# Low frequency noise "pollution" interferes with performance

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**To study the possible interference of low frequency noise on performance and annoyance, subjects categorised as having a high- or low sensitivity to noise in general and low frequency noise in particular worked with different performance tasks in a noise environment with predominantly low frequency content or flat frequency content (reference noise), both at a level of 40 dBA. The effects were evaluated in terms of changes in performance and subjective reactions. The results showed that there was a larger improvement of response time over time, during work with a verbal grammatical reasoning task in the reference noise, as compared to the low frequency noise condition. The results further indicated that low frequency noise interfered with a proof-reading task by lowering the number of marks made per line read. The subjects reported a higher degree of annoyance and impaired working capacity when working under conditions of low frequency noise. The effects were more pronounced for subjects rated as high-sensitive to low frequency noise, while partly different results were obtained for subjects rated as high-sensitive to noise in general. The results suggest that the quality of work performance and perceived annoyance may be influenced by a continuous exposure to low frequency noise at commonly occurring noise levels. Subjects categorised as high-sensitive to low frequency noise may be at highest risk.**

*Keywords: Low frequency noise, performance, annoyance, noise sensitivity*

## Introduction

The introduction of modern technology and computerised machinery in industry has reduced the occurence of high noise exposure situations but introduced other types of occupational noise of more moderate noise levels. In many cases, the change to moderate noise levels has been achieved by building insulated control rooms from which industrial processes are supervised. The noise in such control rooms is often dominated by noise in the frequency range of 20 to 200 Hz (low frequency noise) caused by ventilation and air conditioning systems as well as by the lower attenuation of the low frequencies by the walls, floors and ceilings. Other occupational environments, such as office areas, house a number of noise sources that generate low frequency noise at moderate levels. Major examples of such sources are network installations, ventilation, heating and air-conditioning systems.

There is a growing body of data showing that low frequency noise has effect characteristics that are different from other environmental noises of comparable levels [Persson Waye 1995; Berglund et al. 1994]. Symptoms that have been reported in connection with annoyance caused by low frequency noise and which may also reduce the working capacity are fatigue, headaches and irritation [Tokita 1980; Nagai et al. 1989; Persson Waye and Rylander 2001]. Although the importance of low frequency noise has been acknowledged in the WHO document on community noise [Berglund et al. 2000], the or a reference noise. Based upon responses to questionnaires, the subjects were categorised as having a high- or low sensitivity to noise in general and low frequency noise in particular. Their subjective reactions to the test session were recorded using questionnaires. To assess stress, saliva samples were taken and the amount of cortisol was determined. After each saliva sample, the subjects answered a questionnaire evaluating their perceived stress and energy [Kjellberg et al. 1989]. These latter data will be reported elsewhere [Persson Waye et al. 2001].

## Noise exposure

The exposure noises were two ventilation noises, one of a predominantly flat frequency character (reference noise) and the other of a predominantly low frequency character (low frequency noise). The reference noise was recorded from a ventilation installation. To obtain the low frequency noise, sound pressure levels in the frequency region of 31.5 to 125 Hz were increased using a digital sound processor system [Aladdin interactive workbench, Nyvalla DSP Stockholm, Sweden]. Furthermore, the third octave band centred at 31.5 Hz was amplitude-modulated with an amplitude frequency of 2 Hz. Both noises had a level of 40 dBA.

Figure 1 shows the equivalent third octave band sound pressure levels for the two noises, measured at the position of the subjects' head.

## Subjects

For the study, 19 female and 13 male (n=32) subjects with an average age of 23.3 (Sd= 2.58) were recruited by advertising. Each person underwent a hearing test [SA 201 II Audiometer, Entomed, Malmö, Sweden] and only persons with normal hearing (<20 dB HL) were allowed to participate. The subjects were given financial compensation for their participation.

