Noise annoyance indicators for various industrial noise sources: Results and Discussion

Marion Alayrac[a], Stéphanie Viollon[a] and Catherine Marquis-Favre[b]

[a]EDF R&D, 1 avenue général de Gaulle, 92141 Clamart Cedex, France
[b]Université de Lyon, Ecole Nationale des Travaux Publics de l'Etat, CNRS, URA 1652, Département Génie Civil et Bâtiment, 3, rue Maurice Audin, 69120 Vaulx-en-velin, France
marion.alayrac@edf.fr

Characterizing the environmental impact of an industrial plant goes through a better understanding of the noise annoyance caused by industrial noise sources, which are numerous and various.
A first step was to construct a perceptive typology of various industrial noise sources from a categorization test and based on perceived similarities. Now, laboratory tests are carried out, for each perceptive category separately, through the same experimental procedure, by testing the influence of the sound pressure level and of the noise spectral characteristics (low frequency noise, tonal noise…) on noise annoyance.
Subjects have also to judge the annoyance induced by an ambient noise exposure, built with a background noise and an industrial noise for which the emergence level is controlled. Different types of background noises are studied.
Through a statistical analysis, indicators are developed for each perceptive category, based on classical indicators such as sound pressure level or loudness (for instance), or on indicators improved to suit spectral characteristics noticed.
In this paper, the results of those listening tests are detailed and discussed.

1 Introduction

To evaluate the impact of steady and permanent noise sources from an industrial plant, laboratory tests are carried out on noise annoyance.
In the evaluation of noise, the term "annoyance" is often used [1]. It is also employed in daily life conversation when people talk about the disturbance of noise [1]. Various researches pointed out that loudness or sound pressure level is the primary component of noise annoyance [1,2,3]. But other acoustic factors have an effect on annoyance, such as low frequencies or spectral peaks [4,5,6].

Industrial noise sources are numerous and various, containing various spectral characteristics. Our approach was to study noise annoyance through different categories of industrial sources based on a perceptive typology, which was built from a categorization test based on perceived similarities [7] (detailed in Table 1). Six categories were defined.

People living around an industrial plant are simultaneously exposed to an industrial noise and a background noise (including all noise sources in the area except the industrial source). So two approaches were performed during the listening tests to study two cases of noise exposure:

- one industrial noise source
- one industrial noise source perceived simultaneously with a background noise (ambient noise)

This project is cofinanced by AFSSET, the French Agency for Environmental and Occupational Health Safety.

In this paper, only the study of the first three categories is detailed.

2 Experiments

This work aims at assessing annoyance indicators for industrial noise sources arranged by perceptive categories.

The same experimental procedure was set up for the auditory evaluation of each perceptive category. In this part, major lines of the protocol are reminded. More details could be found in the paper [8].
Stimuli were randomly submitted one by one. Listeners had instructions to imagine themselves at home, exposed to those noises 24 hours a day. They were asked to give a noise annoyance judgement by answering on a continuous scale combining a 0-10 numeric scale and a 5-point verbal scale with the verbal labels used in [9].

Thirty subjects, 15 men and 15 women aged from 18 to 60, had participated in the experiment, and were paid.

All industrial sources were registered in the vicinity of the industrial sources, and filtered to take into account noise propagation from the recording point to virtual dwellings at a distance of 250 m.

In the following paragraphs, the stimuli proposed for the two parts of the listening tests are detailed.

Perceptive category	Functional typology [7]
1	"liquid flow devices ": cooling towers
2	"gas flow mechanical devices" "combustion devices " "machinery halls"
3	"electrical machinery": air cooled transformers
4	"liquid flow devices" – pumps "gas flow mechanical devices" "machinery halls"
5	"electrical machinery" "combustion devices" "machinery halls"
6	"gas flow mechanical devices" "machinery halls"

Table 1 Perceptive typology of industrial noise sources [7]

2.1 Noise annoyance due to one industrial noise

For a given perceptive category, the stimuli were created from four noise sources, which were tested at eleven global sound pressure levels, from 30 to 60 dB(A) with a step of 3 dB(A). The stimuli were 5 seconds in length.

