0.132 (0.866)	0.875 ± 0.130 (0.877)
Median reaction time of naming in the interference conditions	All subjects***	0.779 ± 0.139	0.777 ± 0.163 (0.772)	0.781 ± 0.110 (0.780)
	LFN-	0.753 ±0.102 (0.743)	0.744 ± 0.105 (0.736)	0.760 ± 0.100 (0.751)
	LFN+	0.800 ± 0.160 (0.808)	0.800 ± 0.193 (0.808)	0.799 ± 0.117 (0.809)

* A significant interaction of noise conditions and LFN sensitivity (p = 0.048);
** A significant main effect of LFN sensitivity (p = 0.003);
*** A weak main effect of LFN sensitivity (p = 0.056);
**** A weak simple effect of LFN sensitivity in the LFN conditions (p < 0.100);
***** A weak simple effect of LFN sensitivity in the reference noise conditions (p = 0.065);
****** A significant simple effect of LFN sensitivity in the reference noise conditions (p = 0.031);
SD – standard deviation;
LFN- – subjects classified as low-sensitive to low frequency noise;
LFN+ – subjects classified as high-sensitive to low frequency noise.

Table 5. The results of the Stroop Colour-Word Test: Part II

Number of incorrect reactions	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Reading in the baseline conditions	All subjects	1.02 ± 1.54	1.02 ± 1.71 (1.02)	1.02 ± 1.38 (1.04)
	LFN-	1.12 ± 1.61 (1.14)	1.10 ±2.02 (1.11)	1.14 ± 1.17 (1.16)
	LFN+	0.94 ± 1.50 (0.92)	0.96 ± 1.48 (0.93)	0.92 ± 1.55 (0.92)
Naming in the baseline conditions	All subjects*	0.84 ± 1.30	0.96 ± 1.50 (0.99)	0.72 ± 1.06 (0.75)
	LFN-	1.14 ± 1.57 (1.21)	1.25 ± 1.86 (1.30)	1.05 ± 1.29 (1.12)
	LFN+	0.60 ± 0.99 (0.54)	0.75 ± 1.17 (0.68)	0.44 ± 0.71 (0.39)
Reading in the interference conditions	All subjects	2.03 ± 2.28	1.98 ± 1.99 (1.94)	2.09 ± 2.55 (2.13)
	LFN-	2.17 ± 2.24 (2.42)	1.85 ± 1.76 (2.08)	2.45 ± 2.61** (2.77)
	LFN+	1.92 ± 2.32 (1.65)	2.07 ± 2.18 (1.80)	1.76 ± 2.5** (1.50)
Naming in the interference conditions	All subjects	2.03 ± 2.76	2.10 ± 3.07 (2.17)	1.96 ± 2.44 (1.95)
	LFN-	2.21 ± 3.23 (2.45)	2.55 ± 4.25 (2.75)	1.91 ± 1.97 (2.15)
	LFN+	1.89 ± 2.34 (1.67)	1.79 ± 1.85 (1.59)	2.00 ± 2.83 (1.76)

* A significant main effect of LFN sensitivity (p = 0.034); ** A weak simple effect of LFN sensitivity during exposure to reference noise (p = 0.094); SD – standard deviation; LFN- – subjects classified as low-sensitive to low frequency noise; LFN+ – subjects classified as high-sensitive to low frequency noise.

Table 6. The results of the Comparing of Names Test

Test parameter	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Number of correct responses	All subjects	63.1 ± 14.0	62.8 ± 13.7 (62.8)	63.3 ± 14.5 (63.2)
	LFN-	62.7 ± 13.2 (63.5)	62.0 ± 9.9 (62.9)	63.3 ± 15.8 (64.2)
	LFN+	63.4 ± 14.8 (62.5)	63.4 ± 16 (62.8)	63.3 ± 13.6 (62.2)
Number of incorrect responses	All subjects*	2.6 ± 3.8	3.2 ± 4.8 (3.3)	1.9 ± 2.3 (1.9)
	LFN-	3.0 ± 4.5 (2.6)	3.8 ± 5.7 (3.5)	2.2 ± 2.9 (1.7)
	LFN+	2.3 ± 3.2 (2.6)	2.8 ± 4.1 (3.2)	1.7 ± 1.6 (2.1)

* A weak main effect of LFN sensitivity (p = 0.066); SD – standard deviation; LFN- – subjects classified as low-sensitive to low frequency noise. LFN+ – subjects classified as high-sensitive to low frequency noise.

