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Evaluations of effects due to low-frequency noise in a low demanding work situation

J. Bengtsson[a,*], K. Persson Waye[a], A. Kjellberg[b]

[a] *Department of Environmental Medicine, Göteborg University, Box 414, 405 30 Gothenburg, Sweden*
[b] *Centre for Built Environment, University of Gävle, Gävle, Sweden*

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Abstract

Noise sources with a dominating content of low frequencies (20–200 Hz) are found in many occupational environments. This study aimed to evaluate effects of moderate levels of low-frequency noise on attention, tiredness and motivation in a low demanding work situation. Two ventilation noises at the same A-weighted sound pressure level of 45 dB were used: one of a low-frequency character and one of a flat frequency character (reference noise). Thirty-eight female subjects worked with six performance tasks for 4 h in the noises in a between-subject design. Most of the tasks were monotonous and routine in character. Subjective reports were collected using questionnaires and cortisol levels were measured in saliva. The major finding in this study was that low-frequency noise negatively influenced performance on two tasks sensitive to reduced attention and on a proof-reading task. Performances of tasks aimed at evaluating motivation were not significantly affected. The difference in work performance was not reflected by the subjective reports. No effect of noise was found on subjective stress or cortisol levels.

1. Introduction

The occupational noise environment is changing. Hearing conservation programmes have focused on reducing the very high noise exposure levels and in many cases this has been achieved by building control rooms from which industrial processes and industrial robots are supervised. Unfortunately, due to the poorer attenuation of low frequencies by walls, floors and ceilings, the noise environments in these control rooms often comprise a large content of low frequencies. Low-frequency noise is defined as "a noise with a dominant frequency content of 20–200 Hz" [1].

*Corresponding author. Fax: +46-(0)31-825004.
E-mail address: johanna.bengtsson@envmed.gu.se (J. Bengtsson).

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Sources that can generate low-frequency noise at moderate levels in occupational environments are ventilation, heating and air-conditioning systems and computer network installations. The working condition in a control room requires sustained attention and concentration and, in the case of error messages, rapid and correct decisions. The monitoring instruments in control rooms are often computerized and determine the work speed. The demands in the control room are thus sensitive to reduced attention and increased tiredness.

A great deal of research has been done on the effects of noise on performance [2,3] and some recent field studies give evidence that noise may add to the development of fatigue [4,5]. Less information is available on the effects of low-frequency noise. One study [6] found that tones centred at 40 and 100 Hz (at 25 dB above the individual hearing threshold) caused more errors in a dual task situation than traffic noise (90 dB Lin) and silence. The effects were especially pronounced during the last 10 min of the total 30-min exposure. Furthermore, Benton and Robinson [7] found support for performance impairment caused by a narrowband (1 Hz) low-frequency noise ($f_c = 140$) at the C-weighted sound pressure level of 70 and 95 dB, as compared to speech and white noise (20–20 kHz). The latter exposure were matched for loudness against the narrowband low-frequency noise. The low-frequency noise was also rated as more annoying. In contrast, there was no difference on subject's performance on a complex task when working in a low-frequency noise (one-third-octave band centred at 125 Hz, 90 dB SPL) as compared to noise with a high-frequency character (90 dB SPL) or ambient noise (55 dB SPL) [8].

Previous studies suggest that low-frequency noise and/or infrasound can have a sleep-provoking effect. Reduced wakefulness due to low-frequency noise, measured in recordings of EEG e.g. [9–12], has been found in experimental laboratory and field studies. There are also indications from field studies that low-frequency noise can lead to increased tiredness, measured on a reaction-time task [4]. Tiredness and motivation are closely related to each other. It has been shown that sleepy persons are more likely than rested persons to use excuses for not expending enough effort on a task [13]. It has also been found that the effects of tiredness on performance can be reduced by increasing motivation, e.g. by giving knowledge about results or in other ways making the task more interesting, see review by Kjellberg [14]. Thus, tiredness may reduce motivation and greater motivation may reduce tiredness. Exposure to noise, especially unpredictable noise, during work has previously been found to have effects on the motivation to perform tasks following the exposure. Evans and Johnson [15] found behavioural after-effects, expressed as fewer attempts to solve insoluble puzzles, among personnel who had been working for 3 h with clerical tasks during exposure to simulated open office noise at an A-weighted sound pressure level of 55 dB. Boman et al. [16] found that motivation in an insoluble embedded figures task was lower following exposure for 15 min to unpredictable noise, comprising a conglomerate of noise at a maximum A-weighted sound pressure level of 76 dB, than after exposure to predictable noise. There is at present very little information about whether steady state low-frequency noise would affect motivation.

There are large inter-individual differences in the response to noise. Compared to less sensitive subjects, subjects with a high subjective sensitivity to noise have been found to show greater performance impairments and rate their annoyance higher when carrying out tasks in noisy conditions [17,18]. It has also been found that the categorization of sensitivity to low-frequency noise could be distinguished from the categorization of sensitivity to noise in general [18]. Thus, subjects sensitive to low-frequency noise might be a risk group when working during exposure to low-frequency noise.

