inter.noise HAMBURG 2016

The effect of human activity noise on the acoustic quality in open plan office

Tania Stenholt DEHLBÆK[1]; Cheol-Ho JEONG[2]; Jonas BRUNSKOG[3]; Claus møller PETERSEN[4]; Pierre MARIE[5]

[1] Sweco A/S, Denmark

[2] Technical University of Denmark, Denmark

[3] Technical University of Denmark, Denmark

[4] Sweco A/S, Denmark

[5] Sweco A/S, Denmark

ABSTRACT

A disadvantage of open plan offices is the noise annoyance. Noise problems in open plan offices have been dealt with in several studies, and standards have been set up. Still, what has not been taken into account is the effect of human activity noise on acoustic conditions. In this study, measurements of the general office noise levels and the room acoustic conditions according to ISO 3382-3 have been carried out in five open plan offices. Probability density functions of the sound pressure level have been obtained, and the human activity noise has been identified. Results showed a decrease in STI-values including the human activity noise compared to STI-values including only technical background noise as the standard recommends. Furthermore, at 500 Hz a regression analysis showed that the density of people in an room, absorption area, reverberation time as well as the ISO 3382-3 parameter $D_{2,S}$ have an impact on the variation in the activity noise. At 1 kHz, the technical background noise influences human activity noise positively. In both octave bands, the human activity noise level varies significantly with the office type, from a call center to a lawyer's office.

Keywords: Room acoustics, Human noise, Offices

1. INTRODUCTION

Open plan offices are popular because of the economic benefits with fewer square meters per employee, high flexibility in office design, and the increase of knowledge exchange (1). However, the disadvantage is the noise annoyance.

Many international studies have shown that noise in open plan offices causes a loss of privacy and decreases the employees' ability to concentrate which is undesirable in a working environment (2). The higher the general noise level in the office is, the more annoyed the employees tend to get (3). Several studies have investigated noise levels in open plan offices during working hours but these studies have mainly investigated average noise levels which do not tell much about the variation of noise during the day or the general *background* noise level (2).

A standard which specifically focus on the acoustic conditions in open plan offices was published in 2012, ISO 3382-3. The standard suggests four single number quantities which include the speech intelligibility and background noise level. During measurements all sources which contribute to the typical background noise during working hours must be turned on. However, it is emphasized that, apart from the people needed to carry out the measurement, no people should be present during

[1] TaniaStenholt.Dehlbaek@sweco.dk
[2] chj@elektro.dtu.dk
[3] jbr@elektro.dtu.dk
[4] ClausMøller.Petersen@sweco.dk
[5] Pierre.Marie@sweco.dk

measurements which means that the influence of the human activity noise is not taken into account in the ISO standard.

There has been no specific research about the distribution of human activity noise in open plan offices whereas, the noise from human activities in universities, schools and concert halls have been investigated (4, 5 and 6). These studies were based on a statistical method developed by Hodgson *et al,* 1999 (4), which led to empirical models for student activity noise.

A similar procedure is used in this study to extract the human activity noise from measurements carried out in five open plan offices in Denmark. An empirical model which predicts the sound pressure level of human activity noise is determined and the influence of the human noise on the acoustic condition in the room is investigated.

2. METHOD

Office noise comprises many different noise sources with different characteristics: i.e. continuous noise (ventilation and office equipment), quasi-continuous noise (4), and unpredictable noise (laughter, conversation, human movements).

Office noise can easily be measured; however, in order to extract the noise from human activity it is necessary to identify which sounds are caused by humans and which are caused by technical equipment. A method suggested by Hodgson *et al*, 1999 (4), makes it possible to identify student activity noise during lectures. In this study the method is modified in order to identify and extract the background noise of human activity noise in open plan offices.

2.1 Measurements

Five open plan offices investigated: Measurement data from five open plan offices have been used to extract human activity noise levels. The measurements were carried out in 2014. The level of activity in the chosen offices ranged from very quiet work (lawyer's office) to work areas with constant conversation (call center). The offices can accommodate between 26 and 59 employees, however, the offices were not fully occupied during the recordings (in average between 9 and 31). Four measurement points were placed at different work stations in the office. Further information about the offices is given in Table 1 and a more detailed description is found in reference (7).

