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THE PREVALENCE OF ANNOYANCE AND EFFECTS AFTER LONG-TERM EXPOSURE TO LOW-FREQUENCY NOISE

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A cross-sectional questionnaire and noise measurement survey was undertaken among 279 randomly chosen persons exposed to noise from heat pump/ventilation installations in their homes. The aim was to evaluate the prevalence of annoyance, disturbance of rest and concentration and the presence of psycho-social and medical symptoms in relation to noise exposure. Of the sample, 108 persons were exposed to a noise classified as of a low-frequency character (low-frequency noise exposed). As controls were chosen 171 persons living in similar residential areas, but exposed to a noise classified as of a mid-frequency character. The results showed that the prevalence of annoyance and disturbed concentration and rest was significantly higher among the persons exposed to low-frequency noise as compared to controls. Annoyance was suggested to be related to the sound pressure levels of the dominant low frequencies. The dB (A) noise levels did not predict annoyance. No significant differences in medical or psycho-social symptoms were found between the low-frequency noise exposed persons and controls. Among persons reporting themselves to be "rather" or "very" annoyed by low-frequency noise due to the heat pump/ventilation installations, a higher extent of psycho-social symptoms, sleep disturbance and headaches was found.

1. INTRODUCTION

Low-frequency noise is an environmental pollutant of increasing importance. Many sources in the living and working environment, such as ventilation systems, fans, heat pumps, diesel engines, pumps and compressors, emit noise with a dominant proportion of frequencies in the low-frequency region up to 200 Hz. Data in the literature suggest that low-frequency noise has effect characteristics that are different from other kinds of environmental noise at comparable levels.

The results from a previous questionnaire study show that a large proportion of complaints directed to the environmental health authorities was due to low-frequency noise [1]. Complaints of low-frequency noise from fans, ventilation systems, heat pumps and heavy vehicles comprised 71% of the total number of complaints of noise. It has also been shown in several case studies that complaints of low-frequency noise occur, even though the noise levels in dB (A) are within noise limits for the areas (see, for example references [2–5]). The case studies have included only a small number of persons, usually one or two households. Apart from these, there is little information available as to the presence of annoyance and symptoms in populations after long-term exposure to low levels of low-frequency noise.

A field survey was therefore undertaken among persons exposed to low-frequency noise in their homes. The aim was to evaluate the presence of annoyance and disturbance of rest and concentration due to low-frequency noise, as well as the presence of medical and psycho-social symptoms and sleep disturbance in relation to noise exposure.

2. METHODS

2.1. GENERAL OUTLINE

The investigation was a cross-sectional study comprising six residential areas. The areas included houses with exposure to low-frequency noise at high and medium sound pressure levels from heat pumps or heat pump/ventilation systems and houses with a noise of a mid-frequency character at medium and low sound pressure levels from ventilation or from heat pump/ventilation systems. Comparisons were made of the extent of annoyance, interference with rest and concentration and symptoms between the areas with low-frequency noise exposure and areas with mid-frequency noise exposure (controls).

2.2. STUDY AREAS

The criteria for selection of the residential areas was that the areas should comprise modern houses with a comparable economic and social standard. Each area should also comprise homogenous types of houses, built at the same time, with the same layout and with the same ventilation and heat installations. The background outdoor noise level should be low. No area with widespread complaints of the low-frequency noise was included.

To define the areas, floor planning and ventilation construction plans of modern housing areas were studied at the local councils for planning and building permission. In the presumptive areas, sound pressure levels were measured in one or two randomly chosen houses of each type. The families living in these houses were not included in the survey.

Six residential areas were selected. They were located in five municipalities and the housing comprised leased accommodation or privately owned row houses. The low-frequency noise exposure originated from heat pumps or heat pumps connected to ventilation system in areas in the municipalities of Alingsås, Mölndal, Jonsered and Stenungsund.

As low-level controls (C_L), we selected houses in the municipality of Kungälv, which had a ventilation system not connected to a heat pump and the houses in Alingsås and Mölndal, where the heat pumps were installed in a separate part of the house. In these houses, the noise, which was of a mid-frequency character, originated from the ventilation system in the kitchen and the bathroom. As medium level controls (C_M), we selected another residential area in Jonsered, with houses built at the same time as the houses with low-frequency noise and equipped with the same type of ventilation system but with a different layout. It was found during the initial measurements, however, that the ventilation systems in these house types emitted a noise of a mid-frequency character.