Psychological stress and negative affect are associated with increased secretory activity in the hypothalamic-pituitary-adrenal neuroendocrine system, and one of the main secretory products is the glucocorticoid hormone cortisol. Exposure to high levels of noise has been shown to increase cortisol excretion [5], but little is known about elevations in cortisol levels during exposure to moderate levels of noise. In a previous study [19], the normal circadian decline in cortisol concentration was attenuated by low-frequency noise among subjects sensitive to noise in general when they worked with a very demanding task. It has, however, previously been found [20] that the neuroendocrine reaction to noise habituates during low demanding tasks. It is therefore of interest to evaluate whether the habituation of the cortisol response differ between a low-frequency noise condition and a reference noise condition in a low demanding work situation.

The aim of the study was to compare the effects of exposure to moderate levels of a low-frequency noise and a flat-frequency noise in order to answer the following questions:

- Does exposure to low-frequency noise during work lead to performance impairments, due to loss of attention, increased tiredness and reduced motivation?
- Does low-frequency noise exposure during work lead to negative effects on annoyance and other subjective reports?
- Is the secretion of cortisol affected by low-frequency noise in a low demanding work condition?

2. Material and methods

2.1. General outline

Subjects categorized as sensitive to low-frequency noise carried out performance tasks during exposure to either a low-frequency noise or a reference noise, at the A-weighted sound pressure level of 45 dB. Half of the subjects were exposed to the reference noise and half were exposed to the low-frequency noise. The test sessions started at 2 pm and lasted until about 6 pm, and the subjects were exposed to the noise for 3 h and 40 min. For subjects that completed a voluntary task (a nonsense questionnaire), the whole test session lasted for up to 5 h. The subjective responses to the noise conditions were evaluated using questionnaires, and saliva samples were taken to evaluate cortisol concentrations used as an indicator of the stress response. A between-subject design was chosen since the tasks selected to evaluate motivation could not be repeated and to avoid a probable negative effect on motivation from participating twice in such a long test session. The local ethics committee approved the study.

2.2. Noise exposure

Two ventilation noises were used: one of a predominantly low-frequency character (low-frequency noise) and one of a predominantly flat-frequency character (reference noise). The A-weighted sound pressure level of both noises was 45 dB; the corresponding C-weighted sound pressure levels were 53 dB for the reference noise and 72 dB for the low-frequency noise.

A recording of a ventilation noise with rather flat frequency characteristics (measured in third-octave bands) was used to create the exposure noise. The noise from a ventilation installation was recorded in front of the inlet grids of a large ventilation system. A microphone (B&K 4165) was positioned close to the grid. A measurement amplifier (B&K Nexus 2690 preamplifier) with a flat frequency response down to 20 Hz was used and the noise was recorded on a DAT recorder (Sony TCD-D7). The recording was made during the night to avoid other disturbing sounds from the surrounding. This recorded noise is called the reference noise. In order to obtain a noise with dominant low frequencies, white noise was added by a random noise generator and filtered by a resonance filter with a centre frequency of 31.5 Hz. A sinusoidal tone at 31.5 Hz was added and amplitude-modulated with a modulation frequency of 2 Hz and a modulation degree of 100%. This was done to give the low-frequency noise a rumbling characteristic, which is naturally present in many noises dominated by low frequencies [21]. The processing of the sound was done using a digital sound processor system (Aladdin interactive workbench, Nyvalla DSP, Stockholm, Sweden). The equivalent third-octave band sound pressure levels of the two noises were measured at ear level at the position of a seated subject. The variation of the A-weighted sound pressure level at the two positions in the room was ± 0.3 dB. Fig. 1 shows the equivalent third-octave band sound pressure levels, based on 2 min measurements, for the low-frequency noise and the reference noise at 45 dB.

2.3. Subjects

Thirty-eight female subjects were recruited by advertising at Göteborg University. As a previous study found gender differences on the embedded figures task, only female subjects were included in the experiment [16]. The subjects were all students at Göteborg University, and had an average age of 24.6 years (SD = 4.24). Each subject underwent an audiometric screening (SA 201 II Audiometer, Entomed, Malmö, Sweden), and only persons with normal hearing, <20 dB hearing loss, were included in the study. The subjects received financial compensation for their participation.

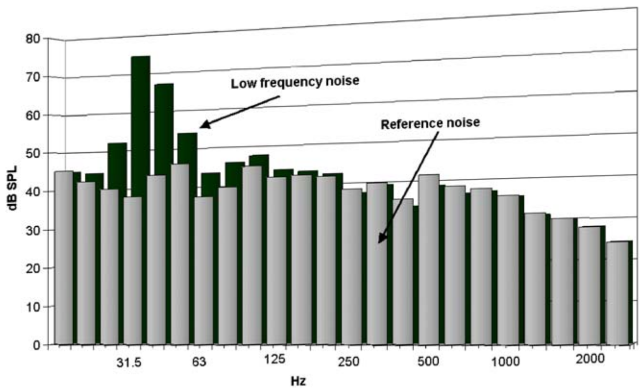

Fig. 1. Third-octave band sound pressure levels of the reference noise and the low-frequency noise (dark coloured bars) used during the test sessions, measured at the position of the subject's ears.