Equipment used: Four ½'' microphones, BSWA type MPA 231, connected to BSWA conditioning unit, type MC 102. The noise is recorded on a two channeled 744T hard disk sound device as WAV-files with a sampling frequency of 44.1 kHz and a bit depth of 24 bit.

Office noise: Approximately two hours of office noise was recorded during working hours. During the recordings the number of occupants were noted every 15th minute. Any unusual noise incidents were noted to be treated later in the analysis process. Calibration signals were recorded before and after the measurement.

Background noise: The technical background noise was measured after office hours in unoccupied rooms. The same microphones and measurement positions were used as in the office noise measurements. The background noise recordings contain mainly noise from ventilation and artificial lightning (no computer noise).

Room acoustic parameters: Measurements were carried out in unoccupied offices according to ISO 3382-3.

Table 1 - Information about the investigated open plan offices.

Investigated offices	N (persons)	No. seats (workplaces)	V (m^3)
Office "A" (lawyer's /economist's office) Danish Energy Regulatory Authority	9	27	1439
Office "B" (engineer's office) Grontmij A/S	17	34	1090
Office "C" (lawyer's/secretary's office) Danish AgriFish Agency	31	59	2180
Office "D" (call center) Tryg Insurance call center	13	26	626
Office "E" (call center) DSB call center	20	37	845

2.2 Statistical distribution of noise levels

The recorded office noise, each with a length about two hours, is split into small time intervals of 125 ms for each octave band (125 Hz to 8 kHz). The equivalent sound pressure level, L_{eq}, is determined for each interval and the office noise levels, L_{eq}, are then statistically distributed relatively to the percentage of time.

An imaginary but realistic time history of a recording of human activity noise and technical background noise is shown in Figure 1 a). *X* represents the human activity noise levels and when there is a break in the activity, the sound pressure level decreases to the level, *Y*, the background noise. The sound pressure levels are distributed according to how often the noise levels occur as a percentage of time, which results in two curves which peak at the middle as illustrated in Figure 1 b). Each curve shows the frequency of the noise levels of the respective noise part (i.e. the background noise, *Y*, and the human activity noise, *X)*. A function which explains the distribution of the noise levels in Figure 1 b) is called a probability density function.

A probability density function is obtained for seven octave bands from 125 Hz to 8 kHz for each microphone position as described above.

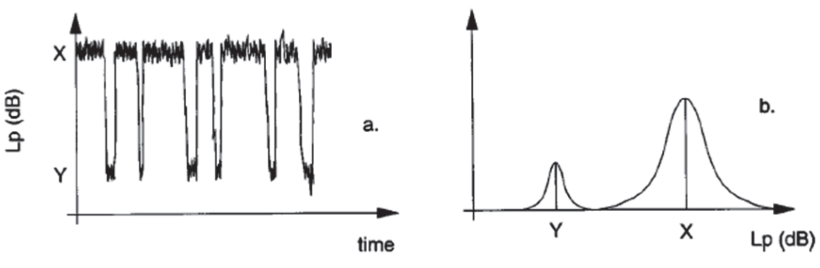

Figure 1 - a) An imaginary time history. b) Statistical distribution of X and Y (4).

2.3 Regression of probability density function

The recordings of office noise are expected to contain two events occurring concurrently: the technical background noise and the human activity noise. It is assumed that the statistical characteristics of each acoustical event recorded in this study can be expressed by one or more normal distributions.

With *two* acoustical events, there are *two* random variables each assumed to have a probability density function that follows a normal distribution, $p_1(x)$ and $p_2(x)$, where x is the equivalent sound pressure level, L_{eq}, of the offices noise. The probability density function model of the office noise can be expressed by a weighted combination of $p_1(x)$ and $p_2(x)$,

$$p_{ON}(x) = W_1 p_{\mu_1\sigma_1}(x) + (1-W_1) p_{\mu_2\sigma_2}(x) \quad (1)$$

where μ, defines the most frequent noise level of the particular acoustic event, σ is the standard deviation and W_1 is the necessary weighting between zero and one, since the integral for all x of the total probability density function has to equal one.

