Annoyance of low frequency noise (LFN) in the laboratory assessed by LFN-sufferers

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In a series of listening tests, test subjects listened to eight different environmental low frequency noises to evaluate their loudness and annoyance. The noises were continuous noise with and without tones, intermittent noise, music, traffic noise and low frequency noises with an impulsive character. The noises were presented at LAeq levels of 20, 27.5 and 35 dB. The main group of test subjects (the reference group) comprised eighteen young persons with normal hearing. A special group of four subjects who had reported annoyance due to low frequency noise in their homes was also included. It was found that the special group generally assessed the annoyance of the noises much higher, especially the annoyance at night.

1. Introduction

Annoyance from low frequency noise and infrasound is a 'hot topic' on both the scientific and the political scene. Some people are very annoyed by this kind of noise and much debate has occurred about noise limits and especially about the measurement methods related to the limits. The measurement of low frequency noise is difficult because it can be hard to isolate the noise in question. In [1] a comparison is made between the results of various objective measuring methods and the subjective annoyance experienced in a laboratory test.

In the same investigation, [1], the subjectively assessed annoyance from a number of environmental low frequency noises was evaluated by two groups of test subjects. One group, the reference group, consisted of 18 young normal-hearing persons. The other group, the special group, consisted of four persons who suffer from low frequency noise in their homes. The present paper is about a comparison between the results from the reference group and the special group. The signals in the investigation were restricted to low frequency sounds. No infrasound signals were used.

Sound in the frequency range below 20 Hz is defined as infrasound. The G-weighting function standardised in ISO 7196 [2], has relates closely to the shape of the hearing threshold in the infrasound region. The loudness and annoyance due to infrasound increase very quickly with increasing level. The hearing threshold for single tones is usually about 95 dB(G), and tones with a 20 dB higher level are expected to be sensed as very loud. It can be assumed that infrasound below the hearing threshold is not annoying.

Whereas infrasound is a well-defined concept, low frequency noise is not. Low frequency noise may be defined to comprise the frequency range 10 Hz–160 Hz [3], but other assessment methods may define other frequency ranges (usually within 8 Hz–250 Hz). Some assessment methods use the spectrum of the noise (1/3-octave spectrum measured indoors), and compare this spectrum to a criterion curve. Other methods calculate a level and compare this to a limit.

Depending on the actual conditions, many types of noise can be regarded as low frequency noise. The firing rate of many diesel engines is usually below 100 Hz, so road traffic noise can be regarded as low frequency noise as well as (diesel) train noise or noise from ferries. Similar considerations apply to engines or compressors in industries or co-production plants. Burners can emit broadband low frequency flame roar. Low frequency noise can be noise or vibration from traffic or from industries, totally or partly transmitted through the ground as vibration and re-radiated from the floor or the walls in the dwelling. By this method of transmission, frequencies above approximately 20 Hz are attenuated. It is a general observation that indoor noise is perceived as more 'low-frequency-like' than the same noise heard out of doors.

2. Listening Test

The listening tests were identical to those described in [1] where more detailed information may be found. Eight noises were used (see table I), presented at three different levels. All presentations were made twice and the sequence of the presentations was randomised. Prior to the listening tests, the subjects were trained using four noise examples. After each presentation the subject gave his/her evaluations of the noise on a paper form.

Noise No 1 has a broadband character and is almost continuous. Noise No 2 consists of a series of very deep, rumbling single blows from a drop forge. The noises 3, 4, 5, and 6 have a tonal component. Noise No 7 has three tones but two of them are at a low level. Noise No 8 has a characteristic rhythmical pulsating sound due to the drums.

The duration of each noise was 2 minutes. The noises were either recorded indoors or filtered to simulate indoor noise. The presentation levels were 20 dB, 27.5 dB, and 35 dB (A-weighted levels) measured at the listening position. The noises sounded 'natural' in the listening room and had a pronounced low frequency characteristic.