2.3. STUDY POPULATION

The study population included each household in the areas. One household member between the age of 18 and 75 years was randomly selected from the population register by the National Central Bureau of Statistics. A further criterion for selection was that the subject should have been resident at that address for at least one year. If there were two or

TABLE 1

Study population

Area	Alingsås C_L	Mölndal C_L	Kungälv C_L	Jonsered C_M	Alingsås LF_M LF_H	Jonsered LF_M	Mölndal F_M	Stenungsund LF_M LF_H
Sample	31†	26†	126	37	41†	38	13†	52
Excluded 1‡	1	4	3	0	8	2	5	2
Remaining sample	30	22	123	37	33	36	8	50
Answers	30	22	90	29	33	30	8	37
Response rate %	100	100	71·4	78·4	100	83·3	100	74

† Indicates number in the first phase of the study. See text.
‡ Excluded from the sample because of e.g moving to new address or hospitalized.

more subjects within the selected age group in the family, the subject with the date of birth nearest to the date of selection was chosen. The study population of the different areas is shown in Table 1.

The response rates in Alingsås and Mölndal were high, as the sample had been preselected through a first questionnaire (see below). The original response rates in these areas were 76 and 67%.

2.4. QUESTIONNAIRE

On the basis of case studies, the underlying assumption in constructing the questionnaire was that low-frequency noise is perceived differently and gives rise to different symptoms than noise of higher frequencies. The questionnaire was therefore developed with the help of in-depth interviews with people sensitive to low-frequency noise. Questions about psycho-social symptoms and sleep disturbance were adapted from questionnaires used to evaluate effects of traffic noise [6]. The questionnaire was then tested in a pilot study.

A first phase of the study was carried out in two residential areas of comparable standard in 1990 (Alingsås and Mölndal). After analysis of the data, the questionnaire was revised to further clarify the questions on annoyance stemming from the different noise sources indoors. The respondents were then asked to answer the revised questionnaire. Only those who answered the revised questionnaire were included in the study (see Table 1). A second phase of the study was performed in four other areas using basically the same questionnaire.

The aim of the questionnaire was masked by presenting the investigation as a general environmental study. In addition to questions related to the domestic environment in general, the questionnaire contained specific questions on annoyance and activity disturbance due to noise from different installations in the building, including heat pumps and ventilation systems. The degree of annoyance was expressed on a four-graded scale from “not annoyed” to “very annoyed” and the degree of disturbance of rest/relaxation and concentration was expressed on a four-graded scale ranging from “not disturbed” to “very disturbed”.

Also included were five questions on perceptions specifically related to exposure to low-frequency noise discomfort. These questions were phrased: “Is there any room in your home where you regularly experience: a pressure build-up on the ear drum, a vibrating feeling in your body, a vibrating feeling in your chest, a feeling of discomfort caused by a low pitch, humming sound or an unexplained feeling of discomfort”. These questions were answered by "yes" or "no". In the analysis the persons who reported yes on one or several on these questions were classified as reporting "discomfort from low-frequency noise".

The section on symptoms included questions on the frequency of more general medical symptoms that could be related to exposure to low-frequency noise, such as nausea, headache, tension or stress, irritation and unusual tiredness. Questions were also posed as to medical symptoms that were not expected to be related to exposure to low-frequency noise, such as pain and stiffness in the neck or in the back and symptoms related to flu/colds. In the first phase of the study, inquiries were made only on symptoms occurring daily or almost daily, while, in the second phase of the study, the symptoms were graded in frequencies: "rarely/never, a few times per month, a few times per week and daily/almost daily". In the analysis, the frequency of a "few times per week" and "daily/almost daily" was, based on a frequency distribution comparison, taken to be comparable with the response of "daily/almost daily".

The extent of psycho-social symptoms was evaluated in eight questions with five verbal alternatives including frequency and degree. Three classes were formed comprising fatigue (questions on mental and physical tiredness), social orientation (questions on social interaction) and well-being (questions on feelings of contentedness and depression). Questions on subjective sensitivity to noise and ventilation noise and habituation to noise, as well as questions on sleep, general health, work and family conditions, were also included.

The questionnaire was distributed by mail and respondents who had failed to answer were sent two reminders.

2.5. NOISE MEASUREMENTS

When the questionnaire study had been completed, noise levels were measured indoors in a random sample of each house type. In the first phase of the study, noise measurements were made in a minimum of two houses of each type using a Nortronic dual channel real-time analyser type 830. It was found that the sound pressure levels were highest in one of the rooms that were nearest to the heat pump installation. In the second phase of the study, residential areas were identified where the noise source effected the rooms more equally. To obtain a more representative value of the noise exposure, the number of noise measurements was increased. Noise measurements were made using a single-channel real-time and frequency analyser B&K 2143. The measurements were made in 4–10 houses of each type, the number depending on the variation in sound pressure levels between the measurements. In total, there were 103 frequency spectra sampled from 20 exposed houses and 26 frequency spectra from 9 control houses in the second phase of the study.