## Subjective sensitivity to noise

To assess sensitivity to low frequency noise and sensitivity to noise in general, two questionnaires were answered after the last test session. On the basis of the subjects' scores on two of the questions in the questionnaires, subjects were categorised as highly sensitive (high-sensitive) or less sensitive (low-sensitive)

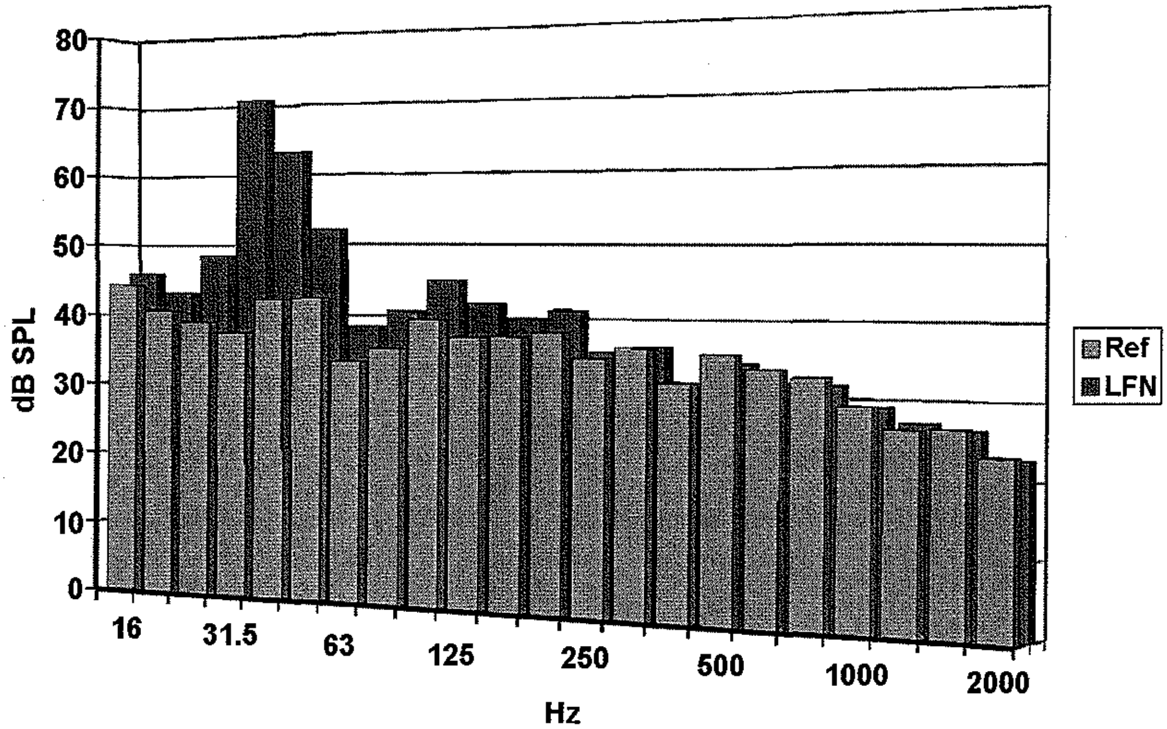

**Figure 1. Third octave band sound pressure levels of the reference noise and the low frequency noise (dark coloured bars) used during the test sessions, measured at the position of the subjects head.**

bookshelf. Behind the subject was a window with a closed Venetian blind so the person could be observed during performance. The sound was produced by four loudspeakers, hidden behind curtains and placed in each corner of the room. To amplify the low frequency noise, there was a subwoofer (ace-bass B2-50) which can reproduce frequencies down to 20 Hz. The background noise from the test chamber ventilation was less than 22 dBA, and the sound pressure levels for frequencies below 160 Hz were below the threshold of normal hearing [ISO 389-7:1996].

## Performance tasks

In the experiment, four performance tasks were used. Tasks I, II and IV involved working with a computer and task III involved working with pen and paper. The tasks were chosen in order to involve different levels of mental processing. A high workload was generated by instructing the subjects to work as rapidly and accurately as possible. All performance tasks were carried out twice in each test session, once in phase A and once in phase B (see Table 2).

Task I was a simple reaction-time task and is part of the SPES computer test battery [Gamberale et al. 1989]. The subject was told to press a button as quickly as possible when a red square appeared on a black screen. Mean response times for the five, one-minute periods were recorded.

Task II was a short-term memory task. A set of numbers, e.g. 1 2 5 4, was shown on the computer screen. This set was followed by one number, e.g. 7. The subject was to respond, by yes or no, to whether that number was also present among the set of numbers shown earlier. The total response time and total number of correct and false answers were recorded.