Since the expression in equation (1) will not describe the curve of the measured data completely, an extra term corresponding to the error, ϵ_i, is added to the equation. A measure to describe the relative fit of the regression model is given by the coefficient of determination, R^2 (8).

The fitting of the regression curve is done by using an unconstrained nonlinear optimization function called *fminsearch* in MATLAB.

A complete fit all over the curve is difficult to achieve. Therefore, different weighting factors using the *weighted least square method*, have been investigated for each of the office cases and octave bands. However, the improvements of fitting with a weighting factor have not been significant. In addition, the value of the weighting factor changed with each octave band and each measurement which caused the weighting system to be inconsistent. Therefore, in this study the results of the regressions of probability density functions *without* any weighting are used.

Figure 2 shows two fitting results at 500 Hz from two different offices, a) where one normal distribution gives the best fit to the distribution of the office noise data, and b) where two normal distributions give the best fit to the unsymmetrical distribution of the data measured in another more quiet office.

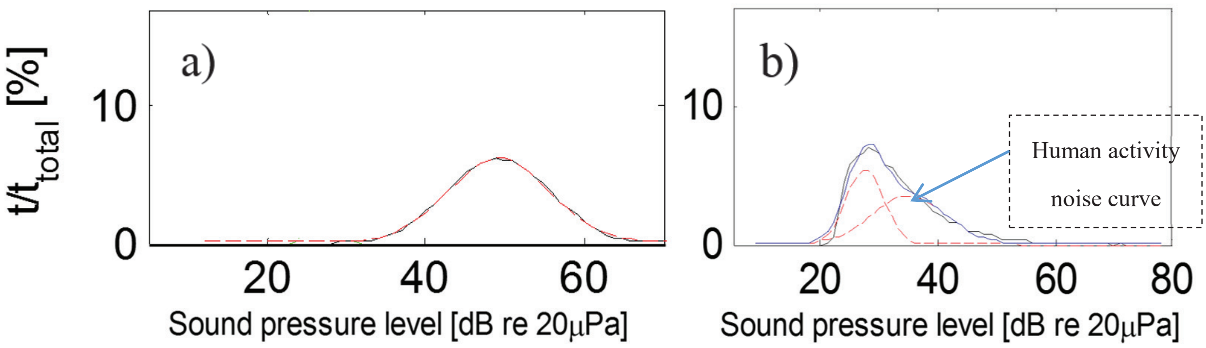

Figure 2 - Regression of a probability density function at 500 Hz, two different offices: a) a call center where one normal distribution gives the best fit and b) an engineer office where two normal distributions give the best fit. ▬ : measured office noise, ▪▪▪ : individual fitted normal distribution and ▬: overall fitted curve of office noise.

2.4 Extraction of human activity noise

For all five office cases Gaussian distributions were identified. To describe the data measured in the offices with the lowest activity levels two normal distributions gave the best fit, as Figure 2 b) shows an example of. The lowest mean level is associated with the technical background noise and the highest mean level is associated with the human activity noise. It is unknown if the distribution of the human activity noise keeps on following a normal distribution in the area where the two fitted normal distributions (red lines) overlap in Figure 2 b), however that is the assumption in this project.

The noise level which is used in the analysis of the human activity noise is the so called '*background noise of the human activity*'. This '*background noise level*' is the level which 90 % of the time is exceeded, $L_{90,HN}$., as illustrated in Figure 3.

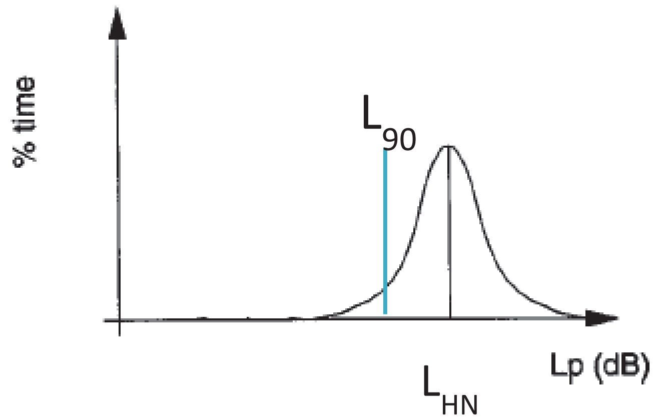

Figure 3 – Illustration of $L_{90,HN}$ at the Gaussian distribution of human activity noise levels.

