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Aircraft noise exposure and public health

TNO Prevention and Health

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TNO Prevention and Health contributes to the improvement of quality of life and to an increased healthy human life expectancy. Research and consultancy activities aim at improving health and health care in all stages of life.

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Abstract

With a view to a possible change in the German aircraft noise exposure regulations, TNO Prevention and Health carried out a project by order of the Umwelt Bundesambt (UBA). The project has been executed in the framework of the Umweltforschungsplan 1999, Forschungs- und Entwicklungsvorhaben 299 51 255, thema "Umweltqualitatsziele zum Schutz vor schädlichen Umwelteinwirkungen durch Fluglärm". The aim of the project is to obtain scientific results that can be used in a decision about future aircraft noise exposure regulations in Germany. UBA formulated questions regarding overall aircraft noise exposure metrics, and consequences for specified adverse aircraft noise-induced effects on public health, if specific limits are exceeded. Questions were also formulated regarding the usefulness of limits of the maximal sound level (L_{Amax}) or the SEL value of single aircraft noise events, in addition to overall limits. To respond to the questions various datasets have been re-analysed and the 1994 report of the Health Council of the Netherlands, in which the health effects of environmental and occupational noise exposure have been assessed, has been up-dated.

At present, in Germany, the so-called Störindex is used as the descriptor of aircraft noise exposure. The German regulation uses two exposure limits (Störindex equal to 67 and 75, respectively). On the basis of data of a recent socio-acoustic survey, the Amsterdam Airport Schiphol study, the relationship between the Störindex and the so-called day-night level (DNL, a L_{Aeq}-based metric with a penalty of 10 dB(A) to the night-time aircraft noise events) has been established. According to this relationship, the values of the Störindex equal to 67 and 75 correspond to DNL values of 65 and 72 dB(A), respectively. From the analysis of the data of the available datasets it is concluded that the correlation coefficient of the Störindex and aircraft noise *annoyance* is statistically not significant different ($\alpha = 5\%$, tested two-sided) from the correlation coefficients of L_{Aeq}-based overall metrics and aircraft noise annoyance. Among the L_{Aeq}-based overall metrics considered are the optimal metric, which gives the highest correlation with aircraft noise annoyance, DNL and LDEN (day-evening-night level, a L_{Aeq}-based metric with a penalty of 10 dB(A) to the night-time aircraft noise events and penalty of 5 dB(A) to the evening-time aircraft noise events).

In the report a model is elaborated to decide whether it is useful to limit L_{Amax} or SEL of single aircraft noise events to limit specific adverse health effects, if there is already an overall limit (based on metrics such as the Störindex) that restricts L_{Amax} or SEL of single aircraft noise events. A possible limit of single aircraft noise event characteristics is considered with respect to the following three adverse noise-induced effects:

- awakening;
- interruption of conversation due to assumed decrease of intelligibility;
- reduction in intelligibility of speech produced by radio or television.

The report describes a stepwise procedure to decide about the introduction of a limit for SEL or L_{Amax} to limit the occurrence of these effects if an overall limit already exists. To be able to decide whether it is appropriate to consider a limit for SEL or L_{Amax}, it is a prerequisite to assess

the maximal number of times a specific noise-induced effect over a specified period of time is considered acceptable from a viewpoint of public health. The procedure is illustrated for aircraft noise-induced awakenings with two examples, in which the overall limits are equal to a Störindex of 67 and 75 dB(A), respectively. In the examples, a maximum of 120 aircraft noise-induced awakenings a year in an "average" person is considered acceptable from a viewpoint of public health. In the calculations several assumptions have been made, such as the sound insulation of bedrooms is equal to 25 dB(A), bedroom windows are closed during each night, the difference between L_{Aeq} of day- and night-time aircraft noise exposure is 8 dB(A), the relationship between the probability of noise-induced awakening and SEL of a single aircraft noise event is correct. Then, the model shows that irrespective of the values of L_{Amax} or SEL of the aircraft noise events during the night, in a situation with a Störindex of 67 the number of aircraft noise-induced awakenings of an "average" person does not exceed 120 a year. This implies that it is superfluous to limit characteristics of single aircraft noise events in addition to the Störindex. For a situation with a Störindex of 75, for an "average" person the maximum number of aircraft noise-induced awakenings is 600 per year. There are two alternative methods to meet the requirement of a maximum of 120 awakenings a year for the area in which the Störindex is between 67 and 75: reduce the limit of the Störindex from 75 to 67 or set a limit to the characteristics of single aircraft noise events. In the example the second alternative would imply a limit of night-time outdoors L_{Amax} of aircraft noise events of 70 dB(A) (SEL equal to 56 dB(A)). It is questioned whether such a limit of L_{Amax} or SEL is feasible.