2.4. Subjective sensitivity to noise

Subjective sensitivity to noise was recorded in a questionnaire distributed to the subjects in beforehand. To mask that only two of the questions in the questionnaire were of interest, the questions on sensitivity to low-frequency noise were included in the six-page questionnaire with different questions. On the basis of the subjects scores on the two sensitivity questions, the subjects were categorised as sensitive to low frequency noise. The first question was "are you sensitive to low-frequency noise", with the five response alternatives "not at all sensitive", "not very sensitive", "rather sensitive", "very sensitive" and "extremely sensitive". The second question was "I am sensitive to rumbling noise from ventilation systems", with the six response alternatives "disagree completely, "practically disagree", "partly disagree", "partly agree", "practically agree" and "agree completely". The minimum and maximum possible scores were 2 and 11. The minimal value for inclusion was set to 6, as this was the breakpoint value used to classify a randomly selected group of test subjects into a low or high sensitive group in a previous study [18]. In that study the same two questions for low-frequency noise sensitivity was used. The categorization of subjects as sensitive to low-frequency noise in the previous study represented about 56% of the randomly selected student group. In this study, the average value on the first low-frequency noise sensitivity question was 3.2 (SD = 0.6, range 2–5), corresponding to "rather sensitive to low-frequency noise", respectively 4.5 (SD = 0.9, range 3–6) on the second question, corresponded to between "partly agree" and "practically agree".

2.5. Performance tasks

Six performance tasks were selected to correspond to relevant assignments or reflect relevant demands that are needed to perform the assignments well in control rooms. The experimental set-up is shown in Table 1. The simple reaction-time task, the bulb-task and the search and memory task (SAM1) were of a monotonous and routine-type character, chosen to evaluate tiredness and sustained and selective attention. The proof-reading task was a somewhat more mentally demanding verbal task, requiring sustained attention and concentration. The embedded figure task and the nonsense questionnaire were chosen to test primarily motivational mechanisms. The simple reaction-time task involved working with a computer, the bulb-task involved pressing different coloured buttons on a control panel and the other four tasks involved working with pen and paper.

The bulb-task [22] was a low demanding vigilance task of monotonous routine-type character, measuring attention and short-term memory. The task consisted of four small light bulbs of different colours placed at four different positions on an arch in the periphery of the subject's field of vision. Each of the four bulbs was illuminated at random intervals varying between 9 and 46 s. and in random sequence. The task comprised two parts, and in each part of the task, 20 yellow signals were to be responded to. Each part lasted in total for 40 min, divided into one 10 min and one 30 min version of the task. The subject's task was to respond only when a yellow bulb was illuminated by pressing a response button that matched the colour (red, green or blue) of the light bulb that lit up at a random interval before the yellow light bulb. The correct response-time, erroneous response-time and total response-time and number of correct and erroneous responses were recorded.

Table 1
The experimental set-up

Min	Moment
	20 min rest in a relaxing room
	Q_{SY} and Q_{MO}
	Subject(s) to test chamber, noise exposure starts
0	Saliva sample 1 and Q_{SE}
5	Performance: Simple reaction-time task (6 min), bulb-task (10 min), proof-reading task(25 min), bulb-task (30 min), and search and memory task SAM1 (10 min).
86	Saliva sample 2, Q_{SE} and Q_{MO}
94	Pause
99	Performance: Bulb-task (10 min), proof-reading task (25 min), bulb-task (30 min), simple reaction-time task (6 min), search and memory task SAM1 (10 min), embedded figures task (instructions + task = 24 min) and simple reaction-time task (6 min)
210	Q_{SY} and Q_{MO}
218	Saliva sample 3 and Q_{SE}
223	Noise exposure ends
225	Performance: Nonsense questionnaire
~400	Q_{SY} (filled out at home, 3 h after the end of noise exposure)

Q_{SY} = questionnaire evaluating presence of symptoms; Q_{MO} = questionnaire evaluating mood; Q_{SE} = questionnaire evaluating stress and energy.

The low-memory load version of *the search and memory task (SAM1)* was a low demanding task that previously has been used to assess effects on sustained attention when performing the task in different combinations of noise, night work and meals [23]. The task involved searching through lines of 60 single-spaced pseudo-random capital letters, searching for the occurrence of one target letter defined at the beginning of each line. There were zero to three targets per line and the lines were arranged in sets of six, with four sets on each page. The number of lines searched during a period of 10 min and the percentage of correct and number of erroneous target letters were recorded.