If $L_{90,HN}$ is lower than the technical background noise measured in the room, the noise level, $L_{90,HN}$, is so low that it will be masked by the technical background noise and not be not relevant. There fore, the criterion for evaluating the $L_{90,HN}$ is if it is equal to or larger than the measured technical background noise. If $L_{90,HN}$ is equal to the background noise, the sum of the two noise parts will be 3 dB higher, and therefore perceptible, compared to the case where the only source is the technical background noise.

In the offices where the activity level was high and breaks in the flow of talk were rare, one normal distribution gave the best fit to the data, as Figure 2 a) shows an example of. In this case the normal distributed curve contains energy from both technical background noise and human activity noise. Therefore, in order to extract the human activity noise levels the levels has to be corrected for technical background noise.

The method used to correct the activity noise levels for technical background noise is as followed: two equally long hypothetical observations of sound pressure levels are generated numerically in MATLAB; one based on the mean and standard deviation of the human activity noise and one based on the technical background noise. The sound pressure levels for each acoustical event are sorted from the minimum level to the maximum level. Next, a logarithmic subtraction is carried out for each term from the minimum level to the maximum level. In this way the lowest background noise level is subtracted from the lowest human activity noise level and the largest background noise level from the largest human activity noise level. The result is hypothetical data of human activity noise corrected for technical background noise. Finally, a normal distribution is fitted to the data and a probability density function which describes the activity noise is determined. The level, $L_{90,HN}$, is then determined from the function, as explained earlier in the paragraph, to be used for further analysis.

2.5 Empirical models

The empirical models are based on the diffuse field theory where the assumption is that the sound level is the same anywhere within the room. Furthermore, the sound pressure level and the sound power level are connected by the absorption in the room. The noise from human activity in the office is seen as one source of noise emitting a certain sound power level.

To ensure that the variables used in the regression models are independent of each other, a correlation analysis is conducted.

The main indicator of how well the regression models explain the variation of human activity noise is the adjusted coefficient of determination, R_a^2, which takes the relation between number of variables and samples size into account.

3. Results

The reverberations times measured in the five investigated open plan offices are listed in Table 2. The reverberation times in four of the offices, “B”, “C”, “D” and “E”, are fairly similar. However, the reverberation times in office “A” are almost about twice the reverberation time in the other offices. Table 3 lists the extracted human activity noise levels, $L_{90,HN}$, and the measured technical background noise levels, L_{BN}.

Table 2 – Measured reverberations times, T_{20}.

Frequency (Hz)	125	250	500	1000	2000	4000
Office "A" (lawyer's /economist's office)	0.76	0.85	0.82	0.74	0.65	0.55
Office "B" (engineer's office)	0.37	0.30	0.29	0.26	0.26	0.29
Office "C" (lawyer's/secretary's office)	0.55	0.39	0.4	0.38	0.39	0.34
Office "D" (call center)	-	0.48	0.37	0.34	0.32	0.33
Office "E" (call center)	0.62	0.49	0.36	0.35	0.42	0.47

Table 3 – Human activity noise levels and the technical background noise levels

Frequency (Hz)		125	250	500	1000	2000	4000	8000
Office "A" (lawyer's /economist's office)	L_{BN}	41.6	39.6	30.4	25.0	20.5	-	-
	$L_{HN,90}$	-	-	31.5	27.6	24.8	19.6	13.0
Office "B" (engineer's office)	L_{BN}	27.9	22.2	17.2	14.0	-	-	-
	$L_{HN,90}$	-	27.6	24.7	20.3	16.9	14.7	-
Office "C" (lawyer's/secretary's office)	L_{BN}	34.4	29.4	19.0	14.4	-	-	-
	$L_{HN,90}$	34.4	32.5	28.2	24.0	21.8	16.5	-
Office "D" (call center)	L_{BN}	31.7	27.4	19.0	14.3	-	-	-
	$L_{HN,90}$	-	41.0	42.0	27.7	26.0	15.3	15.3
Office "E" (call center)	L_{BN}	33.9	31.4	26.4	23.2	19.3	-	-
	$L_{HN,90}$	-	43.3	42.1	31.9	30.4	26.1	15.4

The mean and 95 % confidence interval of all human activity noise levels from the five open plan offices are presented in a bar graph in Figure 4.