The noise level was measured in the corners of a room at a distance of 0·5 m from the walls and in one other position avoiding the middle position. In the areas exposed to low-frequency noise, measurements were made in one room on each floor. The microphone, B&K 4165, was placed at a height of 1·5 m, and the sampling period was 3 min. During the measurements there were no other activities present in the house.

The equivalent sound pressure levels in third octave bands in the first phase and in 1/12 octave bands in the second phase of the study were stored on a computer disk in the measurement instruments for further analysis. The logarithmic average noise levels (dB (A), dB (B), dB (C)), sound pressure levels and standard deviations of the measurements were calculated for each house type.

TABLE 2

Number of respondents, indoor noise levels and background outdoor noise levels in the different areas

Category	C_L	C_L	C_L	C_M	LF_M	LF_M	LF_M	LF_M	LF_H	LF_H
Area	A	M	K	J	A	M	S	J	A	S
Respondents *n*	30	22	90	29	5	8	25	30	28	12
Measured houses *n*	2	3	5	4	3	3	5	10	3	5
Measurements *n*	9	9	10	16	9	9	18	60	9	25
dB (A)	24	24	27	33	26	27	31	33	33	36
(SD)	(0·85)	(3·5)	(2·9)	(2·7)	(2·8)	(3·5)	(2·3)	(3·8)	(4·0)	(4·1)
dB (B)	31	32	33	38	40	40	41	40	51	45
(SD)	(1·0)	(1·3)	(3·9)	(2·0)	(3·0)	(2·9)	(3·0)	(2·8)	(5·5)	(3·5)
dB (C)	43	41	45	49	49	49	50	49	60	52
(SD)	(1·3)	(3·2)	(5·1)	(3·1)	(3·0)	(5·4)	(4·2)	(3·7)	(7·2)	(3·0)
dB (A) L_{eq} 24 h	44	47	46	44	44	47	46	49	44	46
dB (A) L_{eq} night	41	41	41	43	41	41	43	47	41	43

Between the areas the sound pressure levels varied depending on the noise source and the different house types. On the basis of the sound pressure levels of the dominant low frequencies and their relation to sound pressure levels in the higher frequencies the areas were classified into low-frequency noise areas at high (LF_H) or medium level (LF_M) and control areas. The control areas exposed to a mid-frequency noise were classified into medium (C_M) and low (C_L) levels also on the basis of the weighted noise levels.

The outdoor background noise level was measured by using the same equipment as used for the indoor measurements. The equivalent noise levels in dB (A) were measured during 24 h in 4 h intervals. This made it possible to analyze the change of levels over the day and night. The microphone B&K 4165 was placed outdoor in free field, at a height of 1·5 m at one location in the middle of each area. This was done in order to get a general estimation of the outdoor background noise levels in the different areas as the outdoor noise level may have an influence on the perception and annoyance of low-frequency noise indoors.

The average noise levels indoors and the equivalent dB (A) levels outdoors (24 h and night time) for the exposed and control areas are shown in Table 2. The capital letters refer to the first letter in the name of each area.

The noise levels in dB (A) indoors were similar in C_M, LF_M and in one area of LF_H, while the noise levels was from 0 to 6 dB (A) lower in C_L. The outdoor dB (A) L_{eq} levels were comparable between the areas although a somewhat higher background noise level was found in the LF_M area in Jonsered.

Figures 1 and 2 show the average values and standard deviations of the third octave band sound pressure levels for the different areas divided into areas with low-frequency noise (Figure 1) and control areas (Figure 2). The frequency spectra are related to the normal hearing threshold [7].

The noise spectra in the areas exposed to low-frequency noise were mainly dominated by frequencies at 50, 100 and around 160–200 Hz. The frequency spectra in the control areas were of a flatter character and the frequency content below 80 Hz were well below the normal hearing threshold.