The Committee on Noise and Health, an international committee of the Health Council of the Netherlands, assessed in 1994 the health effects of environmental and occupational noise exposure. In this report, the 1994 Health Council report has been taken as a starting point and more recent reviews and results of more recent surveys have been used for an up-date of the 1994 evaluation. In general the more recent reviews and papers concur well with the conclusions of the Health Council in 1994. From the up-dated information, the conclusions about the possibility of adverse aircraft noise-induced effects on public health for situations with the Störindex equal to 67 or 75 are given in table A1.

In the report also an overview is given of present aircraft noise regulations in various countries. The presentation is based on the existing overviews and information obtained from experts in various countries.

Table Abstract *Probability of adverse noise-induced effects on public health. A + sign indicates that it is likely that the effect is induced by aircraft noise exposure. A – sign indicates that it is likely that a noise-induced effect is absent.*

Effect	Long-term aircraft noise exposure with	
	DNL = 65 dB(A) Störindex = 67	DNL = 73 dB(A) Störindex = 75
Hearing impairment	-	-
Hypertension	-	+
Ischaemic heart disease	-	+
Annoyance	+	+
Performance of school children	?	+
Sleep disturbance, changes in:		
sleep pattern	?	+
awakening	+	+
sleep stages	+	+
subjective sleep quality	+	+
heart rate	+	+
mood next day	?	+

Contents

1 Introduction

In line with developments in the European Union (EU/DG Environment, 2000; Berg, 1999), Germany considers changing its regulations for aircraft noise exposure. At present, in Germany aircraft noise exposure of populations is assessed by the so-called Störindex, specified in "Gesetz zum Schutz gegen Fluglärm (Bundestag, 1971" (for terms and definitions, see Annex B). In the framework of the EU a L_{Aeq}- based metric has been proposed by a EU working group as the new uniform noise metric for the European Union (EU/DG Environment, 2000). The working group expressed its preference for a L_{Aeq}-based metric with a 5 dB(A) adjustment for a 4 hours evening-time period and a 10 dB(A) adjustment for a 8 hours night-time period, beginning and end of these periods in regulations of a specific country left to the preference of that country. The German Störindex has been based on a division of the 24 hour period in day-time of 06 – 22 h and night-time of 22 – 06 h.

With a view on a possible change in the German aircraft noise exposure regulations from the Störindex as descriptor of overall aircraft noise exposure to a L_{Aeq}-based metric, TNO Prevention and Health carried out a project by order of the Umwelt Bundesambt (UBA). The project has been executed in the framework of the Umweltforschungsplan 1999, Forschungs- und Entwicklungsvorhaben 299 51 255, thema "Umweltqualitatsziele zum Schutz vor schädlichen Umwelteinwirkungen durch Fluglärm". The aim of the project is to collect and analyse data in order to obtain scientific results that can be used in a political decision about future aircraft noise exposure regulations in Germany.

UBA formulated questions and aims of the project. For the formulation of quality endpoints to be met in regulations, UBA considers the following adverse noise-induced effects of main importance:

- Annoyance;
- Somatic health;
- Speech disturbance;
- Recreation disturbance;
- Sleep disturbance.

With respect to aircraft noise-induced annoyance, the following specific questions have been derived from the preparatory paper by UBA:

1. Is there a difference in the correlation for the relationship between the Störindex and aircraft noise-induced annoyance and that relationship with L_{Aeq}- based metrics?
2. Which values of a L_{Aeq}- based metric (such as DNL) correspond with the Störindex values equal to 67 and 75 dB(A)?
3. Is it possible to give an indication of adjustments for aircraft noise events during winter-, spring- and autumn- time, relative to aircraft noise events during summer-time?

With respect to the other adverse noise-induced health effects, it concerns the following questions:

4. Given the values of the Störindex equal to 67 and 75 dB(A) (or the corresponding L_{Aeq}- based metric values), which other adverse noise-induced health effects are to be expected above these levels?
5. Given the values of the Störindex equal to 67 and 75 dB(A) (or the corresponding L_{Aeq}- based metric values), is it advisable to put a limit to the characteristics of single aircraft noise events? For which other adverse noise-induced health effects would this be appropriate and what should be the limiting SEL or L_{Amax} value?

According to the preparatory paper, questions can be answered by:
1. analysing or re-analysing available datasets;
2. analysing relevant literature;
3. collecting and analysing the present aircraft noise regulations in other countries.

Taking the data available to TNO, different approaches are appropriate with respect to annoyance and with respect to the other four adverse effects. With respect to annoyance; TNO has available several datasets from socio-acoustic surveys with data about annoyance and aircraft noise exposure of respondents. These datasets are analysed to obtain responses to questions related to annoyance and noise exposure. With respect to the other four adverse effects, TNO does not have any datasets available for analysis at the moment. Information will be obtained from the relevant literature.