The human activity noise is generally highest at the octave bands 250 Hz and 500 Hz and then the level decreases for every band having the lowest level at the highest frequency band (4 kHz or 8 kHz). Especially the call centers show high activity noise levels at 250 Hz and 500 Hz compared to the levels at the higher bands. In fact, the difference from 500 Hz to 1 kHz in the call centers is more than 10 dB. Compared to the few occupants in the room, office "A" (the Danish Energy regulatory) data shows rather high activity noise levels. This could be explained by the high reverberation time which is suspected to increase the noise levels. Furthermore, the office has the highest measured background noise levels of all the offices, however, whether this has an impact on the human activity noise is not certain.

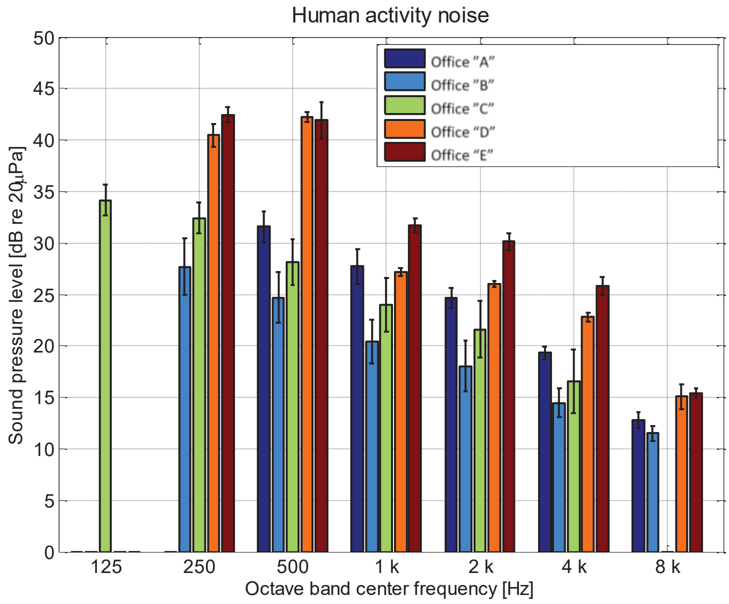

Figure 4 - Extracted human activity noise levels, $L_{90,HN}$, at seven octave bands in the five open plan offices.

In the acoustic software program, DIRAC 5.0, it is possible to investigate how much the measured speech intelligibility reduces if an additional background noise is added, using the function, *Mix Noise*. The mean of the human activity noise levels, $L_{90,HN}$, at octave bands 250-2000 Hz are added as extra background noise to the measured STI in DIRAC. For office "A" no activity levels could be extracted at 250 Hz, so only human activity noise levels at 500-2000 Hz have been added in this case. From the corrected STI-values a distraction distance is calculated for each office.

In Table 4 distraction distances (the distance where STI < 0.5) according to the standard ISO 3382-3, $r_{D,ISO}$, are listed as well as the corrected distraction distances including human activity noise, $r_{D,HN}$. Including the human activity noise levels in the STI calculations definitely have an effect on the distraction distances for all the offices. The extra background noise from people seems to reduce the speech intelligibility in each of the offices. The most significant difference is found in the office with the highest activity noise level, in office "E".

Table 4 - The distraction distances, r_D, at the five offices: $r_{D,ISO}$ (excl. human activity noise), $r_{D,HN}$ (incl. human activity noise) and the percentage difference.