The proof-reading task [24] was a moderately demanding verbal task, requiring sustained attention and concentration. The subject read a printed text for 25 min. The task was to mark errors, typographical and contextual, in the text. The number of lines read, the number of typographical errors detected, the number of contextual errors detected and the total number of correct marks, erroneous marks and total number of marks were recorded.

The simple reaction-time task [25] was a low demanding task of monotonous routine-type character, measuring reaction-time. The subject was instructed to press a button as quickly as possible when a red square appeared on a black screen. The intersignal interval varied between 2.5 and 5.0 s. (mean = 3.75 s.), and the mean reaction-time for each 1-min period was recorded. The task lasted for 6 min. The task has previously been used to evaluate effects of tiredness [4].

The embedded figures task was indended to measure motivation, expressed as time spent trying to solve insoluble tasks. The task has previously been used to evaluate effects on motivation after noise exposure, depending on task load and predictability of the noise [16]. The task consisted of four pages with one complex figure on each page. Five simple figures were shown at the top of each page. The subject's task was to identify which one of the five simple figures, having the same size and orientation, reappeared embedded in the complex one. The tasks on the first and the third pages were insoluble. The maximum time to perform the task was set to 20 min.

The nonsense questionnaire was designed for this study by the author to measure motivational mechanisms. The questionnaire was given to the subject after she had completed the test session and was prepared to go home. She was asked whether she could help us to fill out a rather long questionnaire dealing with her experience of acting as a test person, her work environment and general and specific questions concerning noise. The subject was carefully informed that the questionnaire had nothing to do with the experiment and that it was entirely voluntarily, but that we would be grateful if she could help us. In reality, the questionnaire was of no interest in itself but was used to understand whether the subject was sufficiently motivated to help us after the test session and whether motivation differed between noise conditions. The questionnaire had 21 pages of questions, 13 simple questions and 37 more extensive questions demanding detailed answers. The number of subjects that answered the questionnaire, number of simple and detailed questions answered, estimations of how much each subject wrote on the detailed questions and the total time spent on the questionnaire were recorded.

2.6. Instructions

Before each task, the subject was given both written and verbal instructions about the need to work at her own pace, just as though she was working with the tasks for a whole working day. This was done to put low strain on the subjects, which together with the task demands should emphasize a low workload condition. To minimize subjective influence caused by the attitude to noise, motivation and the individual's own level of expectation before the test sessions, the information about the experiment did not explicitly refer to noise exposure. To avoid stress, the subjects were not permitted to use watches during the test session.

2.7. Questionnaires

A questionnaire evaluating mood was completed before, during and after the test session [26]. The questionnaire consisted of 71 adjectives that described different feelings, classified into the following six mood dimensions: social orientation, pleasantness, activation, extraversion, calmness and control. Each adjective had four response alternatives ranging from "I agree completely" to "I do not at all agree".

Before, directly after and 3 h after the test session, the subject completed questions on the degree of different symptoms, such as headache, tiredness, lack of concentration, irritation, sleepiness and resignation. In the same questionnaire before and directly after the test session, questions were also posed on the occurrence of pressure in the eardrum or head, nausea and the subjects' perception of being in a sociable mood. The answers for the above questions offered five response alternatives ranging from "not at all" to "extremely". Furthermore, after the test session questions were also posed on motivation and annoyance caused by the noise, with five response alternatives ranging from "not at all" to "extremely", and how performance had been affected by noise, temperature or lighting, with seven response alternatives ranging from "major improvement" to "major impairment". Questions were also asked on how interesting the tasks were, with five response alternatives ranging from "very interesting" to "very boring" and how difficult the tasks were, with five response alternatives ranging from "very difficult " to "very easy". One question was also posed on how much effort the tasks required, with five response alternatives ranging from "not at all" to "extremely".

After each saliva sample, the subject answered a questionnaire evaluating stress and energy [27]. The questionnaire consisted of 12 adjectives describing stress and energy, with six response alternatives ranging from "not at all" to "very, very much".

2.8. Saliva sampling and cortisol determination

Three saliva samples were collected and the amount of cortisol was determined to evaluate the response on cortisol level. The samples were taken using a salivette saliva-sampling device (Sarstedt Ltd., Leicester, UK). The subject was asked to chew on a sterile dental swab for exactly 3 min. Samples were kept at -70°C, until analysis. To obtain a proper baseline level [28], the subject was instructed to take nothing by mouth other than water for at least 45 min prior to and during the test session and to avoid stress prior coming to the laboratory. The subject was also instructed to relax for 20 min in the laboratory before the first sample was taken. The noise exposure and test session then started. The first saliva sample served as a baseline value (mean base), the second saliva sample was taken in the middle of the test session and the third and final sample was taken at the end of the test session (see Table 1).