3. Test Subjects

Eighteen young persons (9 males and 9 females, age between 19 and 25 years) comprised the reference group for the listening tests. The reference group was the main group of listeners. In addition four persons, the special group, who have reported annoyance due to low frequency noise in their homes were included in the listening tests. The special group were all members of a society against low frequency noise in the home and they were selected independently by this society for the investigation. The special group consisted of two of each gender and the ages were between 41 and 57 years. No measurement or other kind of objective quantification was made of the noise in their homes.

Pure tone audiometry was carried out over the frequency range 125 Hz to 8000 Hz using a Madsen Midimate 602 audiometer, equipped with Sennheiser HDA 200 earphones. The calibration of the audiometer was according to the values from [4] which are practically identical to ISO 389-8 [5]. Hearing threshold levels at or below 15 dB HL were accepted in the frequency range 125 Hz to 4000 Hz, and a hearing threshold level of 20 dB at a single frequency (including 8 kHz) was also accepted. The average audiogram is seen in Figure 1.

The threshold of the reference group was within the chosen 15 dB limit whereas the special group showed a hearing loss at the frequencies above 2 kHz. Some of the persons in the special group had a considerable hearing loss, partly due to age. It is assumed that the high frequency hearing loss does not influence the subjective evaluations of the low frequency noises used in the present investigation.

The hearing threshold at 31 Hz, 50 Hz, 80 Hz, and 125 Hz was also

Table 1 Description of the noises used for the listening tests

No.	Name	Description	Tones, characteristics
1	Traffic	Road traffic noise from a highway	None – broadband, continuous
2	Drop forge	Isolated blows from a drop forge transmitted through the ground	None – deep, impulsive sound
3	Gas turbine	Gas motor in a power-and-heat plant	25 Hz, continuous
4	Fast ferry	High speed ferry; pulsating tonal noise	57 Hz, pass-by
5	Steel factory	Distance noise from a steel rolling plant	62 Hz, continuous
6	Generator	Generator	75 Hz, continuous
7	Cooling	Cooling compressor	(48 Hz, 95 Hz) 98 Hz, continuous
8	Discotheque	Music, transmitted through a building	None, fluctuating, loud drums

determined: This test was made with a Two Alternative Forced Choice method described in [6]. The average hearing threshold is seen in Figure 2.

The low frequency hearing thresholds (31 Hz – 125 Hz) showed that the special group was about 5 dB less sensitive than the reference group. The threshold data show that the special group – who had reported annoyance due to low frequency noise in their homes – do not have higher (better) hearing sensitivity at the low frequencies. The hypothesis that the special group should be able to hear the low frequency sounds more easily than the reference group is not supported by these hearing threshold measurements.

3.1 Subject's Task

The test persons were given a written introduction to the tests. Information about the sounds was given after all the tests were finalized.

After each presentation the tests persons were asked to mark on a response line their answer to four questions:

- 'How loud is the sound?' (on a line labelled "not audible" in one end and "very loud" in the other end)
- 'How annoying do you find the sound if it was heard in your home during the day and the evening?' (on a line labelled "not annoying" in one end and "very annoying" in the other)
- 'How annoying do you find the sound if it was heard in your home during the night?' (on a line labelled "not annoying" in one end and "very annoying" in the other)
- 'Is the noise annoying?' (answer yes or no).

All response lines were 10 cm long, and the response was measured in cm with a ruler and thus given as a figure between 0 and 10.

4. Results of the Listening Test

As an example, Table II shows the average subjective evaluation – made by the reference group – of the annoyance during the night from the various sounds. Similar tables were made for the special group and for the annoyance during day/evening.

The subjectively assessed annoyance increases when the same noise is presented at a higher level. Different types of noise are not assessed equally annoying.The noises from the drop forge, the discotheque and the cooling compressor are evaluated as more annoying than the other types of noise.