Open plan offices	$r_{D,ISO}$ excl. $L_{90,HN}$ (m)	$r_{D,HN}$ incl. $L_{90,HN}$ (m)	Difference
Office "A" (lawyer's /economist's office)	5.0	2.8	44%
Office "B" (engineer's office)	10.0	8.2	18%
Office "C" (lawyer's/secretary's office)	8.6	6.7	22%
Office "D" (call center)	10.0	6.5	35%
Office "E" (call center)	8.2	3.0	63%

4. Analysis and discussion

4.1 Correlations analysis

The largest sample size of human activity noise and background noise are at 500 Hz and 1 kHz. Because of the large differences in the human activity levels at 500 Hz and 1 kHz a regression analysis for each of the frequency bands is performed.

Human activity noise is likely to depend on the following factors: (1) the number of people per square meter N/A, (2) the number of people per cubic meter N/V, (3) the technical background noise, (4) the absorption area, A_{sab}, (5) the reverberation time, T_{20}, (6) the distraction distance, r_D, (7) the spatial decay of speech, $D_{2,S}$ and (8) the *Boolean variable, d_1*. Is the room used as a call center, $d_1 = 1$, and is the room not used as call center $d_1 = 0$. Under the assumption of a diffuse field the variables (1), (2), (5) and (6) are logarithmically scaled.

The correlation coefficients based on data at 500 Hz and 1 kHz show very similar values. The variables that correlate are the same at both octave bands. The only differences are the degree of correlations which in three cases are slightly more significant at 500 Hz than at 1 kHz. More detailed information about the correlation is found in reference (7).

4.2 Empirical prediction model

The following empirical models, for 500 Hz and 1 kHz, were developed by using multivariate linear regression analysis.

Among the different combinations the regression model which explain most of the variation of the human activity noise at 500 Hz, with R_a^2 = 95 %, is given by,

$$L_{HN,500Hz} = -126.4 + 80.4\log\left(\frac{A}{N}\right) + 15.3\log(A_{sab}) + 34.3d_1 \tag{2}$$

However, both log(G/N) and log(A) correlate with d_1. The correlation is assumed to be caused by the specific office cases in the experiment and is not considered to be a general connection in all offices. With a higher sample size the correlation would probably go away. Nevertheless, with the correlations in the present case in equation (2), neither the values nor the signs of the corresponding beta coefficients are reliable.

The best uncorrelated regression model explains 93% and is a combination of the reverberation time and the call center variable expressed by,

$$L_{HN,500Hz} = 33.1 + 14.3\log(T_{20}) + 15.0d_1 \tag{3}$$

The Boolean variable, d_1, equals 1 for call centers equals and 0 for non-call centers. If the reverberation time at 500 Hz is 0.4 s, the human activity noise would be reduced by almost 6 dB, but if the reverberation time is 0.8 s, then the reduction is in only 1.4 dB. So a higher reverberation time results in a higher human activity noise level according to equation (3). If the office is a call center 15 dB is added to the activity noise level.

Another uncorrelated combination which explains 92 % of the variation of the activity noise at 500 Hz is given by,

$$L_{HN,500Hz} = 36.7 - 1.5D_{2,S} + 13.7d_1 \tag{4}$$

From the equation it is clear that whether the office is a call center or not has most impact on the human activity noise level. Still, if the spatial decay of speech is increased by 1 dB the effect is a decrease of the human activity noise of 1.45 dB which is quite effective.

The combination of variables that explains most of the variation of the human activity noise, 89 %, is described by the regression model including the variables $L_{BN,1kHz}$, $\log(T_{20})$, $\log(A_{sab})$ and d_1. However, because of correlation between several of the variables no details about how much each variable contribute to the variation of the activity noise can be specified. Nevertheless, the prediction model with the highest explanation degree at 1 kHz is given by,

$$L_{HN,1kHz} = 14.8 + 0.3L_{BN,1kHz} + 18.6\log(T_{20}) + 13.5\log(A_{sab}) + 9.4d_1 \tag{5}$$

By removing the variables, $\log(T_{20})$, $\log(A_{sab})$ from the equation, a regression model with no correlated variables appears. This model explains 73 % of the variation of the human activity noise,

$$L_{HN,1kHz} = 18.2 + 0.4L_{BN,1kHz} + 4.5d_1 \tag{6}$$

Whether the office is used as a call center or not affects the human activity noise by almost 5 dB. The influence of the background noise on the variation of the human activity noise is rather small with a coefficient of only 0.4 but its influence is highly significant according to the t-statistics.