With respect to questions about annoyance, the following activities have been carried out in the project:

1. *Analyses or re-analyses of available datasets*
   With respect to annoyance, two sets of data have been used:
   - Dataset Amsterdam Airport Schiphol (TNO-PG and RIVM, 1998). This dataset contains information about aircraft noise annoyance of over 11 000 respondents and about the distribution of sound levels outside the dwelling of respondents (specified as SEL) of all aircraft noise events during a year;
   - TNO database with data of over 60 000 respondents of over 50 socio-acoustic surveys. This database has already been used for specifying exposure-effect relationships between noise annoyance and noise exposure, also for aircraft noise (Miedema and Vos, 1998). Also, effect-modifying factors have been established by analysing the data (Miedema and Vos, 1999). The database includes four datasets that can be used to compare the accuracies (in terms of correlation coefficients) of the relationships between annoyance and Störindex and between annoyance and L_{Aeq}-based metrics. These four datasets are: USA Four Airport Survey (phase I of Tracor Survey) (1967) (3 499 respondents), USA Three

Airport Survey (phase II of Tracor Survey) (1969) (2 828 respondents), USA Small City Airports Survey (small City Tracor Survey) (1970) (1 112 respondents), and Heathrow Aircraft Noise Survey (1967) (4 515 respondents).

2. *Analyses of relevant literature*

1. A model is elaborated to consider whether it is useful to limit L_{Amax} or SEL of single aircraft noise events to limit specific adverse health effects (such as awakening), if there is already an overall limit (based on L_{Aeq}-metrics or Störindex) for annoyance;

2. The Health Council of the Netherlands published two reports (1994, 1997, see also Passchier-Vermeer, 1993) about noise and health and about assessing noise exposure for public health. The reports have been established by two international committees. The conclusions of these two reports are taken as a starting point for an up-date of knowledge about adverse noise-induced health effects by incorporating results of more recent investigations.

The report is structured as follows. Chapter 2 considers items about the quantification of aircraft noise exposure in terms of L_{Aeq}- based metrics and the Störindex. The correlations of annoyance and L_{Aeq}- based metrics and the correlation of annoyance and Störindex are compared. Section 2.2 presents results based on the Amsterdam Airport Schiphol Survey and section 2.3 of the analysis of the USA Tracor and UK Heathrow Surveys. Chapter 3 first discusses the question which adverse noise-induced effects can in principle be limited by limiting characteristics of single aircraft noise events if overall limits are already in existence. The question is further elaborated for three specific disturbances: awakening as part of sleep disturbance, speech interruption as part of conversation, and intelligibility of radio and television as part of recreation disturbance. A stepwise procedure is presented which can be used to decide about a limit for a noise characteristic of single noise events with respect to awakening in addition to an overall night-time limit of aircraft noise exposure. In chapter 4 the present state of knowledge of adverse noise-induced health effects is given. In the conclusion given in chapter 5, questions put forward by UBA are answered. References are given in chapter 6, tables in annex A and terms, definitions, equations and their derivations in Annex B.

2 Quantification of aircraft noise exposure

2.1 Introduction

Many different noise metrics have been proposed for the prediction of aircraft noise-induced annoyance in communities. Three important aspects of aircraft noise metrics are:

- The use of the noise metric to specify a single aircraft noise event. Mainly two metrics are in use: L_{Amax} and SEL (for definitions, see Annex B);
- The quantification of the trade-off between number and levels (L_{Amax}, SEL) of aircraft noise events. By using L_{Aeq}-based metrics for the prediction of aircraft noise annoyance, it is implicitly assumed that the effect on annoyance of doubling the number aircraft noise events can be off-set by a 3 dB(A) reduction of the (SEL) levels of these events;
- The weighting of noise at different times of the day (day, evening, night) and the definition of these periods.

Noise metrics differ in the three aspects given above. The German Störindex and the Netherlands Ke (Kosten Unit) use L_{Amax} as measure to specify a single aircraft noise event. Values of L_{Aeq}-metrics for situations with single noise events, such as in air traffic, can basically be derived from SEL as event descriptor. L_{Aeq}- based metrics with different time-of-day adjustments are $L_{Aeq,24h}$ (no adjustment), DNL (10 dB(A) adjustment for noise events in the period 22 – 7 h) and LDEN (5 dB(A) adjustment for noise events in the period 19 – 23 h, and 10 dB(A) adjustment for 23 – 7 h) [1]. The German Störindex is a somewhat more complicated aircraft noise exposure metric (see Annex B). It is a maximum of two indices, which makes it impossible to express the adjustment for night-time aircraft noise events in a simple way [2].

In Miedema, Vos and de Jong (2000) the optimal quantification of the trade-off and time-of-day adjustments for the prediction of noise annoyance has been investigated by using SEL as the descriptor of an aircraft noise event and by specifying day as 07 – 23 h and night as 23 – 07 h. The publication presents the results of analyses of data from a large aircraft noise effects study (TNO-PG and RIVM, 1998; code NET-371 in a recent, unpublished update of Fields' catalogue), which was conducted in 1996 around Amsterdam Airport Schiphol.