Task II was carried out together with a secondary task, the bulb-task, previously used by Persson Waye et al. [1997]. This task consisted of four differently coloured light bulbs, placed at four different positions on an arch at the periphery of the subject's visual field. Each of the four bulbs was illuminated at random intervals and in random sequence. The subjects' task was to respond only when a yellow bulb was illuminated, after which the subject was instructed to, as quickly as possible, push a response button that matched the colour (red, green or blue) of the light bulb that was illuminated *prior* to the yellow light bulb. The set-up used for task II with a primary and secondary object was designed to require the subject's full attention and concentration. The total response time and number of correct and erroneous responses were recorded.

Task III was a proof-reading task [Landström et al. 1997]. The subject read a text, printed on paper, for exactly ten minutes, and the task was to mark errors in the text. The number of lines read, correct marks, erroneous corrections and the total number of marks were recorded and related to the number of lines read for each subject; correct marks per line, erroneous corrections per line and total number of marks per line.

Task IV was a computerised verbal grammatical reasoning task, translated into Swedish from the original version [Baddeley 1968]. The task is based on grammatical transformation of sentences that have various passive, active, negative and positive structures. The subject was instructed to respond to whether a sentence is false or true in relation to a letter combination following the sentence. For example:

| | | **True** | **False** |
|---|---|---|---|
| *A is not followed by B* | *BA* | √ | |
| *B precedes A* | *AB* | | √ |

The set-up used for task IV was designed to impose a high mental workload. In total, the task consisted of eight blocks of 32 sentences. The mean response time for the eight blocks and the number of correct and false answers were recorded.

## Questionnaires

Following tasks II, III and IV, a questionnaire was administered to evaluate how much effort the subjects judged had used in order to perform each task. The subject could choose between five response alternatives ranging from "none at all" to "extremely".

after the experiment, questions were posed concerning headaches, pressure over the eardrum or head, occurrence of nausea, lack of concentration, irritation, tiredness, dizziness, irritation in eyes or throat or a sensation of unpleasant taste. The subject could choose between five response alternatives ranging from "not at all" to "extremely".

### Experimental design and procedure

The experiment had a 2 (noises) × 2 (phases) × 2 (sensitivity groups) factorial design with repeated measures in the first two factors with independent groups representing the sensitivity factor. In the analyses of the simple reaction-time task and the verbal grammatical reasoning task, a fourth factor, time blocks within the task, was added.

On a separate occasion before the main test session, the subjects learned the procedures and practised on short versions of the performance tasks for about one hour with the reference noise at 35 dBA. Before each task, both written and verbal instructions were given to emphasise the need to "work as rapidly and accurately" as possible. The subjects were also informed that, if needed, they could communicate with the research director through a microphone on the desk.

In the study, each subject took part in two test sessions, on separate days and always in the afternoon. The total exposure time was on average 2 hours and 10 minutes with a variation of ±9 min. The variation was due to the difference in the individuals' performance time carrying out task IV during phase B.

Of the 64 test sessions, 37 started at 12.30, and 27 started at 15.00. The proportion of subjects starting at 12.30 and 15.00 for the two noise conditions was similar, 18/14 for the low frequency noise condition and 19/13 for the reference noise condition. During each test session, the subjects worked with four performance tasks and were exposed to the reference noise or the low frequency noise. A detailed plan of the experimental set-up is found in Table 2. Half of the subjects started with the reference noise and the other half with the low frequency noise. To minimise subjective influence caused by the attitude to noise, motivation and the individual's level of expectations before the test sessions, the written and verbal information about the experiment did not explicitly refer to noise exposure.

### Analysis and statistical methods

Analyses of variance, ANOVA, were performed to evaluate the influence of noise exposure, time, subjective sensitivity and their interactions on the different performance tasks and subjective ratings. The p-values are based on degrees of freedom corrected with Greenhouse-Geisser epsilon, when appropriate. To evaluate the difference of means for specific periods, a Student's t-test for dependent data was applied. Correlations between subjective data and performance were done using Pearson's correlation analysis. All tests were two-tailed, and a p-value of $<0.05$ was considered statistically significant, while a p-value up to 0.10 is reported as a tendency.

The statistical analyses employed SPSS [SPSS base 10.0 for Windows].

### Results

No significant interaction of noise and gender was found for the subjective estimations or for any of the performance tasks.

### Performance

No significant main effect of noise condition on reaction-time in the *simple reaction-time task* was found ($F(1,29)=1.952$, $p=0.173$).