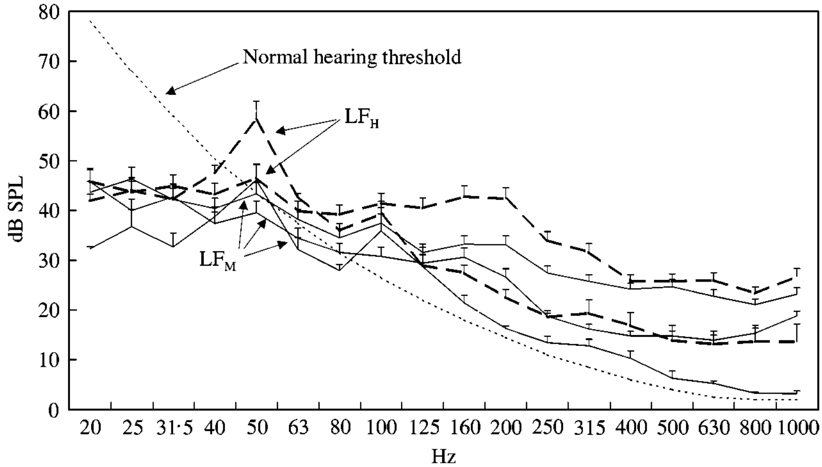

Figure 1. Average value and positive values of standard deviations of the sound pressure levels of third octave bands for the areas exposed to low-frequency noise. The broken lines show the noise spectra of the areas exposed to low-frequency noise at high level. The non-broken lines show the areas exposed to low-frequency noise at medium level. The dotted line shows the normal hearing threshold (ISO 389-7 1996).

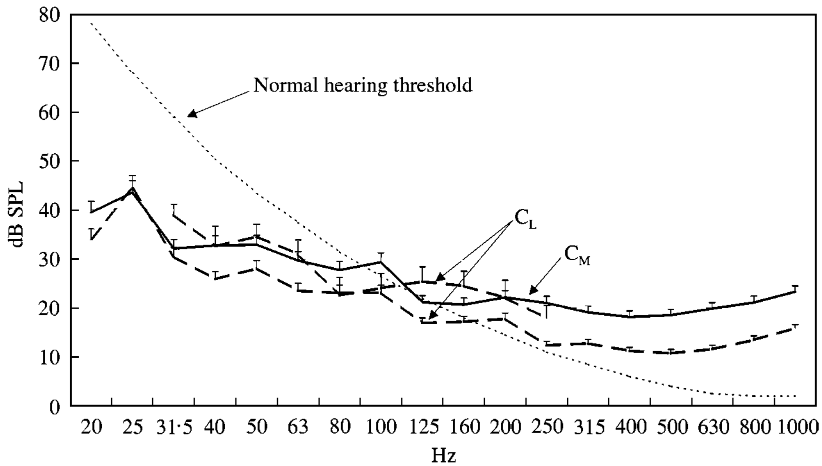

Figure 2. Average value and positive values of standard deviations of the sound pressure levels of third octave bands for the control areas C_M and C_L. The dotted line shows the normal hearing threshold (ISO 389-7 1996).

2.6. STATISTICAL TREATMENT OF DATA

The respondents reporting "rather annoyed" and "very annoyed" were classified as annoyed, and the respondents reporting "no" or "little" annoyance were classified as not annoyed. The same principle was used for disturbed rest/relaxation and concentration. The proportions of respondents expressing annoyance or disturbed activities among exposed and control respondents were compared using confidence analyses of proportions. The proportions of symptoms were compared using the Chi-square test or Fischer's exact test for smaller samples. Comparisons of means were made by Student's t-test. The relationships between average annoyance and average noise levels were analyzed using regression analyses. All tests were two-sided and p values below 0·05 were considered statistically significant.

3. RESULTS

3.1. EXTENT OF ANNOYANCE, DISTURBED CONCENTRATION AND REST/RELAXATION

The proportions of respondents reporting annoyance by heat pump/ventilation noise in the different areas are shown in Figure 3.

Figure 3 shows that the proportions of annoyed respondents were higher in areas with low-frequency noise exposure. In the control areas, the proportions of annoyed respondents were low and similar. The proportion of very annoyed was 0·7% in C_L, 0% in C_M, 2·8% in LF_M and 7·5% in LF_H.

The difference of proportions and the 95% confidence intervals between exposed and control areas are shown in Table 3.

The proportion annoyed was significantly higher in LF_H and LF_M as compared to controls. No difference was found between the low-frequency noise exposed areas (5·3%; 95% CI = −9·7 to 20·3).

To test the annoyance response at similar dB (A) levels, the two control areas with the lowest noise levels as well as one of the areas in LF_H with the highest dB (A) level were omitted from the analysis. The numbers of persons comprised in the different

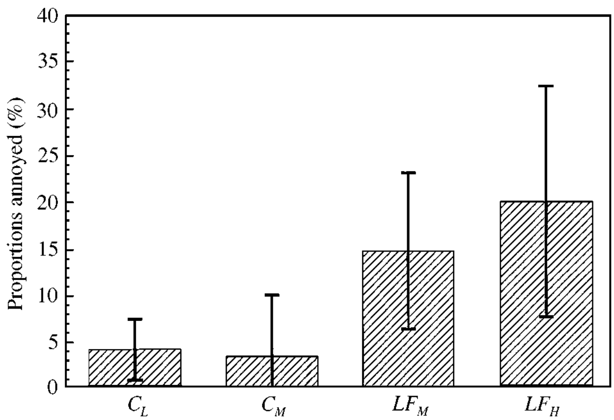

Figure 3. The proportions of respondents reporting annoyance due to heat pump/ventilation noise. Vertical bars indicate the 95% confidence interval of the proportions. Positive values are shown.