A statistical analysis of the data from the

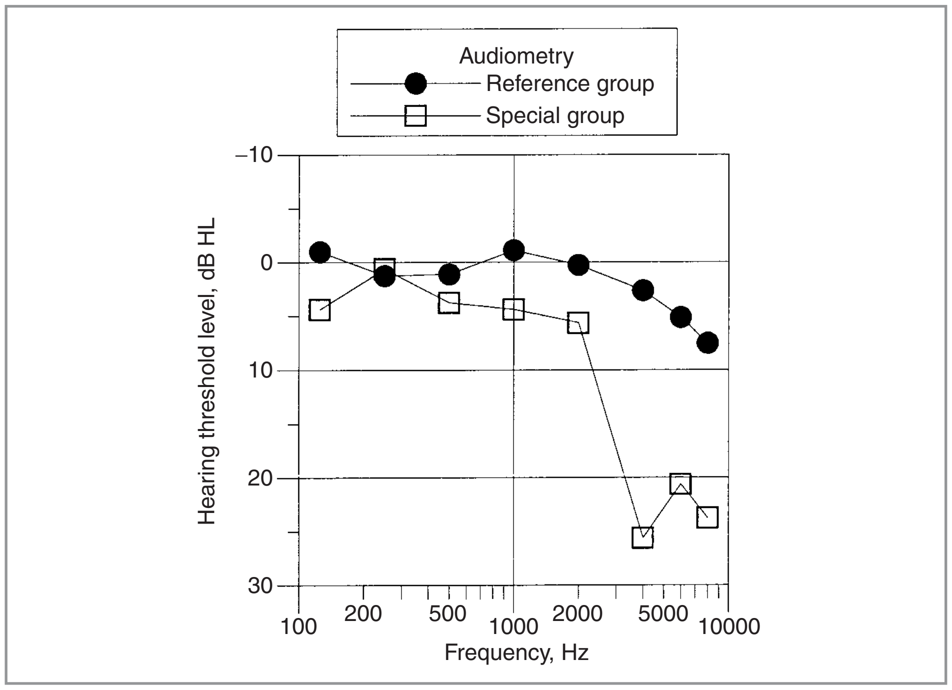

Figure 1 Average hearing threshold level (audiometry, dB HL) for the two subject groups

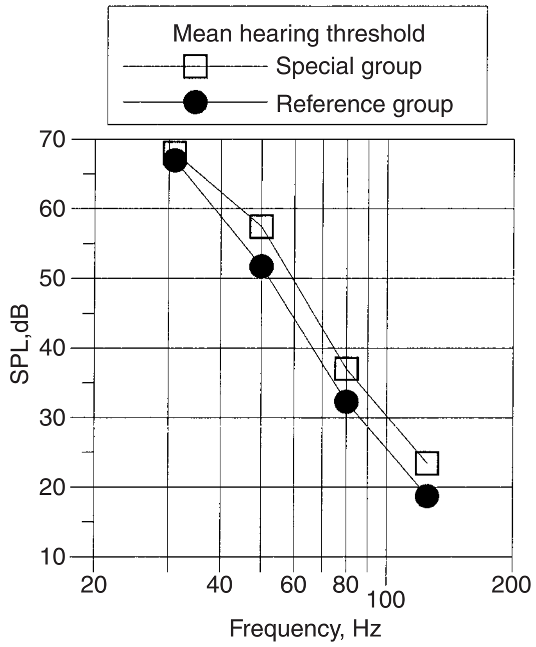

Figure 2 *Average hearing threshold (dB SPL) at low frequencies for the two subject groups*

reference group showed that the noise, the nominal level, the measured dB(A) level and the low-frequency level ($L_{pA,LF}$), are all significant factors. The repetition number (round 1 or round 2 with the same noise presentation) was not a significant factor, which shows the absence of a training effect.

A corresponding analysis was made with the data from the special group. Since this group has only four persons the data are very uncertain and highly dependent on random variations. The result of the analysis is showed that the noise level influenced the evaluations. The influence of noise type on the annoyance was just at the limit of being significant.

The statistical analysis was performed although the data were not perfectly normal distributed.