A tendency to a two-way interaction in reaction-time was found between noise and sensitivity to noise in general ($F(1,29)=4.141$, $p=0.051$). Subjects high-sensitive to noise in general had a somewhat longer reaction-time during the low frequency noise condition compared to the reference noise condition, while the low-sensitive subjects had a similar reaction-time during both noise conditions.

**Table 5. The results from the proof-reading task for the two noise conditions, for all subjects and for the two categorisations of noise sensitivity. (NG - Noise in General; LFN - Low Frequency Noise)**

| | | **Reference noise** | | **Low freq. Noise** | |
|---|---|---|---|---|---|
| | | *Phase A* | *Phase B* | *Phase A* | *Phase B* |
| **Number of lines read** | **All subjects** | **134** | **133** | **136** | **137** |
| | High-sensitive LFN[3] | 126 | 131 | 132 | 129 |
| | Low-sensitive LFN[3] | 144 | 136 | 141 | 148 |
| | High-sensitive NG[4] | 128 | 135 | 139 | 134 |
| | Low-sensitive NG[4] | 139 | 132 | 133 | 140 |
| **Correct marks/line** | **All subjects** | **0.07** | **0.07** | **0.07** | **0.06** |
| | High-sensitive LFN | 0.07 | 0.063 | 0.07 | 0.06 |
| | Low-sensitive LFN | 0.08 | 0.07 | 0.07 | 0.07 |
| | High-sensitive NG | 0.07 | 0.07 | 0.07 | 0.06 |
| | Low-sensitive NG | 0.07 | 0.06 | 0.07 | 0.07 |
| **Erroneous corrections/line** | **All subjects[1]** | **0.06** | **0.06** | **0.06** | **0.04** |
| | High-sensitive LFN | 0.05 | 0.05 | 0.06 | 0.04 |
| | Low-sensitive LFN | 0.06 | 0.07 | 0.06 | 0.04 |
| | High-sensitive NG | 0.05 | 0.05 | 0.05 | 0.04 |
| | Low-sensitive NG | 0.06 | 0.07 | 0.06 | 0.05 |
| **Total marks/line** | **All subjects[1,2]** | **0.13** | **0.13** | **0.13** | **0.10** |
| | High-sensitive LFN | 0.13 | 0.12 | 0.13 | 0.10 |
| | Low-sensitive LFN | 0.13 | 0.14 | 0.13 | 0.11 |
| | High-sensitive NG | 0.12 | 0.12 | 0.12 | 0.09 |
| | Low-sensitive NG | 0.13 | 0.13 | 0.14 | 0.11 |

**[1] : A significant two-way interaction between noise and phase.**
**[2] : A significant difference between the phases.**
**[3] : A significant three-way interaction between noise, phase and sensitivity to low frequency noise.**
**[4] : A significant three-way interaction between noise, phase and sensitivity to noise in general.**

During the bulb-task, Table 4, subjects high-sensitive to low frequency noise had, regardless of noise exposure, a longer response time than low-sensitive subjects (2674 ms compared with 2150 ms, F(1,30)=7.545, $p<0.01$). No significant difference was found for subjects categorised according to general noise sensitivity.

The results of the *proof-reading task* are given in Table 5.