Table 7. Results of the Continuous Attention Test (DAUF)

Test parameter	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Number of correct reactions	All subjects	259.0 ± 25.4	259.4 ± 24.6 (260.2)	258.6 ± 26.4 (259.1)
	LFN-	264.8 ±18.2 (263.7)	265.4 ± 19.4 (264.3)	264.3 ± 17.4 (263.1)
	LFN+	254.5 ± 29.2 (255.6)	255.1 ± 27.3 (256.1)	253.8 ± 31.6 (255.1)
Number of incorrect reactions	All subjects*	16.2 ± 10.3	17.3 ± 10.9 (16.8)	15.2 ± 9.6 (15)
	LFN-	13.3 ± 9.4 (13.6)	13.8 ± 9.6** (14.1)	12.8 ± 9.3 (13.1)
	LFN+	18.5 ± 10.5 (18.2)	19.8 ± 11.3** (19.6)	17.2 ± 9.6 (16.8)
Number of omitted stimuli	All subjects	21.0 ± 25.4	20.6 ± 24.6 (19.8)	21.4 ± 26.4 (20.9)
	LFN-	15.2 ± 18.2 (16.3)	14.7 ± 19.4 (15.7)	15.7 ± 17.5 (17.0)
	LFN+	25.5 ± 29.2 (24.4)	24.9 ± 27.3 (23.9)	26.2 ± 31.6 (24.9)
Mean reaction time (sec)	All subjects	0.72 ± 0.08	0.72 ± 0.07 (0.72)	0.73 ± 0.09 (0.73)
	LFN-	0.71 ± 0.09 (0.72)	0.71 ± 0.08 (0.71)	0.72 ± 0.10 (0.72)
	LFN+	0.73 ± 0.07 (0.73)	0.73 ± 0.06 (0.73)	0.74 ± 0.09 (0.73)

*A weak main effect of LFN sensitivity (p = 0.063); **A weak simple effect of LFN sensitivity during exposure to LFN (p = 0.095);
SD – standard deviation; LFN- – subjects classified as low-sensitive to low frequency noise; LFN+ – subjects classified as high-sensitive to low frequency noise.

Table 8. The subjective ratings of annoyance related to exposure conditions and efforts put into performing tests

Subjective rating	Study group	Total	Noise conditions: Low frequency noise	Noise conditions: Reference noise
		Mean ± SD (mean adjusted for covariates)		
Annoyance	All subjects	36.1 ± 23.7	32.9 ± 23.2 (31.7)	39.3 ± 24 (39.4)
	LFN-	30.2±23.2 (36.8)	27.6 ± 23.6 (33.4)	32.6 ± 23.2 (40.3)
	LFN+	40.7 ± 23.1 (34.2)	36.7 ± 22.5 (30.0)	45.2 ± 23.5 (38.5)
Efforts	All subjects	35.0 ± 20.5	32.2 ± 19.9 (31.7)	37.9 ± 20.9 (38.0)
	LFN-	33.3 ± 20.5 (37)	31.1 ± 20.4 (34.4)	35.3 ± 20.8 (39.7)
	LFN+	36.4 ± 20.5 (32.7)	33.0 ± 19.8 (29.1)	40.1 ± 21.0 (36.3)

SD – standard deviation; LFN- – subjects classified as low-sensitive to low frequency noise; LFN+ – subjects classified as high-sensitive to low frequency noise.

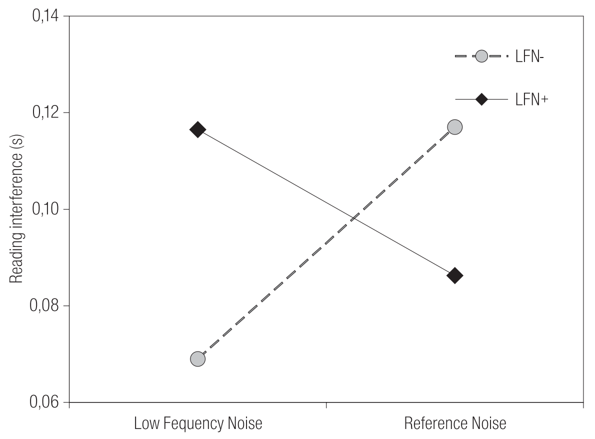

Fig. 4. Reading interference in the Stroop Color-Word Test – mean values adjusted for gender and sensitivity to noise in general.