5. Comparison of the Results from the Two Subject Groups

Table III shows the subjective evaluation made by the special group for annoyance at night. Table III show the same data for the special group as Table II shows for the reference group. Table III shows that the subjectively assessed annoyance increases with increasing level (apart from the noise from the generator, which apparently is equally annoying at both a nominal level of 20 dB and at 27.5 dB). By comparing Tables 2 and Table 3 it is seen that the special group assesses the noises much more annoying than the reference group does. The annoyance found by the special group at a nominal level of 20 dB corresponds almost to the annoyance reported by the reference group at a level of 35 dB.

An interesting result is that it is not the same noises that are evaluated as most annoying by the two groups. The reference group clearly found the drop forge, the discotheque, and the cooling compressor the most annoying. This rank holds at any of the three presentation levels. In contrast, the special group found the generator the most annoying (at the lowest presentation level) and the discotheque as one of the lesser annoying sounds.

The evaluations made by the two subject groups are compared in the following figures.

Figure 3 shows that there is a good correlation between the assessments of loudness made by the two groups. The correlation coefficient is calculated to be 0.82. The special group generally finds the noise examples somewhat louder than the reference group does. The points are rather close to a line that would be offset from but parallel to the line indicated in Figure 3 (showing an assumed 1:1 relationship).

Table 2 *The average assessment of the night-annoyance made by the reference group. Annoyance ratings were given on a scale from not annoying (0) to very annoying (10)*

Nominal presentation level **Noise example**	**20 dB** **Subjective annoyance Night**	**27.5 dB** **Subjective annoyance Night**	**35 dB** **Subjective annoyance Night**
Traffic noise	1.6	3.4	5.2
Drop forge	4.3	5.9	6.9
Gas turbine	0.9	2.5	5.2
Fast ferry	0.9	3.2	5.4
Steel factory	1.0	2.7	4.9
Generator	1.7	3.2	5.0
Cooling compressor	2.7	4.4	6.0
Discotheque	3.0	5.4	6.7

The relation between the assessments of day/evening annoyance of the two groups, Figure 4, is less clear. The correlation coefficient drops to 0.75 and especially the group of points from the highest nominal level (triangles) shows a considerable scatter. The special group finds the noises more annoying than the reference group does. On the average the special group rate the annoyance at day/evening about 2 to 3 scale units higher that the reference group. An increase in the rating of 2 to 3 units corresponds roughly to an increase in level of about 10 dB.

For the assessment of annoyance at night, Figure 5, the picture is shifted. The special group finds the noises much more annoying at night than at day (or evening), and the difference between the assessments of the two groups increases considerably. Figure 5 shows a 'saturation' phenomenon, that is, one or more of the test persons in the special group uses the maximum indication of the annoyance scale. The correlation coefficient is 0.73. On the average the special group rate the annoyance at night about 4 to 5 scale units higher that the reference group. Such an increase in the rating of 4 to 5 units corresponds roughly to an increase in the level of about 17 dB.

The responses to the 'yes/no' question are shown in Figure 6. The figure show how many percent of the group that have marked the noise as annoying. The saturation is obvious as all (four) persons in the special group have marked several noise examples as annoying.

5.1 Assessments Within the Special Group

The relation between loudness and annoyance (day/evening) made by the special group is almost linear and the correlation coefficient is as high as 0.96.

Table 3 *Results of the subjective evaluation of annoyance during the night time made by the special group. Annoyance ratings were given on a scale from not annoying (0) to very annoying (10)*

Nominal presentation level **Noise example**	**20 dB** **Subjective annoyance at night**	**27.5 dB** **Subjective annoyance at night**	**35 dB** **Subjective annoyance at night**
Traffic noise	4.7	7.2	8.5
Drop forge	7.5	8.3	8.9
Gas turbine	5.0	8.1	9.8
Fast ferry	6.6	8.8	9.3
Steel factory	5.9	8.2	9.3
Generator	8.4	8.3	9.0
Cooling compressor	7.4	8.5	9.1
Discotheque	6.0	7.9	8.6