TABLE 3

Proportions and 95% confidence intervals of the differences of annoyance for respondents exposed to low-frequency noise and controls

Proportions %	95% confidence interval of the difference
LF_H - C_M 20 - 4·2	15·8% (3·0 - 28·6)
LF_H - C_L 20 - 3·4	16·6% (2·5 - 30·0)
LF_M - C_M 14·7 - 4·2	10·5% (1·5 - 19·5)
LF_M - C_L 14·7 - 3·4	11·3% (0·6 - 22·0)

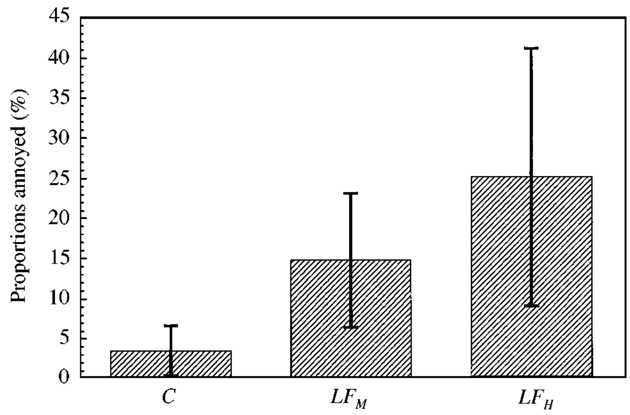

Figure 4. The proportions of persons reporting annoyance in areas of similar dB (A) levels. Vertical bars indicate the 95% confidence interval of the proportions.

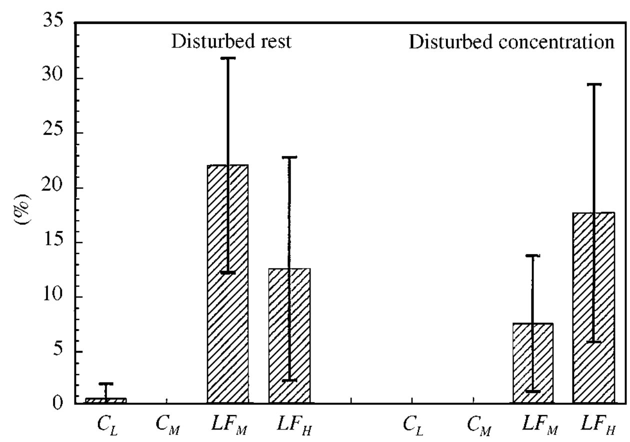

Figure 5. The proportions of respondents reporting disturbed rest/relaxation and concentration due to heat pump/ventilation noise. Vertical bars indicate 95% confidence interval of the proportions. Positive values are shown.

categories in this analysis were 119 in C, 68 in LF_M and 28 in LF_H. The results are shown in Figure 4.

As can be seen in Figure 4, the increasing annoyance response in relation to the different categories is still present. The difference between the LF_M and LF_H, respectively, and the controls at similar dB (A) levels were significant, even though the number of respondents in each category was lower. (The 95% confidence intervals of the differences of LF_H and C was $21{\cdot}6 \pm 17{\cdot}2$ and $11{\cdot}4 \pm 9{\cdot}2$ for LF_M and C.)

The proportions of respondents reporting disturbed rest/relaxation and concentration in LF_M and LF_H were significantly higher in comparison with the controls (Figure 5).

The data indicate that the proportions of respondents reporting disturbed rest/relaxation were higher in LF_M than in LF_H. However, no significant difference was found between LF_M

Table 4

Proportions and 95% confidence intervals of the differences of disturbed rest/relaxation and concentration for respondents exposed to low-frequency noise and controls

Rest/relaxation %	95% confidence interval of the difference
LF_H - C_L 12·5 - 0·7	11·8% (1·5 - 22·1)
LF_H - C_M 12.5 - 0	12·5% (2·3 - 22·7)
LF_M - C_L 22 - 0·7	21·3% (2·3 - 32·2)
LF_M - C_M 22 - 0	22% (12·2 - 31·8)
Concentration	
LF_H - C_L 17·5 - 0	17·5% (5·7 - 29·3)
LF_H - C_M 17·5- 0	17·5% (5·7 - 29·3)
LF_M - C_L 7·5 - 0	7·4% (1·2 - 13·6)
LF_H - C_M 7·5 - 0	7·4% (1·2 - 13·6)

Table 5

Average value of psycho-social symptoms and factors related to sleep disturbance among respondents annoyed and not annoyed by low-frequency noise from heat pump/ventilation systems. A higher value indicates more fatigue, lower well-being, etc.