In the following section the same analysis method is applied to the data of the Amsterdam Airport Schiphol study to obtain for a L_{Aeq}-based metric the optimal quantification of trade-off and

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[1] If all aircraft noise events have equal SEL, for LAeq metrics an adjustment of 5 dB(A) implies that 3.16 aircraft noise events during the not adjusted period off-set one aircraft noise event during the adjusted period. An adjustment of 10 dB(A) implies an off-set of 10 to 1 event.

[2] The Störindex is the maximum of an index for aircraft noise events during the day (06 – 22 h) (night-time aircraft noise events are not taken into account) and an index for all aircraft noise events with an off-set of 5 to 1 event for the period 22 – 6 h.

of the night-time adjustment by specifying day as 06 – 22 h and night as 22 – 06 h. The results are compared with those obtained by specifying aircraft noise exposure with the German Störindex.

As mentioned in the Introduction, also four studies from the TNO database can be used to study relationships between annoyance and Störindex and relationships between L_{Aeq} – based metrics. This is further elaborated in section 2.3.

2.2 Amsterdam Airport Schiphol study

2.2.1 Description

In the study a sample was drawn from dwellings within a circle around Schiphol with a radius of 25 km. The sample was stratified according to noise load and distance to the airport. A total of 11 812 respondents (response rate: 39 %) returned the mail questionnaire. The questionnaires of 10 495 respondents have been analysed, because 1 317 respondents were excluded: 670 respondents in the highest exposure zone with dwellings heavily insulated against aircraft noise in a special program funded by the government and 647 respondents with relevant missing values.

Respondents rated, among other aspects, aircraft noise annoyance. First they answered the question 'How often do you hear the following noise sources at home?' ('Hoe vaak hoort u thuis de volgende geluidbronnen?'). One of the sources to be rated was aircraft. Except when the response for a source was 'never', the next question 'How annoying or not annoying is the noise of the following sources at home according to you?' ('Hoe hinderlijk of niet hinderlijk vindt u bij u thuis het geluid van de volgende bronnen?') had to be answered for that source. There were eleven numbered response categories with label 'not at all annoying' ('helemaal niet hinderlijk') at category 0 and label 'very annoying' ('heel erg hinderlijk') at category 10. The annoyance score was obtained by assigning the numbers 4.5, 13.6, ..., 86.4, 95.5 to annoyance categories. (The general rule applied is $\text{score}_{\text{category } i} = 100\,(i - ½) / m$, where m is the number of categories and i = 1,..,m is the rank number of the category) Respondents who never heard aircraft noise were assumed to be not at all annoyed by aircraft noise.

For each of the respondents various noise metrics were calculated with the method that is legally prescribed in the Netherlands aircraft noise regulations (Rijksluchtvaartdienst, 1996). Input for the calculations were the actual flight data of each flight (time, takeoff or landing, type of aircraft, flight path recorded by the flight tracking system) obtained from the airport for the year preceding the survey. In addition to overall noise metrics, also frequency distributions of SEL were determined for each dwelling of a respondent for each of the following time periods: 7 - 19h, 19 - 22h, 22 - 23h, 23 – 6 h, and 6 – 7 h. For the calculation of the Störindex the 24 hours period is divided in the two periods 6 – 22 h en 22 – 6 h.

Following the analyses in Miedema, Vos and de Jong (2000) this analysis takes into account two important specific weaknesses of the Amsterdam Airport Schiphol study, namely, a low response rate (usual for a mail survey) and uncertainties in the calculated SEL values. The possible impact of the low response rate was explored by using results from a non-response study in which 271 persons who did not respond in the main study answered through the telephone a limited set of questions. Results in this section will be presented in which selective non-response of the respondents is taken into account by weighting the results of the study (weighted values) and in which this has not been implemented (unweighted values). The possible impact of inaccuracies in the calculated SEL was explored by using the results from a study (Jonkhart, 1997) in which aircraft noise event measurements were compared with results from noise levels calculated with the same model and software implementation used in the Amsterdam Airport Schiphol study. In Miedema, Vos and de Jong (2000) an equation was derived to convert the calculated SEL values (the so-called uncorrected SEL values) into SEL values that would have been measured (the so-called corrected SEL values)[3]. Results in this section are be presented in which corrected and uncorrected SEL values are used.

Table 1 (Annex A) gives the distributions of the (corrected and uncorrected) SEL values of the aircraft noise events over a period of a year preceding the questionnaire survey. The numbers are averages over the 10 495 respondents used in the analyses. Numbers of events are given for day- and night-time separately and for respondents weighted and unweighted for selective non-response.