2.9. Matching

On a separate occasion before the test session, the subject learned the procedures and practiced on short versions of the performance tasks for about 1 h during exposure to the reference noise at the A-weighted sound pressure level 35 dB. The results of the proof-reading task and the embedded figures task in the learning session were used to create two noise exposure groups that were as equal as possible with regard to performance. In the proof-reading task, the number of lines read in a 10-min period was registered, and the number of figures solved during a 15-min period was registered in the embedded figures task. Sixteen figures were used, all soluble and all on the same page [29]. Based on these results, four performance groups were created: (a) subjects who read more than 108 lines and solved 11 or more figures; (b) subjects who read more than 108 lines and solved 10 figures or less; (c) subjects who read 107 or fewer lines and solved 11 or more figures; and (d) subjects who read 107 or fewer lines and solved 10 figures or less. The two noise exposure groups were created by randomly placing the subjects from each of the four performance groups into either the reference noise exposure group or the low-frequency noise exposure group. A statistical analysis between subjects placed in the reference noise group and those placed in the low-frequency noise group showed no significant differences regarding number of lines read in the proof-reading task (103 lines vs. 116 lines; $t = 0.129$, $p = 0.230$) or number of figures solved in the embedded figures task (10.8 figures vs. 11.5 figures; $t = -0.531$, $p = 0.598$). There were no significant differences between the noise exposure groups regarding average sensitivity to low-frequency noise (mean value 7.3 in the reference noise group and mean value 7.8 in the low-frequency noise group, $t = 1.250$, $p = 0.219$) or age.

2.10. Test environment

The experiment was carried out in a room measuring 24 m^2, furnished as a working area in a control room. The noise was emitted from four loudspeakers placed in each corner of the room and concealed behind curtains, and a subwoofer, which could reproduce frequencies down to 30 Hz, placed on one of the short sides of the room, also concealed behind curtains. The A-weighted sound pressure level from the background noise due to the test chamber ventilation was below 22 dB, and the sound pressure levels for frequencies less than 160 Hz were below the threshold of normal hearing [30].

Normally, two subjects performed the test session at the same time. They worked individually on the tasks and were not allowed to talk to each other during the test session. The subjects' desks were placed opposite each other in the room with a large screen between the desks. Owing to difficulties in co-ordinating all subjects, 12 of the subjects carried out the test session alone (five subjects in the reference noise condition and seven subjects in the low-frequency noise condition).

2.11. Analysis and statistical methods

The experiment had a 2 (noises) $\times$ 2 or 3 (times) factorial design with repeated measures in the second factor (tasks, questionnaires and saliva samples) and measures of independent groups in the noise factor. Two-way analyses of variance, ANOVA, were performed to evaluate the influence of noise condition and time and their interactions on the different performance tasks, subjective reports and saliva samples. Student's *t*-test for dependent data was used when ANOVA was not suitable. Pearson's correlation analyses were used to identify relationships between performance results, subjective reports and subjective sensitivity.

To correct for baseline values, the subjective reports in the questionnaires were related and analyzed in relation to the initial reports given at the beginning of the test session. Product moment correlations were calculated between the subjective reports, performance and cortisol levels. Square root transformations were made of cortisol levels to counteract skewed distributions. Cortisol levels were expressed as the percentage change in relation to the initial sample in the session (sample 1). The same procedure was also used for reported stress and energy. In the analysis of the relationship between cortisol levels and reported stress and energy, reported stress and energy were related to the corresponding saliva sample. To analyze relationships between cortisol levels, reported stress and energy with other subjective reports, a mean value of samples 2 and 3 was computed to reflect the test session. In order to analyze the relationship of cortisol levels, reported stress and energy with performance, the tasks carried out during the first part of the test session were related to sample 2 and tasks carried out during the second part of the test session were related to sample 3. Student's *t*-test was used to analyze differences between different subjective reports.

Because some subjects misunderstood the instructions, the results of one proof-reading task performed in the second part of the test session and one embedded figures task are missing in the low-frequency noise condition. Four of the 114 simple reaction-time tasks and the number of correctly answered bulbs in two bulb-tasks in the second part of the test session in the low-frequency noise condition are missing because of technical difficulties.

In the bulb-task, a multivariate analysis of variance including both response-time and number of bulbs responded to did not alter the outcome in any way. Consequently, only the results of the separate analyses are reported. In the search and memory task (SAM1), no analysis was made of the erroneous marks, as only five subjects made any erroneous marks.

All analyses were two-tailed, and a p-value below 0.05 was considered statistically significant, while a p-value up to 0.10 is reported as a tendency. The p-values in the analyses of variance are based on degrees of freedom corrected with Greenhouse–Geisser epsilon, when appropriate. To control for multiple comparisons in the correlation analyses, a p-value below 0.01 was set as the limit for being considered as statistically significant. The statistical analyses were carried out using the SPSS software (SPSS base 11.0 for Windows).

3. Results

3.1. Effects of noise on performance

The results of the bulb-task are shown in Table 2. A significantly lower number of bulbs were responded to correctly in the low-frequency noise condition compared to the reference noise condition ($F(1,35) = 4.345$, $p<0.05$). The analysis showed a significant interaction between noise and time on erroneous response-time ($F(1,36) = 6.586$, $p<0.05$). Subjects in low-frequency noise increased their erroneous response-time over time while subjects in reference noise decreased their erroneous response-time over time. The result on the correct response-time showed a tendency towards the same pattern ($F(1,34) = 3.205$, $p = 0.082$).