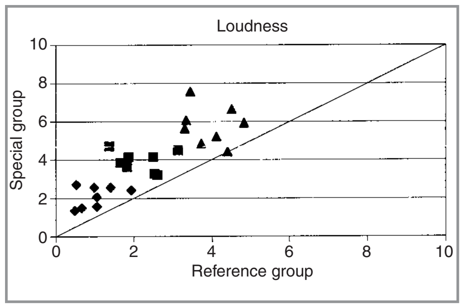

Figure 3 *Assessments of loudness made by the reference group and the special subject group*

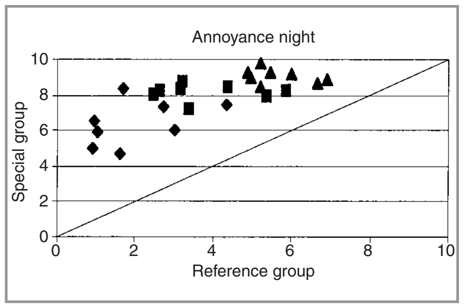

Figure 5 *Assessments of annoyance at night made by the reference group and by the special group*

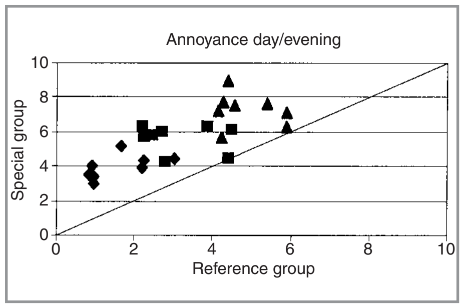

Figure 4 *Assessments of annoyance during day/evening made by the reference group and by the special group*

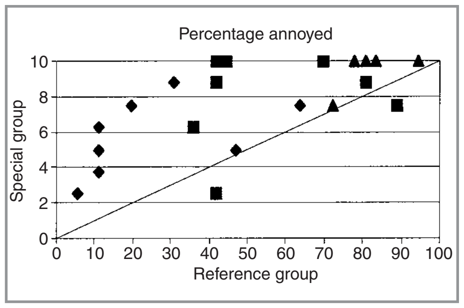

Figure 6 *Percentage of yes-responses to the yes/no question made by the two subject groups*

The loudness ratings are less than the annoyance ratings and thus the noises are perceived more annoying than loud.

The relation between annoyance at day/evening and at night is illustrated in Figure 5. A non-linear relation due to saturation is clearly seen.

The saturation effect indicates the need (in this case) for a stronger assessment than 'very annoying'. The group of points from the middle level (filled squares) is evaluated 2–3 'units' more annoying when they occur at night than at daytime, but the points from the highest presentation level are only indicated 1–2 'units' more annoying. For the special group the annoyance generally increase by two 'units' from day to night corresponding roughly to a 10 dB change in the noise level. For the reference group the annoyance at night was generally rated about one 'unit' higher than at day – at all presentation levels. Such a one-unit change in the rating corresponds approximately to a 5 dB change in the noise level and supports thus the 5 dB penalty in the noise limits at night.

6. Subjective Evaluation of Annoyance compared with Objective Measures

The special group's evaluation of annoyance in the night period was compared to a number of objective measures used in European countries. The details of the procedures are described in [1] and the analysis for the reference group is also given in that reference. Table 4 shows the results of the analysis made for each of the objective assessment methods based on the annoyance ratings made by the special group.

It can be seen from Table IV that none of the assessment methods gives any particularly successful correlation to the subjective assessment made by the special group. Two examples are illustrated in Figure 8 and 9, the Swedish and the Danish method. The groups of points from the intermediate and the highest presentation level both line up reasonably well with a slightly sloping line in the upper part of the figures, while the group of points from the low presentation level

Table 4 Summary of results of regression analysis of the relation between the assessments made by the special group and the different objective assessment methods