2.2.2 Models

In Miedema, Vos and de Jong (2000) a general model has been presented which allows the assessment of the optimal quantification of the trade-off between SEL and number of aircraft noise events, and of the optimal time-of-day adjustments for predicting noise annoyance. The model combines SEL values of single aircraft noise events with parameter α for the trade-off and parameters w_k for time-of-day weights. This model will be fitted to the data, and the estimates of the parameters will give an insight in the optimal trade-off, time-of-day adjustment and correlation between aircraft noise exposure (over a year) and annoyance. The model with parameter $\alpha = 1$ (which implies the usual L_{Aeq}-based metrics) will also be fitted to the data.

The results of the optimalisations are compared with the results obtained if the Störindex (used in the present German legislation of aircraft noise exposure) is used as aircraft noise metric. The German Störindex takes into account differences in aircraft noise exposure over a year, by specifying the observation period as the noisiest six months of the year. This aspect, unfortunately, could not be taken into account in the present analysis.

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[3] The following formula was derived: SEL = 0.65 SEL' + 31.1, in which SEL is the corrected value, and SEL' the uncorrected value. This implies, e.g., SEL' = 68 dB is adjusted to SEL = 75 dB, and SEL' = 113 dB is adjusted to SEL = 105 dB.

The model (Miedema, Vos and de Jong, 2000) of the relation between SEL of individual noise events (aircraft overflights) and noise annoyance consists of three equations. The first linear equation describes the relation between a metric and annoyance and the following two equations define the noise metric $L_{\alpha,w}$,:

(1) $A = p\ (L_{\alpha,w} - q)$ for $L_{\alpha,w} > q$ ($A = 0$ for $L_{\alpha,w} \leq q$),

where A is the noise annoyance score, and the rate of increase of the annoyance p and annoyance threshold q are (positive) parameters. A simple linear relationship has been found earlier to give an adequate description if annoyance scores are used with $L_{Aeq,24h}$ or DNL as noise metrics (Miedema, 1992). These latter metrics are special cases of $L_{\alpha,w}$.
The composition of metric $L_{\alpha,w}$ is formulated in two steps. The first step concerns the combination of SEL of single events into a measure, $L_{Aeq,\ \alpha}$, for noise during a particular period of the day. The combination rule is taken the same for different periods of the day. The second step concerns the combination of the $L_{Aeq,\ \alpha}$'s for the periods of the day into the overall metric, $L_{\alpha,w}$.

A general rule for combining SEL values into a measure of long-term noise exposure $L_{Aeq.\alpha}$ (which is equal to the common L_{Aeq} if $\alpha = 1$) is:

(2) $L_{Aeq.\alpha} = 10 \lg [(1/T) \sum_i x_i^{\alpha}]$ [dB(A)]

x_i : $10^{SEL/10}$ of event i [dB(A)]
α : positive trade-off parameter
T : duration of the period [s].

The right-hand side of the above equation is a special case of a (logarithmic transformation of a) so-called power sum. Using the approach and results from measurement theory (Krantz et al., 1971; Narens, 1985; Luce et al., 1990), Miedema (1996) discusses basic qualitative properties of power sums that can be empirically tested.
Compared to L_{Aeq} (i.e., $\alpha = 1$) the events with the highest SEL have a larger effect on $L_{Aeq.\alpha}$ if $\alpha > 1$ and a smaller effect if $\alpha < 1$. In other words, the effect on $L_{Aeq.\alpha}$ of events with the lower SEL is smaller if α is higher.

The following rule for combining the $L_{Aeq.\alpha}$'s from various periods of the day into the noise measure $L_{\alpha,w}$ for the 24 h day is also a special case of the above-mentioned power sum:

(3) $L_{\alpha,w} = 10 \lg [\sum_k (T_k/T).w_k x_k]$ [dB(A)]

x_k : $10^{L_{Aeq.\alpha}/10}$ of period k [dB(A)]
w_k : positive time-of-day weights
T_k : duration of period k [s]
T : duration of the total period [s].

The time-of-day weights w_k in equation 3 are weights relative to the weight for the daytime, which is taken equal to 1. Various common metrics can be obtained by setting $\alpha = 1$ and using the appropriate distinction in periods and values for weights w_k for these periods. For example, when the 24 hours period is divided in the periods 7 - 22h and 22 - 7h, and w_k is set equal to 1 and 10, respectively, for these periods, then $L_{\alpha,w}$ is equal to DNL.

2.2.3 Results

The first objective of the analyses is to find optimal values for the trade-off parameter α and the time-of-day weights w_k in the model (equations 1, 2, and 3) for the prediction of annoyance caused by aircraft noise, if the day-time period is 06 – 22 h and the night-time period 22 – 06 h. Estimates are obtained by fitting the model to the data from the Amsterdam Airport Schiphol study. The results are obtained with the day-time weight $w_{06\text{-}22h}$ set equal to 1. For the assessment of the optimal time-of-day weights, the analysis could only be performed with the 24 hours period divided in two periods, due to the high correlation between day- and evening-time data. Therefore only one other time-of-day weight (night-time weight $w_{22\text{-}06h}$) has to be optimised.