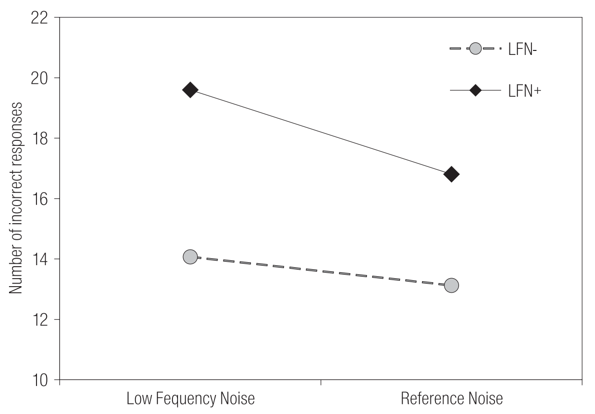

Fig. 5. Number of incorrect responses in the Continuous Attention Test (DAUF) – mean values adjusted for gender and sensitivity to noise in general.

Comparing of Name Test. As seen in Table 6, regardless of the individual sensitivity to LFN, the subjects showed tendency to make more errors during exposure to LFN than in the reference noise conditions.

The results of the Continuous Attention Test are shown in Table 7. Generally, no significant differences in test results between low frequency and reference noises were found. A weak main effect of noise sensitivity was noted in the number of incorrect responses ($p = 0.063$). In particular, that effect was observed during exposure to LFN. In those noise conditions, the LFN high-sensitive subjects showed tendency to a higher number of errors compared to others ($p = 0.095$), while during reference noise there was no difference related to noise sensitivity (Fig. 5).

Subjective ratings

There were no significant main effects of noise exposure, LFN sensitivity and their interaction with annoyance rating. Similar relations were found in case of the subjective assessment of effort put into performing tests (Table 8).

Noise (sounds) perceived during the test session were significantly more often described as humming (58.3% vs. 27.7% of answers) and low (37.5% vs. 17.0%) in the LFN conditions than in the reference noise ($p < 0.050$).

Symptoms subjectively related to exposure conditions during the test session are given in Table 9. Generally, drowsiness, fatigue, problems with concentration, discomfort and pressure in ears or head were the most frequently reported symptoms, but a significant difference between LFN and reference noise was only found in case of drowsiness (Table 9).

A significant influence of noise sensitivity on answers given in the questionnaire was noted in case of problems

Table 9. The subjective sensations and complaints reported during test sessions

Symptoms	Low frequency noise	Reference noise
	Rates of answers (%)	
	Sensations	
No sensations	12.5	2.1
I heard sounds (noise)	72.9	83.3
I felt pressure in ears	25.0	20.8
I felt pressure in head	16.7	27.1
I felt vibrations in room	6.3	4.2
I felt vibrations in part of body	0	2.1
I felt discomfort	27.1	31.3
Others	20.8	22.9
	Complaints	
No complaints	18.8	12.5
Headache	12.5	14.6
Problems with concentration*	29.2	31.3
Dizziness	0.0	2.1
Drowsiness**	52.1	75.0
Fatigue	47.9	43.8
Others	10.4	8.3

* A significant influence of sensitivity to LFN ($p = 0.040$);
** A significant influence of noise conditions ($p = 0.022$).

with concentration as well as in case of noise (sounds) description. Regardless of noise conditions, the subjects classified as high-sensitive to LFN reported problems with concentration more often than others (38.9% vs. 19.0% of answers, $p = 0.040$). On the other hand, the LFN low-sensitive persons more frequently (compared to high-sensitive ones) described noise (sounds) during test sessions as bearable (52.4% vs. 27.8% of answers, $p = 0.021$).