Assessment method	Slope	Intersection (x = 0)	Degree of explanation, r2	Correlation coefficient, ρ
Danish	0.16	6.52	0.60	0.78
German A-level	0.16	3.83	0.69	0.83
German tonal	0.05	7.99	0.39	0.54
Swedish	0.17	6.44	0.72	0.85
Polish	0.17	5.47	0.66	0.81
Sloven	0.15	6.84	0.59	0.77
C-level	0.09	4.40	0.31	0.55

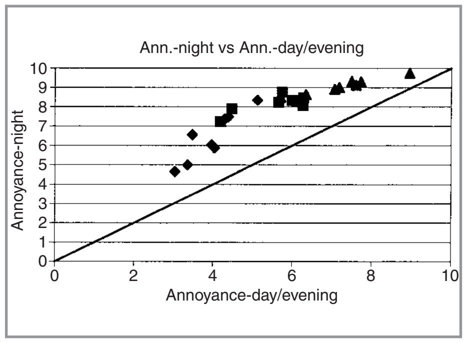

Figure 7 Assessment made by the special group of annoyance (night) and of annoyance (day/evening)

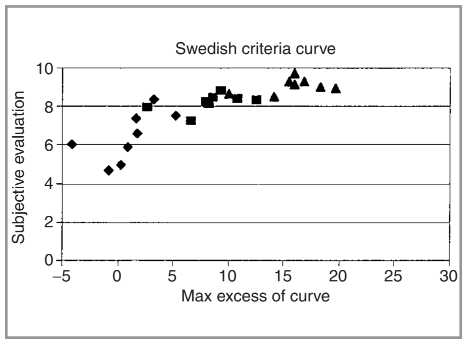

Figure 8 Illustration of the relationship between the Swedish assessment method and the subjective evaluation made by the special group

appears very different in the two figures. In Figure 8 showing the Swedish method these points have a curved tail-like appearance, while they in Figure 9 showing the Danish method appear as a diffuse cloud.

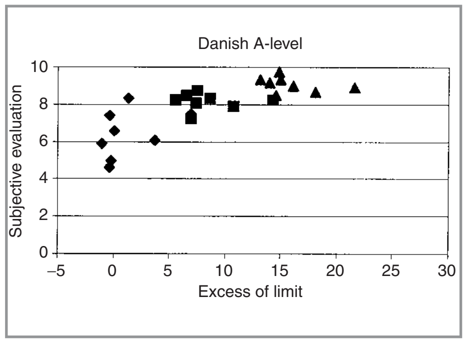

Figure 9 Illustration of the relation between the Danish assessment method and the subjective evaluation made by the special group

The other assessment methods show results without any particular trend like it is seen with the Danish assessment method. Obviously there is no strong connection between the subjective assessment made by the special group and the objective results found by the objective measuring methods. It should be noted though that only four subjects are included in the special group. However, the results give rise to a number of questions about how low frequency noise in the environment is experienced and how it can be assessed.

6.1 Discussion of Results from the Special Group

The results show clearly that the special group made the annoyance evaluations differently from the reference group. The overall annoyance rating (averaged over all annoyance evaluations, presentation levels and noises) was 3.5 for the reference group and 6.7 for the special group. This difference can also be illustrated by ordering the noises from the most annoying to the least annoying. This is done in Table 5.

The reference group has the Drop forge and the Discotheque on top of the list. These two noises have an 'impulsive' character and thus a 5 dB penalty is added to the calculated level in the Danish evaluation method. The Generator and the Traffic noise are in the middle of the list and the Gas turbine is evaluated as the least annoying.

For the special group the Generator is on top of the list whereas the Discotheque and the Traffic noise are evaluated as the least annoying. It is interesting that Traffic noise gives the lowest overall scaling for this group. The value 5.6 is well below the next one (Discotheque) at 6.2. The order of the noises could indicate that the special group paid more attention to those noises, which resemble the typical low frequency noises that they complain about. On the other hand it has not been possible to demonstrate a biased, individual connection between the laboratory evaluations and the kind of noise they are bothered by at home.

7. Discussion

A general discussion about the experimental method, noises and evaluation methods is given in [1] and is not repeated here. The discussion here will concentrate on the aspects related to the two subject groups.