Symptoms	Not annoyed	Annoyed	*p*-value
Number	90	18	
Social orientation	1·9 (0·65)	2·2 (0·60)	< 0·05
Fatigue	1·8 (0·55)	2·3 (0·54)	< 0·01
Well-being	1·8 (0·67)	1·9 (0·56)	N.S.
Total psycho-social symptoms	5·4 (1·6)	6·4 (1·4)	< 0·05
Subjective sleep quality	1·8 (1·04)	2·2 (0·88)	N.S.
Difficulties in falling asleep	1·5 (0·77)	1·9 (0·83)	< 0·05
Waking up during the night	1·4 (0·73)	1·5 (0·62)	N.S.
Feeling lethargic in the morning	2·7 (1·26)	3·3 (1·19)	N.S.
Feeling tense in the morning	2·2 (1·04)	2·9 (1·16)	< 0·01
Total sleep disturbance	9·6 (3·09)	11·9 (3·05)	< 0·01

and LF_H. In the C_L and C_M, there were very few persons, respective none reporting activities disturbed by heat pump/ventilation noise.

The differences and the 95% confidence intervals between exposed and control areas are shown in Table 4.

3.2. PSYCHO-SOCIAL AND MEDICAL SYMPTOMS

No significant differences could be found in the extent of medical or psycho-social symptoms between the different categories of respondents exposed to low-frequency noise and controls.

The differences in psycho-social symptoms and parameters related to sleep disturbance among respondents who were annoyed and those who were not annoyed by low-frequency noise from heat pump/ventilation systems are shown in Table 5.

Among persons exposed to low-frequency noise from heat pump/ventilation systems there was a higher value for psycho-social symptoms, particularly in relation to fatigue and social orientation among respondents annoyed by low-frequency noise. There was also more total sleep disturbance, particularly regarding difficulties in falling asleep and a feeling of tension in the morning, while there was a tendency to feel more lethargic in the morning ($p = 0{\cdot}06$), and to have a poorer sleep quality ($p = 0{\cdot}10$) among subjects annoyed by low-frequency noise.

An analysis was made of the proportion of respondents reporting medical symptoms daily or a few times a week among the respondents exposed to low-frequency noise reporting annoyance or not. Among the annoyed respondents, the proportion reporting headaches was 22% as compared to 2% among those not annoyed ($p < 0{\cdot}01$). The proportions of easily irritated and unusually tired were 33 and 28% among those annoyed and 13 and 9% among those not annoyed ($p = 0{\cdot}10$ and 0·08, respectively). No statistical significant difference between the groups was found for nausea or for the symptoms not hypothesized to be related to low-frequency noise exposure, such as pain or stiffness in the neck or back or flu symptoms.

For the controls no difference in psycho-social symptoms, sleep disturbance or medical symptoms were found between respondents reporting annoyance from heat pump/ventilation noise or not. The number of persons annoyed was, however, small.

Psycho-social symptoms were related to sleep disturbance in general and to feeling lethargic and tense in the morning in particular, in the areas with low-frequency noise exposure ($r = 0{\cdot}43$ and 0·37), and in the control areas ($r = 0{\cdot}62$ and 0·61). Psycho-social symptoms were also significantly related to disturbed rest/relaxation and annoyance from heat pump/ventilation noise ($r = 0{\cdot}34$ and 0·30) among respondents in the area with low-frequency noise exposure, while no significant relationships were found in the control areas.

No significant differences could be found between the respondents in the low-frequency exposed areas reporting annoyance or no annoyance from heat pump/ventilation noise as regards age, sex, marital status, employment status, presence of chronic diseases, hearing impairment or tinnitus. There was also a similar distribution of these factors between the exposed areas and the controls.

3.3. RELATIONSHIPS BETWEEN ANNOYANCE, NOISE SENSITIVITY, DISCOMFORT AND SYMPTOMS

There was a similar distribution of sensitivity to noise in general and sensitivity to ventilation noise between respondents in the low-frequency noise exposed areas and controls.

The relationships between annoyance from heat pump/ventilation noise and sensitivity to noise in general and to ventilation noise were rather weak ($r = 0{\cdot}24$ and 0·26) although significant $p < 0{\cdot}05$. Among the persons exposed to low-frequency noise, there was a significant relationship between total psycho-social symptoms and annoyance ($r = 0{\cdot}33$), while there were no relationships between total psycho-social symptoms and sensitivity to ventilation noise or to noise in general ($r = 0{\cdot}14$ and 0·13).