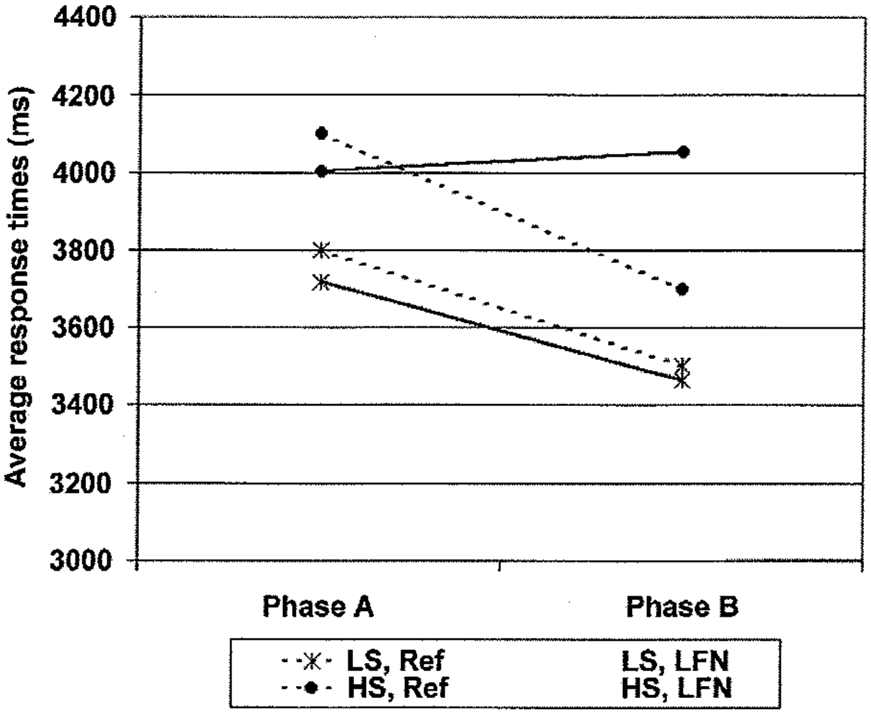

**Figure 3. Average response times (ms) of the verbal grammatical reasoning task in phases A and B for subjects high-sensitive (HS) or low-sensitive (LS) to low frequency noise, during exposure to reference noise and low frequency noise.**

two-way interaction between noise and phase was significant (F(1,31)=5.750, $p<0.05$).

Subjects high-sensitive to low frequency noise had on average a similar response time between noises in phase A. Figure 3 shows that the difference in response time during low frequency noise and reference noise conditions was larger in phase B, and a tendency to a three-way interaction between low frequency noise sensitivity, noise and phase was found (F(1,30)=3.319, $p=0.078$). For subjects categorised as high-sensitive to noise in general, no difference between the noise conditions was detected.

In summary, the main results from the performance tasks were that during work with the proof reading task a lower number of erroneous marks as well as total marks were made during low frequency noise. During work with the verbal grammatical task subjects showed a greater improvement over time during reference noise exposure compared to low frequency noise exposure.

**Table 6. The average value of rated effort for three of the tasks, for all subjects and for the two different noise conditions.**

| *Noise condition* | **Short-term memory task** | **Proof-reading task** | **Verbal gram. reasoning task** |
|---|---|---|---|
| **Reference noise** | 3.2 | 2.7 | 3.8 |
| **Low freq. noise** | 3.2 | 2.9 | 3.8 |

Low frequency noise was on average considered to impair the working capacity more than the reference noise (5.2 versus 4.8; F(1,31)=6.808, $p<0.05$). When the data was subdivided into the two noise sensitivity groups, no significant effect due to noise condition could be detected.

No significant main effect of noise condition was found for the mood dimensions. There was, however, a significant three-way interaction between noise, phase and low frequency noise sensitivity (F(1,29)=4.352, $p<0.05$) for perception of "being in control" (Figure 4). The figure demonstrates that the high-sensitive subjects' perception of being in control was lower after (3.3), as compared to before (3.4) the exposure to low frequency noise. The opposite results were found for low-sensitive subjects (3.5 after compared to 3.4 before). A tendency to the same three-way interaction, between noise, phase and low frequency noise sensitivity, was present for "activation" (F(1,29)=3.837, $p=0.06$). The interaction showed a lower value for perception of activation during both noise conditions for subjects high-sensitive and subjects low-sensitive to low frequency noise, but the decrease was greater for high-sensitive subjects during the low frequency noise condition. However, when the analysis on control and activation was conducted with subjects categorised according to general noise sensitivity, these effects were not present.

No significant main effect of noise condition was found for the different symptoms.

In summary, the main results from the subjective estimations were that the low frequency noise was rated as more annoying and also considered to impair working capacity more than the reference noise. No direct effects of noise condition for symptoms were found.

### Relations between performance and subjective estimations

Impaired working capacity due to reference noise exposure was negatively correlated to number of lines read in phase A (rxy -0.495, $p<0.005$).

A significant correlation was also found between rated tiredness and response time in the verbal grammatical reasoning task in phase B during low frequency noise (rxy=0.524, $p<0.005$). For the reference noise, there was a correlation between response time in the simple reaction-time task in phase B and headaches (rxy=0.517, $p<0.005$).

Impaired working capacity due to low frequency noise exposure was significantly correlated to lack of concentration (rxy=0.507, $p<0.005$), nausea (rxy=0.460, $p<0.01$), tiredness (rxy=0.471, $p<0.01$) and a feeling of pressure on the head (rxy=0.494, $p<0.005$). No significant correlation between noise impairment due to reference noise and symptoms was found.