The test subjects made their response by a mark on a 10 cm long horizontal line. The results from the special group of subjects showed in some cases a saturation effect that made the results more difficult to interpret. A way to alleviate the saturation effect could be to include an extension to the response line beyond the 'very annoying' mark. Another way of reducing the saturation effect could be to exchange the word 'very' with a stronger adjective like e.g. 'extremely'.

The number of subjects (18 in the reference group; 4 in the special group) could be increased in order to obtain more certainty in the results. For the reference group it is believed though that an increase of the number of test subjects would not change the general results. For the special group, an increase in the number of test subjects would certainly improve the validity of the group results. On the other hand it may be misleading to handle the persons with low frequency problems as a homogeneous group of subjects. The individual evaluations from this small group vary between test persons. The problems they experience are different and it might thus be more relevant to look at the results from these test persons individually. It has not been possible to demonstrate a connection between the laboratory evaluations and the kind of noise they experience at home.

The low frequency pure-tone hearing threshold was measured for both subject groups. The result showed that the special group was less sensitive to low frequency sounds than the reference group. Although this is an interesting result, it might be more informative to

Table 5 Ordering of the noises from most annoying to least annoying for the two groups of test subjects

Order, reference group	Average Scaling	Order, special group	Average Scaling
Drop forge	5.1	Generator	7.3
Discotheque	4.6	Cooling generator	7.2
Cooling compressor	4.1	Drop forge	7.0
Generator	3.1	Gas turbine	6.9
Traffic noise	3.0	Fast ferry	6.9
Fast ferry	2.9	Steel factory	6.8
Steel factory	2.7	Discotheque	6.2
Gas turbine	2.7	Traffic noise	5.6
Grand average	3.5	Grand average	6.7

measure the loudness growth curve for the test subjects. It is believed that the loudness growth curve would be a much better predictor for annoyance than just the hearing threshold. Measurement of loudness growth is time consuming and is certainly not straightforward at low frequencies.

There is a good agreement between the annoyance evaluations from the reference group and the Danish measurement/calculation method [1]. The same good agreement is not found for the special group. This raises a question about the aim or objectives of a measuring method. Should such an evaluation method be made for the average person (the general population) or should a method be made with special emphasis on the persons who react more strongly to low frequency noise? The criteria and evaluation methods are all based on some kind of measurement of the noise level. For the reference group there is a clear connection between the noise level and the experienced annoyance and thus it makes sense to use such criteria and evaluation methods. For the special group this connection between level and annoyance is less clear and thus an evaluation method based on noise level measurements may be of little value for this subject group. There is a need for further research, with larger number of such test subjects, into the factors, both subjective and objective, that determine the low frequency annoyance. The results from the special group also underline the need of more awareness about the limitations of objective methods based on sound level measurements.

8. Conclusions

A laboratory investigation of the annoyance of low frequency noises was performed for two subject groups. A reference group consisted of eighteen normal hearing subjects. A special group of consisted of four persons who were known to experience problems with low frequency noises. The subjects listened to eight different noises and evaluated the loudness, the annoyance at day/evening and the annoyance at night.

The low frequency hearing threshold of the four special test subjects was not found to be better than the hearing threshold of the ordinary test subjects.

The annoyance evaluations made by the four special test subjects were clearly different from the evaluations made by the ordinary test subjects. The ratings were systematically higher. Especially at night the annoyance was rated as close to maximum and thus not dependent on the level of the noise. The four special test subjects were not annoyed by the impulsive noises to the same degree as the ordinary test subjects were. The connection between level and annoyance is unclear in the results of the special group and thus an evaluation method based on noise level measurements may be of little value for this subject group.

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noise notes

Construction in Laramie

The City Council approved an ordinance prohibiting construction noise in residential areas from being louder than a refrigerator or air conditioner. The new law limits construction noise to 50 decibels between 8 p.m. and 7 a.m. Noise levels will be measured at the property line of the nearest occupied dwelling. Each violation could cost a developer $750.