2.2 Noise annoyance due to an ambient noise

The French legal criterion is based on the sound emergence of the industrial noise on background noise, at daylight 5 dB(A) and at night 3 dB(A). So listening test were performed on ambient noise constituted of an industrial noise source and a background noise.

Five background noises were selected to test different sound environments where residents around an industrial plant could live:

- Brook and birds at 38.5 dB(A)
- Residential area (with birds) at 39.5 dB(A)
- City (quiet street) at 45 dB(A)
- Building site (noisy) at 49 dB(A)
- Busy road noise (noisy) at 51 dB(A)

Same industrial noise sources as in the first part were selected to test eight emergence levels from 1 to 8 dB(A) (see [8] for more details). The stimuli were submitted one by one, rated for each background noise separately. Their duration was 7s.

3 Noise annoyance due to the first category ("noises from cooling towers")

This first perceptive category contains solely all cooling tower noises of the typology (see Table 1). Those noises could be described as broadband noises (see Fig.1). The levels of the three frequency bands (partition used by Kjellberg *et al.* in [4]), low, middle and high frequencies, are similar for the four noise sources (see Table2). Only the noise source n°51 has a significant component at 1266 Hz.

3.1 Noise annoyance due to one industrial noise source

3.1.1 Stimuli

The four noise sources of the category were studied for this listening test: n°22, n°35, n°46 and n°51.

3.1.2 Results

As an expected result, without spectral characteristics, mean annoyance responses increase as A-weighted sound pressure levels increase. The sound pressure level has a strong impact on the perceived annoyance [$F(10,19) = 135.1$; $p < 0.001$], explaining 74.1% of the variance.

And more, the noise source n°51, made up with a spectral peak at 1266 Hz, is significantly more annoying than the other noises studied [Tuckey's HSD test: $p < 0.001$]. Still, the influence of the spectral feature differences between sources is limited, explaining only 1.2% of the variance [$F(3,26)=33.1$; $p < 0.001$].

We can notice on Table 3 that a better correlation is found with the loudness level (expressed in phons) than with the loudness (expressed in sones).