The results of the search and memory task (SAM1) are shown in Table 3. The analysis showed a significant interaction between noise and time on the number of lines searched through ($F(1,36) = 7.828$, $p<0.01$). The number of lines the subjects searched through the first time the task was carried out was about equal in both noise conditions. The second time the task was carried out, the subjects in the reference noise condition showed a greater improvement than the subjects in the low-frequency noise condition.

The results of the proof-reading task are shown in Table 4. There was a tendency to read a greater number of lines during the low-frequency noise condition ($F(1,35) = 3.774$, $p = 0.060$). As the subjects already exposed to low-frequency noise during learning session read the text somewhat faster, but not significantly faster, the co-variance of the results from the learning session was analyzed in relation to the number of lines read in the test session. However, the

Table 2
The results of the bulb-task

	Reference noise		Low-frequency noise		p-Value	
	First time	Second time	First time	Second time	Main effect (noise)	Interaction (noise × time)
Erroneous response-time (s)	2.1	1.8	2.1	2.4	$p = 0.111$	$p<0.05$
Correct response-time (s)	1.9	1.8	2.0	2.1	$p = 0.172$	$p = 0.082$
Number of correct responses	14.7	14.8	13.8	13.6	$p<0.05$	$p = 0.591$

Table 3
The results of the search and memory task (SAM1)

	Reference noise		Low-frequency noise		p-Value	
	First time	Second time	First time	Second time	Main effect (noise)	Interaction (noise × time)
Number of lines searched	54	69	55	63	$p = 0.595$	$p < 0.01$
Correct marks	96%	96%	96%	95%	$p = 0.611$	$p = 0.918$

Table 4
The results of the proof-reading task

	Reference noise		Low-frequency noise		p-Value	
	First time	Second time	First time	Second time	Main effect (noise)	Interaction (noise × time)
Number of lines read	283	325	350	382	$p = 0.060$	$p = 0.527$
Typographical marks/line	0.034	0.041	0.038	0.038	$p = 0.915$	$p < 0.05$
Contextual marks/line	0.032	0.025	0.030	0.024	$p = 0.556$	$p = 0.575$
Correct marks/line	0.067	0.066	0.068	0.062	$p = 0.815$	$p = 0.320$
Erroneous marks/line	0.043	0.043	0.024	0.025	$p = 0.095$	$p = 0.843$
Total marks/line	0.110	0.108	0.092	0.087	$p = 0.149$	$p = 0.788$

subjects in the test session with low-frequency noise still read a larger number of lines compared to the reference noise condition. For the number of typographical marks per line, a significant two-way interaction was found between noise and time ($F(1,35) = 4.654$, $p < 0.05$). Subjects exposed to low-frequency noise made on average an equal number of typographical marks per line the first and the second time the task was carried out, while subjects exposed to reference noise found a greater number of typographical marks per line the second time the task was done. As can be seen in the table, there was also a tendency to make more erroneous marks per line during the reference noise condition compared to the low-frequency noise condition ($F(1,35) = 2.947$, $p = 0.095$).

No significant difference between noise conditions was found on the simple reaction-time task or the time spent on solving the insoluble figures in the embedded figures task.

Fifteen subjects (79%) filled out the nonsense questionnaire after exposure to the reference noise while 11 subjects (58%) filled out the nonsense questionnaire after exposure to the low-frequency noise. The difference between noise conditions was not significant ($\chi(1) = 1.949$; $p = 0.163$).

3.2. Effects of noise on annoyance and subjective symptoms

A significant two-way interaction was found between noise and time on reported irritation ($F(1,35) = 5.802$, $p < 0.05$). As can be seen in Fig. 2, subjects exposed to low-frequency noise reported a higher value on irritation directly after but not before the test session compared with subjects exposed to the reference noise. No significant effect of noise condition was found for the other symptoms.

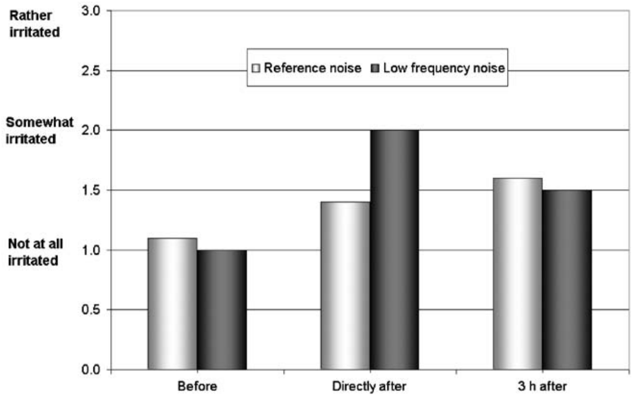

Fig. 2. Average reported perception of irritation for the reference noise condition and the low-frequency noise condition.