Annoyance due to low frequency noise was correlated to subjective estimation of the following symptoms: a feeling of pressure on the head (rxy=0.664, $p<0.001$), tiredness (rxy=0.519, $p<0.005$), dizziness (rxy=0.519, $p<0.005$), and lack of concentration (rxy = 0.537, $p<0.005$). Reference noise annoyance was correlated only to nausea (rxy=0.522, $p<0.005$).

In summary, relationships between annoyance respectively impaired performance and several symptoms were found after work in low frequency noise, while a relationship between annoyance and nausea was found after work in reference noise.

## Discussion

The experiment was designed to test the effects of low frequency noise in a situation requiring an increased level of attention and awareness for a fairly prolonged time period. As the experiment was performed under laboratory conditions, the relevance of the results for normal working conditions must be evaluated with care. Alterations in performance found under experimental conditions could incorporate a bias induced by the experimental situation and particularly by the acute exposure conditions [Rylander and Persson Waye 1997]. On the other hand, tiredness and decrease in performance induced by a particular environmental stimulus, in this case low frequency noise, would probably compared with exposure to traffic noise at 90 dB lin, or silence. The effects were especially pronounced during the last 10 minutes of the total 30-minutes exposure. Some support for impaired performance caused by low frequency noise was also given by Benton and Robinson [1993]. Previous studies are thus in agreement with the findings presented here, but further studies need to be carried out to evaluate more specifically how low frequency noise affects performance and which tasks or situations that are most vulnerable for noise interference.

The results do not give direct support for the hypothesis that low frequency noise would induce different symptoms that could impair performance. No direct effects of noise condition on symptoms, or clear relationships between symptoms and performance effects, were found. However, the relationships between symptoms and annoyance respectively, symptoms and impaired performance, were particularly frequent after work in the low frequency noise condition, while for the reference noise a relationship was found only between annoyance and nausea. Although the study is not able to predict whether symptoms impair performance or whether the strain of performing during the low frequency noise condition could lead to a development of symptoms, the findings support a link between symptoms and the experience of impaired performance.

The reasons for choosing the specific low frequency noise used in this study was to achieve a noise that resembled a realistic ventilation noise, which often includes a tonal component and a modulation characteristic [Broner 1994]. The effects observed after low frequency noise could be related to specific acoustical characteristics such as amplitude modulation and the tonal character at 31.5 Hz. In one study, the presence of modulations was found to lead to increased sleepiness [Persson Waye et al. 1997], but the influence of a tonal character in the low frequency range has been shown to be of little or no importance for annoyance, reduced wakefulness or performance [Landström et al. 1991; Landström et al. 1995; Holmberg et al. 1993]. While the presence of amplitude modulations thus could have increased the effects, the tonal character was of less importance.

Subjects high-sensitive to low frequency noise generally performed less well and also reported the highest annoyance due to low frequency noise. In other studies, subjects high-sensitive to noise in general have been found to have the lowest performance accuracy during exposure to traffic noise [Belojevic et al. 1992]. Interestingly, this study also indicate that the response between the two categorisations of sensitivity to low frequency noise and sensitivity to noise in general were partly different. Some of these differences were found regardless of noise exposure, such as the difference in response time in the simple reaction-time task found using the categorisation of sensitivity to low frequency noise, while this difference was not found using the categorisation of sensitivity to noise in general. Other differences were related to noise exposure, such as the longer response time found in phase B during low frequency noise on the verbal grammatical reasoning task, for subjects high-sensitive to low frequency noise, while no difference between noise conditions was found using the categorisation according to sensitivity to noise in general. Differences related to noise exposure were also found for some of the subjective responses such as a higher rating of annoyance and lower perception of control among subjects high-sensitive to low frequency noise, while this difference was not found using the categorisation according to sensitivity to noise in general.

While the results from the study show that subjects categorised as high-sensitivity to noise in general or to low frequency noise generally gave a higher subjective rating of annoyance and impaired working capacity, the difference caused by noise exposure upon performance and subjective estimations was most obvious among subjects categorised with regard to sensitivity to low frequency noise. This agrees with previous observations that low frequency noise sensitivity is a specific issue. The validity and practical

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