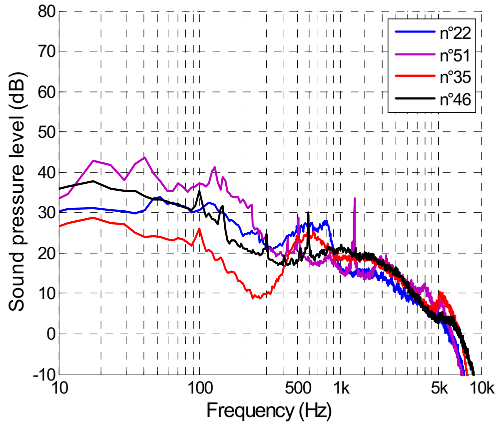

Fig. 1 Spectra of the first perceptive category

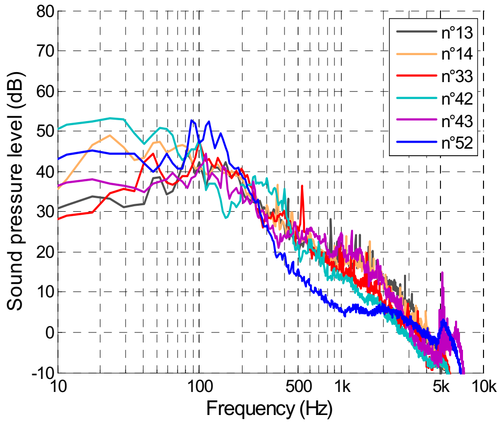

Fig. 2 Spectra of the second perceptive category

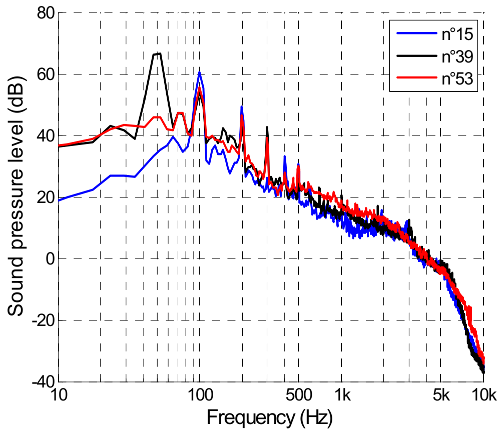

Fig. 3 Spectra of the third perceptive category

Noise source		n°22	n°35	n°46	n°51	n°13	n°14	n°33	n°42	n°43	n°52	n°15	n°39	n°53
dB(C)-dB(A)		3.4	0.3	2.4	6	8.7	10.6	9.2	13.9	8.1	15.6	16	22	13.6
dB-dB(A)		3.7	0.6	3.6	7	9.2	11.5	11.6	16.3	8.5	16.1	16.3	23.3	14.2
Frequency band [4]	25-250 Hz	45	34.4	44.5	50.3	52.9	56.8	55.7	60.3	61	61.1	68.1	58.8	41.1
	315-1250 Hz	45.2	43.7	42.7	42	44.8	44.2	45.2	48.5	37.1	40.7	45.2	44.7	44.6
	1.6-12.5 kHz	36.9	39.6	40.1	40.3	36.5	35.9	32.4	29.8	32	33.8	34.2	35.8	36.1

Table 2 Acoustic indicators calculated for each industrial noise of the three categories studied at 45 dB(A).

	dB(A)	Loudness (ISO 532B)	Loudness level	Sharpness
Mean annoyance response	0.98*	0.96*	0.99*	-0.77*

Table 3 Pearson's correlation coefficients between mean annoyance response and indicators (* for p<0.05)

This laboratory experiment showed that in the case of this industrial noise category, the annoyance is highly correlated with the loudness level (r=0.99; p<0.05) or with the A-weighted sound pressure level (r=0.98; p<0.05).

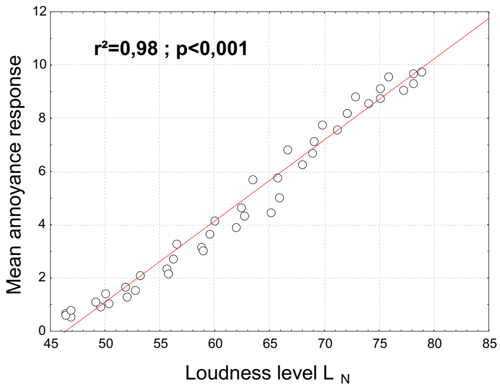

Fig. 4 Linear regression model plotted between mean annoyance and loudness level (in phons)

An annoyance indicator would be simply proposed through a linear regression model (see Fig. 4 and Eq.(1)) calculated from the loudness level in phons (r^2=0.98; p<0.001):

$$Annoyance = -14.1 + 0.3 \times L_N \quad (1)$$

3.2 Global noise annoyance due to an ambient noise

3.2.1 Stimuli

For this second part of the test, the emergence level of the industrial noise source on five different background noises was controlled. The noise source n°35 was tested for the eight emergence levels selected. For the noise sources n°22, n°46 and n°51, only noise emergence 3 and 5 dB(A) were proposed.

3.2.2 Results

As expected [10], the annoyance increases as the emergence level of the industrial noise increases [F(7,22)=22.7; p<0.001]. But the factor Background noise is more influent, explaining 57% of the variance, than the factor Emergence, explaining only 4.9% of the variance. Indeed, the trend for mean annoyance responses to increase as the industrial noise emergence level increases is similar for the five background noises (no significant interaction between the two factors: F(28,1)=6.2; p<0.31). Annoyance judgments increase significantly with an increase of the industrial noise emergence level of 2 dB(A) (Tuckey's HSD test: p<0.05).

Though the French legal criterion (sound emergence) is weakly correlated with annoyance (0.41<r<0.89) according to the studied background noises, the loudness level (the annoyance indicator found to assess noise annoyance for cooling tower noises) is highly correlated (r=0.97; p<0.05) with global annoyance responses without distinguishing background noises.