The average experience of being motivated was 2.5 in the reference noise condition and 2.0 in the low-frequency noise condition ($t = 1.486$, $p = 0.146$). The corresponding means of reported annoyance were 3.2 and 3.4 ($t = -0.617$, $p = 0.541$).

No significant main effect of noise condition was found on reported mood or reported performance impairment due to noise, lighting or temperature ($t = -0.754$, $p = 0.455$; $t = 0.662$, $p = 0.512$; $t = -1.118$, $p = 0.271$).

The subjects in the low-frequency noise condition rated the bulb-task and the simple reaction-time task as less difficult compared with the subjects reports in the reference noise condition (1.5 vs. 2.0, $t = 2.041$, $p < 0.05$; 1.1 vs. 1.6, $t = 2.486$, $p < 0.05$). Furthermore, subjects in the low-frequency noise condition rated the bulb-task to require less effort compared to subjects in the reference noise condition (1.8 vs. 2.4, $t = 2.072$, $p < 0.05$). No significant main effect of noise condition was found for the perceived difficulty or perceived effort in any of the other tasks, and no significant main effect of noise condition was found in the subjects' reports of how interesting they perceived the performance tasks to have been.

3.3. *Cortisol levels and subjective stress and energy*

The analyses of the saliva samples showed that the cortisol levels decreased significantly during the test session in comparison with the mean base sample ($F(1, 36) = 20.420$, $p < 0.001$), in accordance with expectations based on the known circadian rhythm. There was no significant effect of noise condition ($F(1, 36) = 0.578$, $p = 0.452$). No significant effect of noise condition was found for reported stress or energy ($F(1, 36) = 0.001$, $p = 0.981$; $F(1, 36) = 0.033$, $p = 0.856$), and there were no significant relationships between cortisol levels and reported stress or energy.

3.4. *Relationships*

A relationship was found between a decrease in motivation and lack of concentration after work in both noise conditions (low-frequency noise $r_{xy} = 0.676$, $p < 0.001$; reference noise $r_{xy} = 0.634$, $p < 0.005$). Noise annoyance in the low-frequency noise condition was positively correlated to lack of concentration, sleepiness and pressure in the eardrums ($r_{xy} = 0.616$, $p < 0.005$; $r_{xy} = 0.672$, $p < 0.005$; $r_{xy} = 0.621$, $p < 0.005$), while these relationships were not found for the reference noise condition. No other relationships that reached significant level were found.

3.5. Effects of the test situation as such

The working situation per se introduced effects that occurred independently of noise exposure. This section describes the most important effects. The reaction-time in the simple reaction-time task was longer the second time the task was carried out as compared to the first and third times. The subjects read more lines the second time they performed the proof-reading task and also found more typographical marks per line and fewer contextual marks per line. A larger number of lines were searched the second time the search and memory task (SAM1) was performed. As regards the subjective reports, higher reports of tiredness, headache, lack of concentration and sleepiness were given during the test session as compared to before and 3 h after the end of the test session. The subjects' perception of being in a sociable mood and the mood dimensions of activation and extroversion decreased over time during the test session. The subjective perception of stress was higher during and after the test session and the subjective perception of energy was lower during and after the test session.

4. Discussion

4.1. Material and methods

The A-weighted sound pressure level, performance tasks and instructions to the subjects were chosen to create conditions representative of a normal workday in a control room environment. The tasks were of a primarily monotonous routine-type character, chosen to be sensitive to tiredness and motivation. The results of the saliva samples and the subjective reports confirmed that the aim of creating a low demanding working situation was attained.

4.2. Performance tasks

The hypothesized mechanisms of negative effects of low-frequency noise were poor attention, increased tiredness and negatively affected motivation. The hypotheses of poorer attention were partly supported by the results of the bulb-task, the search and memory task (SAM1) and the proof-reading task, while the results of the simple reaction-time task, the embedded figures task and the nonsense questionnaire did not lend support to the hypotheses of increased tiredness and negatively affected motivation. The difference found between noise conditions on work performance was not reflected by the subjective reports.

The most important findings in the study were that the low-frequency noise had a negative effect on the performance of the bulb-task. It has previously been found that performance on monotonous, machine-paced tasks, such as signal-monitoring tasks comparable with the bulb-task, are tasks that are most sensitive to wakefulness changes [31]. Previous studies [18,22] found no effects on the bulb-task related to low-frequency noise. In those studies, however, the bulb-task was used as a secondary task in order to emphasize a high workload and a high stress level and it is thus likely that the extra effort exerted by the subjects counteracted any effects of reduced attention. The results here indicate that subjects in the low-frequency noise condition needed a longer response-time to make decisions, whether they were correct or erroneous, and that, despite this longer response-time, they gave a greater number of erroneous answers. It can therefore be hypothesized that low-frequency noise made the subjects less attentive, which then negatively affected their performance.