As specified in Miedema, Vos and de Jong (2000) the parameters (p, q,) α, and w_k cannot be estimated with the standard regression technique that finds the optimal weights for a linear combination, because eqs. 2 and 3 are non-linear. Instead, the parameters are estimated with the iterative Marquardt procedure (cf. Draper, 1981). Like the analytical regression procedure for linear combinations this technique determines the values of the parameters that minimise the sum of squared deviations of the predicted values from the observed ones. Results are presented in table 2 for all four combinations of no SEL correction applied versus SEL correction applied (the 'columns' within the cells of table 2) with no weight for selective non-response applied versus weight for selective non-response applied (the 'rows' within the cells of table 2).
If trade-off parameter α and night-time weight $w_{22\text{-}06h}$ (and p and q) are optimal (first main row of table 2), then applying the SEL correction (which is a linear function) or not has no impact on the correlation coefficient, parameter p and the time-of-day weight $w_{22\text{-}06h}$. In case of the optimal quantification of α and night-time weight $w_{22\text{-}06h}$ (and p and q), the correlation coefficient is equal to 0.317 if no weight for selective non-response is applied and 0.295 if this weight is applied. This implies that even for the optimal noise metric the variance explained by aircraft noise exposure is only about 9 to 10%.
The second main row gives the results if trade-off parameter α is set equal to 1 and only the night-time weight $w_{22\text{-}06h}$ is optimised (second main row). The correlation coefficient hardly decreases (0.001) compared to the results with optimisation of α and $w_{22\text{-}06h}$. In the third main row the results of a linear regression analysis is given if $\alpha = 1$ and $W_{22\text{-}06h} = 10$ (this implies a metric comparable to DNL, but with day- and night-time of 06 – 22 h, and 22 – 06 h, respectively). The 95% confidence limits of each of the correlation coefficients in the table are ± 0.017. This implies that the correlation coefficient of the relationships between annoyance score and noise metrics with $\alpha = 1$ (including the model with $W_{22\text{-}06h} = 10$) is not statistically significant lower than the correlation coefficient for the optimal solution.

The German Störindex (SI) is the maximum of an index (SI(day)) for aircraft noise events during the day (06 – 22 h) (in which night-time aircraft noise events are not taken into account) and an index (SI(day + night)) for all aircraft noise events with an off-set of 5 to 1 event for the period 22 – 6 h. The last three rows of table 2 present the results of linear regression analyses with SI(day), SI(day + night) and SI as independent variables. Although there are no statistically significant differences between the correlation coefficients in these three cases, the model with SI(day) as noise metric gives somewhat lower correlation coefficients than the models with SI or SI(day + night).

There are only minor, and statistically not significant, differences in the correlation coefficients for the model with the Störindex as noise metric and for the models with the optimal noise metric and with $\alpha = 1$ (including the model with $W_{22\text{-}06h} = 10$). This implies that the analysis of the data in the Amsterdam Airport Schiphol study shows that the correlation of the Störindex and aircraft noise annoyance is about the same as the correlations of L_{Aeq}-based overall metrics with an adjustment of about 10 dB(A) to the night-time aircraft noise events during the period 22 – 6 h and aircraft noise annoyance.

2.3 UK Heathrow Aircraft Noise Survey and USA Tracor Airport Surveys

2.3.1 Introduction

The TNO database contains four datasets that are suitable to compare the correlation of annoyance and Störindex on one hand and the correlations of annoyance and L_{Aeq}-based metrics on the other hand. These four surveys are: USA Four Airport Survey (phase I of Tracor Survey) (1967) (3 499 respondents), USA Three Airport Survey (phase II of Tracor Survey) (1969) (2 828 respondents), USA Small City Airports Survey (small City Tracor Survey) (1970) (1 112 respondents), and Heathrow Aircraft Noise Survey (1967) (4 515 respondents). A detailed description of these surveys is given in Miedema and Vos (1996). That report also contains the information how DNL and other L_{Aeq}-based metrics were derived from the data available in the database. The four datasets contain information about t(-10) (period during which the sound level is between L_{Amax} and L_{Amax} -10) and L_{Amax} (or maximum PNdB level) of (combinations of) aircraft noise events. This information allows the assessment of an approximation of the Störindex.

2.3.2 Methods

For the four surveys the Störindex was derived as described below.

Heathrow Aircraft Noise Survey
The noise data consist of maximum noise levels L, durations D and number of aircraft N for three periods of the day. The noise level L is the average value over of the maximum PNdB levels of the aircraft noise events. The average value of L_{Amax} (in dB(A)) is taken equal to L – 13. From D,

the time during which PNdB exceeds 80 dB (corresponding to the time during which the A-weighted sound level exceeds 67 dB(A)), t(-10) is calculated by using the equation:

$$t(-10) = 10D/(L_{Amax} - 67) \quad [s]$$

From the noise metrics, for each of the respondents an estimate of the Störindex was derived by using the equations given in Annex B. It is an approximation of the Störindex , since the data are expressed in terms of average t(-10) and average L_{Amax}.values.