The analysis of variance pointed out that the interaction between the three factors, Background noise, Industrial noise, Emergence level, is significant [F(12,17)=3.4; p<0.01]. Indeed, on average, annoyance response variations between industrial noises studied and the two emergence levels selected are different for the "brook and birds" noise. This background noise was the only one constituted of solely natural sounds. So, hearing an industrial noise may have influenced the subject responses.

In fact, background noise has complex effects on perceived global noise annoyance by interacting with the industrial noise and its emergence level.

4 Noise annoyance due to noises from the second category

This second industrial noise perceptive category consists of low frequency noises, from various industrial source types. On the one hand, some of the six noise sources contain several spectral peaks (n°13, n°14, n°33 and n°43), when the noise sources n°42 and n°52 do not have any (see Fig.2). On the other hand, the repartition of the sound pressure in low, middle and high frequencies varies between each other (see Table 2).

4.1 Noise annoyance due to one industrial noise source

4.1.1 Stimuli

Four noise sources of the second category, n°13, n°33, n°43 and n°52 were selected to evaluate the effect on annoyance of those spectral features:

- the relative distribution of the sound pressure in the three frequency bands (see Table 2)
- the presence of spectral components (see Fig.2)
- the relative difference between the industrial noises of the category

4.1.2 Results and Discussion

The influence of the sound pressure level prevails on annoyance responses [F(10,19)=77.8; p<0.001], contributing to 74.6% of the variance, in comparison with the spectral features tested [F(3,26)=4.9; p<0.01], contributing only to 0.2% of the variance.

Kjellberg *et al.* [4] had performed a survey on noise annoyance at work place on workers exposed to low- and middle frequency noises. They showed that the dB(C)-dB(A) difference reflects noise qualities that can be of importance for the annoyance. The proportion of explained annoyance variance was increased by 1.4% when the dB(C)-dB(A) was added to the analysis.
In our study, the variation of the indicator dB(C)-dB(A) is too weak to assess its effect on annoyance, compared to the experiment of Kjellberg *et al.* [4]. Mean annoyance responses are highly correlated with those indices (see Table 4):

- A-weighted sound pressure level
- Loudness level (in phons)
- $I_{lin,1/3oct,25\text{-}250Hz}$ (in dB; see Eq.2)

	dB	dB(A)	dB(B)	dB(C)	dB(D)
Mean annoyance response	0.95*	0.99*	0.97*	0.96*	0.98*

	Loudness	Loudness level	Sharpness
Mean annoyance response	0.96*	0.99*	-0.66*

	dB(C)-dB(A)	dB-dB(A)	$I_{lin,1/3oct,25\text{-}250Hz}$
Mean annoyance response	-0.13*	-0.23*	0.99*

Table 4 Pearson's correlation coefficients calculated between mean annoyance responses and indicators (* for p<0.05)

$$with\ I_{lin,1/3oct,25-250Hz} = 10\log_{10}\left(10^{0.1\times L_{eq}} - 10^{0.1\times L_{eq,25-250Hz}}\right)\quad (dB) \quad (2)$$

Kjellberg *et al.* [4] found a lower correlation coefficient for A-weighted sound pressure level, studying similar stimuli varying from 40 to 85 dB(A). And more, Persson and Björkman [11] showed that the A-weighting underestimates annoyance for a broadband continuous low frequency noise.

Small spectral differences between the studied industrial noises may have highlighted the influence of the A-weighted sound pressure level. Persson and Björkman [11] used reference sounds to compare the results obtained on low-frequency noises. In our experimental procedure, stimuli belong to the same perceptive category according to their similarities. One consequence is to reduce the number of spectral differences per perceptive category and a drawback is that the sound pressure level could predominate if the effect of the spectral features is weak.

Thanks to the high value of the correlation coefficients, linear regression models are performed from the three indices found before to propose annoyance indicators. For statistical reasons (distribution data), the A-weighted sound pressure level (see Fig. 5) is chosen.