Generally, the annoyance rating on the graphical scale was correlated with the number of reported sensations ($r = 0.61$, $p < 0.001$) and complaints ($r = 0.73$, $p < 0.001$) subjectively related to exposure condition during performing tasks.

DISCUSSION AND CONCLUSIONS

The study was designed to investigate whether exposure to moderate levels of LFN can influence human mental performance and subjective well-being. Another objective was to analyze the relationship between sensitivity to LFN and LFN effects on both performance and subjective ratings.

Four standardized psychological tests were applied for that purpose. Those tests are usually used as a measure of visual differentiation ability (test I), perceptiveness and concentration (test III), continuous attention (test IV), and selective attention and visual functions (test II). A high workload was generated by instructing the subjects to work as quickly and accurately as possible.

The tasks were carried out in two different acoustic conditions, low frequency and reference noises at the same dB(A) levels of 50 dB. An earlier study showed that sound pressure levels normally occurring in industrial control rooms remained within the range of 48-66 dB(A) [21]. Thus, a sound pressure level of 50 dB(A) corresponded with the lower limit of the measured levels. Moreover, it was 15 dB lower than the currently admissible level established in Poland to ensure suitable working conditions for operators of control equipment in control booths or remote control rooms [22].

To avoid learning effects, each subject performed tasks only once in randomly-assigned exposure conditions. Only pre-selected volunteers took part in the experiment. Moreover, two sub-groups working in various exposure conditions did not differ with respect to age, education and subjective sensitivity to noise in general and to LFN in particular.

As the experiment was carried out under laboratory conditions and between-subject design was chosen, the relevance of the results for normal working conditions must be evaluated with caution. Nevertheless, the study supports a hypothesis that LFN at levels normally occurring in the control rooms (at about 50 dB(A)) might adversely influence the human mental performance and lead to work impairment. Moreover, it points to the importance of considering individual sensitivity to LFN when evaluating its effects.

Generally, the influence of noise sensitivity on performance during exposure to noise was shown in earlier studies. For example, Jelnikova [15] found that persons recognized as sensitive to noise had a reduced working ability and attention during exposure to recorded traffic noise at equivalent continuous A-weighted sound pressure level of 75 dB compared with persons tolerant to noise. Similarly, Bolejovic et al. [16] not only confirmed the influence of noise sensitivity on performance during exposure to traffic noise at 55 and 75 dB(A), but also found a relationship between noise sensitivity and subjective assessment of noise annoyance.

It is worth noting that previous studies on the effects of community LFN (in dwelling rooms) showed that subjects sensitive to this type of noise were not necessarily sensitive to noise in general as measured by general noise sensitivity scales [1]. Moreover, later investigations on the influence of LFN on performance confirmed that sensitivity to this special type of noise was somewhat different from sensitivity to noise in general [12]. It seems, therefore, advisable not only to take account of subjects' sensitivity to noise in general, but also to categorize people with respect to their LFN sensitivity. That is why these two types of noise sensitivity were taken into consideration in this study.

To assess sensitivity to noise in general, the Weinstein noise sensitivity evaluation questionnaire [14] was suitably adapted. On the other hand, the evaluation of the sensitivity to LFN was based on three statements taking into consideration subjective sensations related to low frequency sounds. Interestingly, in some recent studies [12,13], sensitivity to LFN was also based on similar statements or questions (e.g., "Are you sensitive to low frequency noise?" or "I am sensitive to rumbling noise from ventilation system").

The findings presented here generally confirm earlier observations that higher sensitivity to LFN was not necessarily connected with higher sensitivity to noise in general.

All in all, research data on the influence of LFN at sound pressure levels normally occurring in control rooms and office areas are rather sparse. For example, Persson et al. [11] found in a pilot study that LFN from ventilation at a level of 42 dB(A) (approx. 71 dB(LIN)) could increase the response time in a verbal grammatical reasoning task in comparison with ventilation noise at the same A-weighted sound pressure level, but without low frequency components (approx. 51 dB(LIN)).

Another laboratory study, a continuation of the work performed in the pilot study quoted above, confirmed that LFN at relatively low A-weighted SPL (about 40 dB) could be perceived as annoying and adversely affecting the performance, particularly when mentally demanding tasks were executed, while the effects on the routine tasks were less clear. Moreover, persons classified as sensitive to LFN may be at the highest risk [12].