USA Airport Surveys (phases I, II and III of Tracor Survey)
The data about the aircraft noise exposures contains information separately for day (06 – 21 h) and night (21 – 06 h). Equations are given for the relationship between t(-10) and a measure of maximum level (PNdB(peak)) for arrivals and departures separately. PNdB(peak) has been converted to L_{Amax}. In the database the number of aircraft noise events and the energy-averaged value of the individual PNdB(peak) values is given for different categories of aircraft (aircraft with 4 jet engines flying over 2000 miles and those flying less than 2000 miles, aircraft with 2 or 3 jet engines). From these data estimates of the Störindex and of DNL have been derived. From the information given about the distribution of number of aircraft over the 24 hours period, for the calculation of the Störindex it is estimated that 3% of the 24 hours aircraft is between 21 and 22 h. The estimated values are approximations since only the average value of t(-10) for each category of aircraft is available and not the combination of t(-10) and L_{Amax} for each aircraft noise event separately.

For each of the four surveys the correlation coefficients have been calculated for the relationship between annoyance score and Störindex (with night-time 22 – 06 h) and for the relationships between annoyance score and DNL and LDEN (with night-time 23 – 07 h).

2.3.3 Results

In table 4 the correlation coefficients of the relationships between annoyance score and Störindex and between annoyance score and DNL and LDEN are given. The table shows about the same values of the coefficients for the Heathrow study, a somewhat smaller coefficient for SI than for DNL and for LDEN in the first phase of the USA Tracor study, a larger coefficient for SI than for DNL and for LDEN in the second and third phases, be it that the differences in the third phase are smaller than in the second phase. Especially for the second phase of the Tracor Survey the variance in the annoyance score explained by the noise exposure is very small: only 4% with DNL and LDEN as noise metrics and 6.5% with Störindex as noise metric. For each study, the correlation coefficient for SI has been compared to those for DNL and LDEN. Only for the second Tracor study, the correlation coefficient for SI is statistically significant different (larger) than that for DNL (T = 2.65, $\alpha = 5\%$, tested two-sided).

2.4 Conclusion

The analysis of the Amsterdam Airport Schiphol study (a survey carried out in 1996) shows that the correlation of the Störindex and aircraft noise annoyance is nearly the same as that of L_{Aeq}-based overall metrics (with an adjustment of 10 dB(A) to the night-time aircraft noise events during the period 22 – 6 h) and aircraft noise annoyance. In each comparison, the correlation coefficients obtained are not statistically significant different from each other ($\alpha = 5\%$, tested two-sided). The power of the study is that it contains the SEL values of each single aircraft noise event during a period of a year for each respondent, and that the SEL values are classified according to time-of-the-day. Notwithstanding, the variance in the annoyance score explained by aircraft noise exposure is also for the optimal description of the noise exposure only 9 to 10%. Three of the four older British and American surveys (reported between 1967 and 1970) show the same trend: minor and statistically not significant differences ($\alpha = 5\%$, tested two-sided) between correlation coefficients. The second phase of the USA Tracor Survey gives a statistically significant higher correlation between Störindex and annoyance than between DNL and LDEN and annoyance. For this survey, the variance in the annoyance score explained by the Störindex is 6.5% and by the other two metrics only 4%.

In the final conclusion for various reasons much more weight should be given to the results of the Amsterdam Airport Schiphol study than to the results of the other surveys. The Amsterdam Airport Schiphol study was carried out recently, and therefore incorporates the characteristic features of modern aviation. Also, the number of respondents in the Amsterdam Airport Schiphol study is much larger than in the other surveys. Finally, the noise data of the Amsterdam Airport Schiphol study are much more detailed, since it consists of characteristics of each aircraft noise event separately and in the other four surveys average values of characteristics are given for classes of aircraft noise events. Therefore, the final conclusion of the analyses is that Störindex, DNL and LDEN perform equally well in specifying aircraft noise exposure.

3 Limiting adverse effects by setting limits to parameters of noise events

3.1 Relevant aspects of noise events

This chapter has been adapted from Miedema and Passchier (1999) (in Dutch) and it discusses the question which aspects of single noise events may cause a larger adverse effect on annoyance and sleep disturbance than should be expected on the basis of their contribution to overall measures, such as L_{Aeq} and the Störindex. At the same time it is considered which of these aspects are related to SEL or L_{Amax} and can be reduced by limiting SEL or L_{Amax} of single noise events. The discussion does not take into account the increase in noise complaints in case of (usually unexpected) loud overflights. As is shown by the complaints received by the 'Commissie Geluidhinder Schiphol' (Committee Noise Annoyance Amsterdam Airport Schiphol) the number of complaints and complainers is very strongly related to aircraft noise events which are relatively very loud in a given residential area. The discussion of aspects, related to noise events, which may possibly cause an extra adverse effect on annoyance and sleep disturbance concerns:

- fear and anxiety;
- startle;
- awakening;
- interruption of conversation due to assumed decrease of intelligibility;
- effect on recreation, such as listening to radio and television;
- vibrations and other environmental aspects;
- avoidability.