There was, however, among persons exposed to low-frequency noise a relation between discomfort due to low-frequency noise and medical and psycho-social symptoms. The persons who reported discomfort also reported a higher degree and frequency of total psycho-social symptoms ($p < 0{\cdot}01$), particularly regarding fatigue ($p < 0{\cdot}001$) and social orientation ($p < 0{\cdot}01$). They also reported more sleep disturbance, particularly regarding subjective sleep quality ($p < 0{\cdot}01$) and difficulties in falling asleep ($p < 0{\cdot}05$).

Among the persons reporting discomfort to low-frequency noise only about 50% also reported annoyance by low-frequency noise.

3.4. NOISE EXPOSURE AND ANNOYANCE

The correlations between the average annoyance and average noise levels for the different areas were 0·50 for dB (A), 0·75 for dB (B) and 0·72 for dB (C). The correlations with dB (B) and dB (C) reached the level of significance ($p < 0{\cdot}05$).

4. DISCUSSION

4.1. METHODS

The response rate in the different areas ranged from 71 to 98%. This is satisfactory for studies of this kind.

The residential areas included in the survey were located in suburban areas with no nearby major roads or airports. The outdoor noise measurements showed that there were no large variations in background noise levels between the areas. The measurements were made outdoors for practical reasons, but with an estimated attenuation of 25 dB (A) applicable for the houses included in the survey, it can be concluded that the outdoor noise levels had little influence of the equivalent indoor levels. It has been noted in case studies that low-frequency noise is particularly annoying in areas with, or during periods of a low background noise level [8, 9]. This is probably due to the lack of a masking effect of higher levels of environmental noise. The results should therefore be generalized with caution to areas of high background noise levels.

The houses were leased or privately owned row houses. Although income level has not been found to significantly influence the extent of annoyance [10, 11] it is possible that ownership of the dwelling and the opportunity to control the noise source could be of importance for the extent of annoyance. When the noise measurements were made in the homes, it was spontaneously reported that the heat pump/ventilation system was turned off during the night to prevent sleep disturbance. As the proportions of persons reporting disturbed rest/relaxation were highest in the areas with medium levels of low-frequency noise, it could be hypothesized that in LF_H, the levels were so disturbing that a threshold for acceptance was reached. It was however not possible to estimate the importance of this for the response in this study. The possibility to control the noise source might also have had an influence on the annoyance response. In a review article of stress by Thompson [12], it was concluded that the behavioural control of, for example, a noxious event in general effects people's tolerance to the noxious stimulus. The evidence of the influence on the final effect of the actual stimulus is however less clear. If parallels can be drawn to the field situation, the control of the noise source might have decreased the annoyance response, while the influence of the extent of medical or psycho-social symptoms is less certain.

Based on data from more extensive studies, e.g. reference [13], we concluded that rather and very annoyed was a relevant measure of annoyance. The study carried out here gave no indication that the relationship of very annoyed differed with regard to medical and psycho-social symptoms from the relationship obtained using rather annoyed.

It was found in the first phase of the study that the noise levels varied between rooms inside the dwellings. In these dwellings the noise was mainly transmitted via the construction. This problem was partly overcome by choosing dwellings where the noise source was mainly transmitted by air, thus making the noise exposure more widely spread inside the dwellings. We also choose to increase the number of dwellings measured and the number of measurements per dwelling. It was also found that the room resonance could effect single third octave bands in the low-frequencies by up to 15 dB SPL. By choosing one corner position and one other position in the room the variation between dwellings of the same type was minimized. However, the noise emitted was a steady state noise and the noise source was of the same make and type within the different categories of the dwellings. We therefore concluded that the benefit of a more extensive measuring program would be rather modest, especially as the personal noise exposure probably showed a larger variation.

4.2. RESULTS

The prevalence of respondents reporting annoyance from heat pump/ventilation noise was higher in areas with low-frequency noise and also tended to increase with increasing sound pressure levels of the low frequencies. The prevalence of annoyed respondents in the areas with low-frequency noise exposure was significantly higher than the prevalence in control areas at medium- and low-level exposure.

The results also show that low-frequency noise interfered with the ability to concentrate at home i.e., when reading. Although the reported effects on concentration can be expected to vary with the subject's normal activities at home, if working at home or studying, it seems to be a robust effect which can be experienced in a general population.