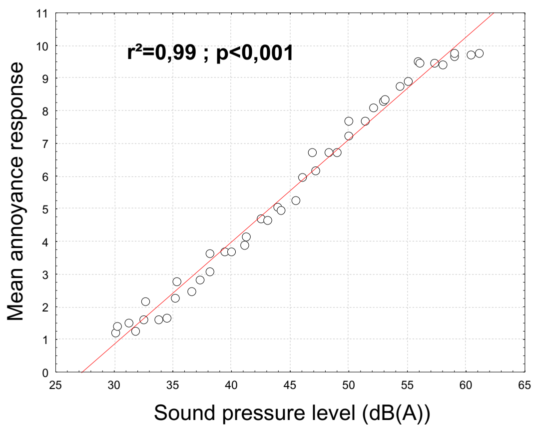

Fig. 5 Linear regression model plotted between mean annoyance responses and SPL calculated in dB(A)

4.2 Global noise annoyance due to an ambient noise

4.2.1 Stimuli

The noise sources n°33 and n°52 were studied for the eight emergence levels selected. For the noise sources n°13 and n°43, only noise emergence 3 and 5 dB(A) were proposed.

4.2.2 Results

Similar main results as the first category are found. On average, the perceived annoyance depends strongly on the background noise, contributing to 64.2% of the variance, and weakly on the emergence level (only 5.6% of the variance). The trend for mean annoyance responses to increase as the industrial noise emergence level increases is similar to the five background noises (no significant interaction between the two factors: $F(28,1)=1.7$; $p<0.54$).

As the previous category studied, the three indicators found to assess noise annoyance induced by an industrial noise of the second category are highly correlated with global annoyance responses given for an ambient noise. Likewise, variations of annoyance judgments are observed for the "brook and birds" background noise (like the first category), and more for the "residential area" noise, in comparison with the other background noises.

The new result for this perceptive category is that the French legal criterion is better correlated with mean annoyance responses by type of background noises (0.96>r>0.90), than the three other indicators. A global annoyance indicator could be developed from the industrial noise emergence:

$$Global\ annoyance = a \times E + b \quad (3)$$

$$with\quad E = L_{A,ambient\ noise} - L_{A,background\ noise}\quad (dB(A))$$

with a depending on the industrial noise category and b on the background noise.

5 Noise annoyance due to the third category ("air cooled transformers")

The experimental procedure and the annoyance response analysis are detailed in the paper [8]. Only main results for this category are thus reminded here.

The three noise sources of the third category ("air cooled transformer" noises), are low-frequency noises (see Table 2), with a main component at 100 Hz, and without or very few harmonics (see Fig.3).

5.1 Noise annoyance due to one industrial noise source

As expected, the sound pressure level has a strong effect on annoyance, explaining 66.7% of the variance, but the proportion explained is lower than for the two categories studied before. Indeed, an additional study pointed out the simultaneous influence of the 100-Hz component level and of the middle and high frequency level on annoyance responses (explaining 10% of the variance). So, an indicator was assessed to take into account those three parameters:

$$I_{A,1/3oct100Hz} = 10 \times \log_{10}\left(10^{0.1\times L_{Aeq}} - 10^{0.1\times L_{A100Hz}}\right)\quad (dB(A)) \quad (4)$$

Another index deriving from this one but taking into account perceptive aspects (I_{spec}) was also created [8].

5.2 Global noise annoyance due to an ambient noise

On average, same observations as for the two previous categories can be done.
The factor Background noise has a weaker impact on annoyance, contributing to 47.6% of the variance, than for the other categories studied. On the other hand, the emergence level contributes to 8.5% of the variance. But, the French legal criterion is weakly correlated with global annoyance responses (see more details in [8]).