4.3 Further work

The project has shown that the human activity noise is most significant in the two call centers. It would therefore be interesting to acquire more office noise data for these types of offices. This would give a better statistical foundation for predicting a more accurate human activity noise level to include in the STI-calculations.

To achieve usable data for more than two frequency bands (500 Hz and 1 kHz) it is suggested that microphones with even lower dynamic range should be used for the measurements. Due to the relatively high inherent noise in the measurement chain, the measured technical background noise could in most of the cases not be evaluated at the frequency bands higher than 1 kHz.

Furthermore, during the process of identifying acoustical events in the office noise it was noticed that the probability density functions which were associated with background noise had a mean a few dB higher than the technical noise measured in an unoccupied room. This indicates that the background noise which is measured in unoccupied open plan offices is different from the actual background noise during office hours. How this affects the acoustical parameters from ISO 3382-3 would be interesting to study further.

Finally, it could be highly interesting to obtain subjective parameters concurrently with the objective parameters to see whether the objective results matched the perception of the acoustics of the employees in the open plan offices.

5. Conclusion

A method for measuring human activity noise has been suggested and applied in five open plan offices. The five offices included three rather quiet offices and two call centres.

The office noise levels have been statistically distributed according to occurrence and probability density functions which describe the distributions have been determined for each octave band.

Human activity noise levels, $L_{90,HN}$, have been extracted for each of the office cases. The highest levels were detected at 250 Hz and 500 Hz. Generally, the activity noise was highest in the call centres.

STI values including the human activity noise has been estimated. The results showed a decrease in speech intelligibility compared to STI-values including only the technical background noise as ISO 3382-3 recommends.

Furthermore, at 500 Hz a regression analysis showed that the density of people in an room, absorption area, reverberation time as well as the ISO 3382-3 parameter $D_{2,S}$ have an impact on the variation in the activity noise. At 1 kHz, the technical background noise influences human activity noise positively. In both octave bands, the human activity noise level varies significantly with the office type, from a call center to a lawyer’s office.

In order to estimate a reliable model that predicts the human activity noise level, acoustic data from more open plan offices should be included in the analysis.

REFERENCES

1. BAR FOKA, Branchearbejdmiljørådet Finans/offentlige Kontor & Administration, & Slots- og Ejendomsstyrelsn (2008). Arbejdsmiljø i det åbne kontor - forskningens bud på problemer og løsninger.
2. Navai, M. & Veitch, J. A. (2003). Acoustic Satisfaction in Open-Plan Offices: Review and Recommendations National Research Council Canada, Institute for Research in Construction, IRC-RR-151.
3. Sailer, U. & Hassenzahl, M. (2000). Assessing noise annoyance: an improvement-oriented approach. ERGONOMICS 43, 1920-1938.
4. Hodgson, M., Rempel, R., & Kennedy, S. (1999). Measurement and prediction of typical speech and background-noise levels in university classrooms during lectures. JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA 105, 226-233 and JASA J. Acoust. Soc. Am. 131 (4), April 2012 2753-2761.
5. Sato, H. & Bradley, J. S. (2006). Estimation of speech-to-noise ratio during active speech communication in noisy rooms. Institute of Noise Control Engineering of the USA - 35th International Congress and Exposition on Noise Control Engineering, INTER-NOISE 2006 7, 4605-4610.
6. Marie, P., Jeong, C. H., Brunskog, J., Marie, P., & Petersen, C. M. l. (2012). Audience noise in concert halls during musical performances. 41st International Congress and Exposition on Noise Control Engineering 2012, INTER-NOISE 2012 3, 2231-2240.
7. Dehlbæk, T. (2014). The effect of human activity noise on the acoustic quality in open plan offices, M.

Sc. Thesis, Technical University of Denmark.
8. Harnett, D. L. (1975). Introduction to statistical methods, 2nd ed Addison-Wesley Publishing Company.