Evidence of a direct relationship between low-frequency noise exposure and psycho-social or medical symptoms was not found, as no difference could be shown of the presence of medical or psycho-social symptoms between the respondents in areas exposed to low-frequency noise and the controls. A close relationship between total psycho-social symptoms and annoyance caused by heat pump/ventilation noise was however found among the respondents exposed to low-frequency noise, but not among controls. Persons reporting annoyance due to low-frequency noise from heat pump/ventilation noise also reported a higher occurrence of headaches and showed a tendency toward a higher occurrence of irritation and unusual tiredness daily or a few times a week. A higher degree and frequency of psycho-social symptoms and higher assessments on difficulties in falling asleep and feeling tense in the morning among respondents annoyed by low-frequency noise from heat pump/ventilation noise was also found.

The high proportion of respondents reporting interference of noise from heat pumps/ventilation systems with rest/relaxation may indicate that low-frequency noise prevented people from obtaining sufficient rest. Lack of sleep and rest may also induce the psycho-social symptoms. A relationship between the total psycho-social symptoms and disturbed rest/relaxation and sleep disturbance in general supports such a link.

This agrees with results from one of the few previous population studies on low-frequency noise [14]. In this study, 368 families answered a questionnaire on living conditions, and a health questionnaire was obtained from a total of 988 family members 15 years of age or older. Symptoms of irritation, headaches, "head feels heavy", pain in arms or legs, feel languid, sleepless and dizziness were reported to occur more often among persons exposed to infra-sound, low-frequency sound and vibrations from a super highway. The frequency of these symptoms showed a significant relationship with the distance to the highway.

There is little experimental data on sleep disturbance caused by low-frequency noise, although persons complaining of low-frequency noise often report that they are much less tired in the morning, when they sleep in places without low-frequency noise. In one study by Inaba and Okada [15], six subjects were exposed to sounds with frequencies of 10, 20, 40 and 63 Hz at several sound pressure levels ranging from 50 to 105 dB SPL, depending on frequency. The exposure was for 30 s every 20 min period. They found no significant difference in sleep efficiency index (time in bed/sleep period time), number of changes in sleep stage or changes of the proportion of each sleep stage between the exposure and the control night. A significant difference between the sounds were found of the changes within the sleep stages for sound pressure levels at or above 85 dB SPL. These "reaction rates" were higher for 40 and 63 Hz as compared with 10 and 20 Hz. In this study, no evaluation was made on time to fall asleep or subjective tiredness in the morning, which would have been interesting with regard to the effects seen in the present study.

It has been shown in earlier studies of environmental noise that working conditions, chronic illnesses [16] and noise sensitivity [11] may have an influence on psycho-social and medical symptoms. A multiple regression analysis could have been performed to evaluate such interrelationships. This was not within the scope of this study and was not performed because the size of the populations was too small. As there was a similar distribution of age, sex, noise sensitivity, family status, chronic illness, employment status and work load between persons in the exposed and control areas, these factors would probably not have had an impact on the results.

The prevalence of annoyance in the areas exposed to low-frequency noise was between 15 and 20%. This prevalence was high considering that the areas with medium exposure had a noise level in dB (A) that only marginally exceeded Swedish recommendations for new buildings [17] in bedrooms at 30 dB (A) and 50 dB (C), and as the area with high exposure had a dB (A) level that only marginally exceeded the recommendations for permissible levels in living rooms in general (35 dB (A)). This indicates that the excessive annoyance was caused by the low frequencies in the noise.

The difference in annoyance response at similar dB (A) levels further support the hypothesis that the dB (A) levels were of less importance for the annoyance response. The shortcomings of the dB (A) weighting in evaluations of annoyance caused by low-frequency noise have been demonstrated in previous laboratory experiments [18, 19]. They have also been observed in several case studies on low-frequency noise [5, 20].

It is also possible that other acoustical factors, which it was not possible to evaluate in this study may be of importance. Acoustical characteristics like the throbbing sound induced by double peaks in the frequency spectra [2] or by amplitude modulations [20, 21] have been suggested to be particularly annoying. The presence of tones in low-frequency noise has been found to increase the annoyance response in a field study by Åkerlund *et al.* [22]. Another experimental study obtained, however, contradictory results [23]. In comparing a broadband and a tonal ventilation noise, no difference in annoyance, performance or wakefulness was detected between the noises. Further research should be undertaken to evaluate the relative annoyance of acoustical characteristics in low-frequency noise.

5. CONCLUSION

This study shows that the prevalence of annoyance, disturbed concentration and rest was greater in areas with low-frequency noise exposure. In addition, the data suggest that medical and psycho-social symptoms are related to general annoyance or may be a result of disturbed sleep and rest caused by low-frequency noise exposure. This hypothesis requires to be further studied. There is also a need to experimentally evaluate sleep disturbance due to low-frequency noise. The study supports previous findings of the dB (A) weighting being a poor predictor of annoyance due to low-frequency noise. Annoyance is, from these results, suggested to be related to the sound pressure levels of the dominant low frequencies.

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