It has previously been found that due to practice and learning, subjects working with the search and memory task (SAM1) generally become faster over time [23]. Although there was an increase in work speed in both noise conditions the second time the task was performed, fewer lines were searched in the low-frequency noise condition than in the reference noise condition. An explanation for this effect could be decreased attention and/or increased tiredness, during low-frequency noise exposure, although increased tiredness was not supported by the subjective reports of tiredness. A second explanation may be that the low-frequency noise impaired the ability to learn. Support for this effect was found in a previous study [18]. In that study, a larger decrease in response-time over time was found during work with a verbal grammatical reasoning task in the reference noise, as compared to the low-frequency noise condition.

Proof-reading tasks has in many studies before been used to measure effects of noise exposure, but rather inconsistent results have been found on number of different marks made see e.g. Refs. [32–34] and how fast the text was read see e.g. Refs. [32,33]. In this study, subjects exposed to the reference noise found more typographical marks per line the second time the task was performed. Subjects in the low-frequency noise condition read the text somewhat faster and seemed to make less erroneous marks per line. The larger amount of number of lines read and lower amount of erroneous marks made by the subjects working in the low-frequency noise condition could indicate that they performed the task better in this noise condition. On the other hand, as the subjects at the same time failed to find the errors in the text they were instructed to find, another interpretation of the results is that the subjects treated the text material less thoroughly when working with the task during exposure to low-frequency noise. Strategies to cope with extra load from e.g. noise exposure could be to work more rapidly and less thoroughly [3,35,36], to work at a slower working speed or to add extra effort to complete the task correctly [3]. Another strategy could be the reverse, where a person continues to work as before even though the working condition has changed.

The simple reaction-time task has previously been found to be sensitive to fatigue caused by noise [4]. No effect on the simple reaction-time task related to noise condition was detected in this study. The reaction-time in both noise conditions was somewhat longer the second time the task was carried out, indicating greater tiredness over time. The noise thus seems to have had less importance than the exposure time.

The embedded figures task and the nonsense questionnaire were included to evaluate noise effects on motivation. Two previous studies have found a noise effect on the performance of embedded figures task [15,16] whereas the nonsense questionnaire has not been used in any previous study. There is no obvious explanation for the absence of effects, but different kinds of noises and noise levels may be part of the explanation.

4.3. Questionnaires

In a previous study [18], subjects who worked under high workload with mostly high demanding cognitive verbal tasks rated the low-frequency noise as more annoying than the reference noise. In this study, using a different design with a somewhat higher A-weighted sound pressure level, but the same noises, different kind of performance tasks and a lower workload, no significant difference between noise conditions on annoyance was found. The difference in task demands and strain put on the subjects could be the explanation for the different results, which together in this study created a lower workload than in the previous study. This is in accordance with the suggestions that noise tends to be more annoying when complex tasks are being carried out [1]. It should also be noted that there are previous studies that have not found any effect on annoyance in spite of performance impairments [2].

Subjects in the low-frequency noise condition reported higher values on irritation than subjects in the reference noise condition. No other effects on subjective reports caused by noise condition were found; however, irrespective of noise, higher reports of tiredness, headache, lack of concentration and sleepiness were given during the test sessions compared to before and 3 h after the end of the test sessions. Noise annoyance in the low-frequency noise condition was related to lack of concentration, sleepiness and pressure in the eardrums. Similar observations of relationships between annoyance due to low-frequency noise and subjective symptoms have been found in a previous study [18]. Although the subjective symptoms were not directly related to noise condition, the relationships between the subjective symptoms and annoyance in the low-frequency noise condition indicate a negative influence by the working environment.

4.4. Saliva sampling and cortisol determination

The expected decrease of cortisol levels during the test session was found, although the decrease did not differ between noise conditions. In a similar test situation, behavioural after-effects and elevated epinephrine levels were found after 3 h of work with clerical tasks during exposure to simulated open office noise [15] without any effect on subjective stress, urine cortisol or norepinephrine.

4.5. The relevance of the results

As the experiment was carried out under laboratory conditions, using a sample of young, normal hearing, female students, the relevance of the results for normal working conditions must be evaluated with care. One question is whether general conclusions could be drawn on low-frequency noise or whether the effects found in this study and the previous studies [18,19] are produced only by the specific low-frequency noise used in these studies. To answer such questions, studies evaluating the specific importance of different sound characteristics, e.g. modulation frequency, and their relevance for performance effects and annoyance need to be conducted. The effects on performance in this study were rather modest in absolute terms; however, if the results are valid for normal work conditions the practical relevance of missing one or two signals and/or having a longer response-time may be critical and of great importance in certain situations.

In conclusion, the major finding was that low-frequency noise negatively influenced performance on two tasks sensitive to reduced attention and on a proof-reading task, while performance of tasks aimed at evaluating motivation were not significantly affected. The negative effects on performance were not reflected by the subjective reports; however, noise annoyance in the low-frequency noise condition was related to lack of concentration, sleepiness and pressure in the eardrums. As could be expected, no difference between noise conditions was seen on cortisol levels or subjective stress.

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