Finally, the noise annoyance indicator, $I_{A,1/3oct,100Hz}$, fits well the two approaches performed (same results for I_{spec} [8]):

- one industrial noise source (r^2=0.96; $p<0.001$)

$$Annoyance = 0.34 \times I_{A,1/3oct,100Hz} - 9.15 \quad (5)$$

- one industrial noise source perceived simultaneously with a background noise (r^2=0.95; $p<0.001$)

$$Global\ annoyance = 0.39 \times I_{A,1/3oct,100Hz} - 13.4 \quad (6)$$

6 Discussion and Conclusion

Through the three studied perceptive categories of steady and permanent industrial noise sources, the impact of three different noise spectral characteristics on annoyance was assessed:

- broadband noise
- low frequency noise
- low frequency noise with a main component at 100 Hz

Hellman and Broner [5] measuring loudness and annoyance regarding low-frequency noises (some of them containing dominant tonal peaks located below 100 Hz), found that loudness is slightly a better predictor of annoyance than the A-weighting. But for low-frequency noises containing dominant tonal peaks, Hellman and Broner showed that another perceptive attribute must also play a role.
In our research work, similar results are observed. Indeed, for low-frequency noises (second category) and broadband noises (first category), the loudness level or the A-weighted sound pressure level provides a good understanding of noise annoyance responses. But for low frequency noises with a main component at 100 Hz (third category), other spectral features are necessary to explain annoyance: the 100 Hz emergence level compared with the middle and high frequency level [8].

This first step allowed us then to propose annoyance indicators that contribute to global annoyance when an industrial noise is associated to a background noise.

Indeed, in the case of ambient noise, the emergence of the industrial noise source contributes to the annoyance but the influence of background noises, for different sound pressure levels, prevails (on average 60% of the variance explained). For the three perceptive category tested, the sound emergence effect is the same for the five background tested. But, background noise has complex effects on perceived global noise annoyance by interacting with the industrial noise.

Noteworthy, the annoyance indicators assessed for each perceptive category suits the two approaches performed:

- one industrial noise
- one industrial noise source perceived simultaneously with a background noise

Those first results make part of the aim to study the impact of an industrial plant, taking into account exposure to multiple industrial noise sources and a background noise.

References

[1] S. Kuwano, H. Fastl, S. Namba, "Loudness, annoyance and unpleasantness of amplitude modulated sounds", *Internoise 99 proceedings*, 1195-1200 (1999)

[2] B. Berglund, U. Berglund, T. Lindvall, "Scaling loudness, noisiness, and annoyance of aircraft noise", *J. Acoust. Soc. Am.* 57, 930-934 (1975)

[3] B. Berglund, U. Berglund, T. Lindvall, "Scaling loudness, noisiness, and annoyance of combined community noises", *J. Acoust. Soc. Am.* 60, 1119-1125 (1976)

[4] A. Kjellberg, M. Tesarz, K. Holmberg, U. Landström, "Evaluation of frequency-weighted sound level measurements for prediction of low-frequency noise annoyance", *Environmental International* 23, 519-527 (1999)

[5] R. Hellman, N. Broner, "Assessment of loudness and annoyance of low-frequency noise from a psychoacoustical perspective", *Internoise 99 proceedings*, 1893-1898 (1999)

[6] S. Meunier, A. Marchioni, "Relations entre les caractéristiques physiques et les attributs subjectifs des signaux acoustiques", *Rapport CNRS n°95N84/0113*, 67 p. (1998)

[7] G. Le Nost, "Contribution à l'étude de l'impact environnemental sonore des sites industriels: une typologie perceptive de sources de bruit", *PhD report*, 247p. (2007)

[8] M. Alayrac, C. Marquis-Favre, S. Viollon, "Annoyance from industrial noise: Laboratory study regarding noises from transformers fitted with a huge air-cooling system", *ICA 2007 Proceedings*, 6p. (2007)

[9] J.M. Fields, R.G. De Jong, T. Gjestland, I.H. Flindell, R.F.S. Job, S. Kurra, P. Lercher, M. Vallet, T. Yano, R. Guski, U. Felscher-Suhr, "Standardized general-purpose noise reaction questions for community noise surveys: research and a recommendation", *J. of Sound and Vibration* 242, 641-679 (2001)

[10] S. Viollon, C. Marquis-Favre, C. Baumann, "Annoyance due to industrial noise: perceptual assessment of legislation standard", *CFA 2004 proceedings*, 367-368 (2004)

[11] K. Persson, M. Björkman, "Annoyance due to low frequency noise and the use of the dB(A) scale", *J. of Sound and Vibration* 127, 491-497 (1988)