In the quoted study, subjects categorized in terms of sensitivity to noise in general and to LFN in particular, performed a series of tasks involving different levels of mental processing (e.g., simple reaction-time task, short-term memory task and bulb-task, proof-reading task and verbal grammatical reasoning task) during exposure to ventilation noise of a low frequency character or a flat frequency (reference) noise, both at the same A-weighted SPL of 40 dB and different linear (unweighted) SPL (approx. 70 and 50 dB, respectively). All performance tasks were carried out twice in each test session, once in phase A and once in phase B. Thus, the experiment comprised 2 noises • 2 phases • 2 sensitivity groups, but sensitivity to noise in general and to LFN in particular was considered separately. The results showed a distinct improvement in response time over time, during work with a verbal grammatical reasoning task in the reference noise, indicating a better learning effect in this noise condition compared with LFN. The results also showed that LFN interfered with a proof-reading task by lowering the number of marks made per line read. The persons reported a higher degree of annoyance and impaired working capacity during exposure to LFN. The effects were more pronounced in the subjects classified as sensitive to LFN, while somewhat different results were found in those rated as sensitive to noise in general [12].

In another study aimed at evaluating effects of moderate levels of LFN on attention, tiredness and motivation in low demanding work situations, only subjects categorized as high-sensitive to LFN were enrolled. As previously, two ventilation noises at the same A-weighted SPL of 45 dB were used, one of predominantly low frequency content (at approx. 76 dB(LIN)) and one with flat frequency spectrum (at approx. 54 dB(LIN)). The subjects worked with six performance tasks. Most of them were of monotonous and routine type. The major finding in that study was that LFN adversely affected performance in two tasks sensitive to reduced attention and in a proof-reading task. Performance of tasks aimed at evaluating motivation were not significantly influenced. Moreover, no significant difference between noise conditions was found in annoyance rating [13].

In this study, the influence of exposure conditions on performance was noted in two of the four tests. However, there was no significant difference in annoyance rating of low frequency and reference noises.

In the Comparing of Names Test, the subjects, regardless of the noise sensitivity, showed tendency to make more errors during exposure to LFN than in the reference noise conditions. On the other hand, in the Signal Detection Test, persons had longer median detection times in the reference noise. Thus, during exposure to LFN, the subjects reacted faster. However, in that noise conditions some of them, those categorized as high-sensitive to LFN, showed tendency to work less precisely (achieved a lower number of correct responses) compared with the low-sensitive to LFN subjects, while no difference related to noise sensitivity was noted in the reference noise.

A significant interaction of exposure conditions and sensitivity to LFN was found for reading interference index in the Stroop Color-Word Test. A higher value of the reading interference index during exposure to LFN was noted in the subjects categorized as high-sensitive to LFN than in the reference noise, while the opposite relation was observed in case of low-sensitive persons.

Regardless of noise exposure, differences related to LFN sensitivity were found in some variables from the Stroop Color-Word Test (e.g., the number of errors of naming in the baseline conditions and median reaction times of naming in the baseline and interference conditions) as well as in the Continuous Attention Test. In the latter, during exposure to LFN, the subjects classified as high-sensitive to LFN showed tendency to make more errors than other subjects, while in the reference noise there was no difference between subjects of various sensitivity to LFN.

To sum up, the adverse effect of LFN at 50 dB(A) (compared to reference noise without dominant content of low frequencies) on performance was found in task demanding perceptiveness and concentration (test III). Moreover, during exposure to LFN differences in performance between higher and lower sensitive to noise subjects were observed in tasks requiring visual differentiation and selective or continuous attention; the persons categorized as high-sensitive to LFN achieved worse results than low-sensitive ones (tests I, II and IV).

Since the study was carried out under laboratory conditions, the relevance of its results to normal work situations should be evaluated with caution. Nevertheless, findings presented here suggest that LFN at levels normally occurring in the industrial control rooms might adversely influence visual functions, concentration, continuous and selective attention and lead to work impairment, particularly in case of jobs requiring selective attention and/or processing high load of information. Moreover, the subjects recognized as high-sensitive to LFN may be at higher risk. Our findings are thus in agreement with recent studies concerning LFN effects on human mental performance.

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