Anxiety has an important effect on annoyance. If people are exposed to the same noise load, those persons who express fear for the noise source express a higher degree of annoyance than those persons who do not express this fear. This may be explained by an increased attention to the noise due to an association with danger (Miedema and Vos, 1999). A well known example is noise from low flying fighter jets (Spreng, Leupold, Emmer, 1988).

Fear is not so much caused by high sound levels as by the feeling that the noise implies danger. To limit SEL or L_{Amax} of aircraft noise events therefore is not an effective means to counteract this effect. A more direct approach to reduce feelings of anxiety seems more effective, e.g. by regulations for a minimum height of aircraft in low-flying corridors over residential and recreational areas.

Startle due to a noise event may be caused by an unexpected rapid increase of the sound level. Even without startle such an unexpected rapid increase may be extra disturbing because it may attract attention. It is difficult to 'adjust' to unexpected noise events with a rapid increasing sound level. If the event is expected to occur the rate of increase in loudness will be less important.

Laboratory studies show in which way an extra disturbing effect is related to the onset rate (rate of change in sound level (R in dB(A)/s) at the start of a noise event). Until about 15 dB/s no extra effect is discernible. This category encompasses nearly all traffic noises (rail, road, air). Between 15 and 150 dB/s an extra adverse effect increases about linearly with lg R. This category includes low flying jets. The extra disturbing effect of these events corresponds to the annoyance from events with lower onset rates (< 15 dB/s) with a 11.lg (R/15) higher SEL value. Noise events with onset rates in excess of 150 dB/s are more annoying by about 11 dB. This category encompasses highly impulsive noises (ISO 1996-2, addendum 1, 1998). This increase by 11 dB corresponds well with the extra annoyance of shooting noise found in field investigations. (Vos, 1995, 1996, 1997) concludes on the basis of an analysis of published data that impulse noise causes the same amount of annoyance as road traffic noise with a value of DNL which is 10 - 15 dB(A) higher.
Startle is mainly caused by an unexpected quick increase of the sound level, not by a high level as such. Loud noisy events, that are expected or that increase gradually will startle less and will also attract less attention. Unexpectedness of an event is difficult to quantify. High onset rates can be assessed by a penalty, as recommended by the Health Council of the Netherlands (1997). To limit SEL or L_{Amax} of individual noise events in addition to an adjustment for a high onset rate of a noise event seems unnecessary.

Awakening is considered the most adverse effect of a noise event during sleep period time. However, the threshold for awakening by traffic and industrial noises is rather high relative to the threshold for other adverse effects during sleep periods. For instance, when trying to fall asleep or when awake during the night or early morning, noise events with sound levels below the threshold for awakening can attribute to annoyance. On average, for persons who are used to sleep in a surrounding with traffic or industrial noise events, the probability of awakening by a such an event starts if the SEL value of the event is 55 dB(A) (*indoors in the bedroom*). This value was proposed by the Health Council of the Netherlands (1997). With which *outdoors* SEL value an *indoors* SEL of 55 dB(A) corresponds depends on the sound insulation of the bedroom. In the Netherlands a value of 55 dB(A) indoors inside the bedroom corresponds *on average* with 76 dB(A) outdoors in front of the façade of the bedroom, if windows of the bedroom are closed and with 70 dB(A) for windows slightly opened. Awakening by traffic or industrial noise events, therefore on average hardly occurs when the outdoors SEL of the events do not surpass 70 or 76 dB(A). In Germany the average sound insulation of bedrooms for closed windows is higher (Ortscheid, personal communication), and therefore the threshold for awakening expressed in outdoors SEL may also be approximately 5 dB(A) higher than 76 dB(A). Noise events with higher SEL values possibly contribute to sleep disturbance annoyance to a larger extend than assumed by their contribution to an overall measure, if they cause noise-induced awakenings. Above the awakening threshold for single noise events (of 55 dB(A) indoors) the risk for awakening due to a noise event is dependent on the sound levels of the event. In this respect the use of SEL should be given preference over the use of L_{Amax} because SEL takes into account also the duration of the event (Health Council of the Netherlands, 1997). The Health Council of the Netherlands (1997) tentatively recommends for the probability of noise –induced awakenings to take into account an adjustment for impulsive, tonal, and low frequency components of noise events.

The feeling of a speaker during a noisy event to be *unintelligible* causes interruption of the conversation and is therefore an important case of disturbance. At the same time, comfort during conversation may decrease because the speaker has to speak louder and the listener has to increase his effort to understand what is spoken. In section 3.5 it is tentatively assumed that on average a speaker does usually not interrupt a conversation, held at a distance of 1 m between speaker and listener, if the SEL of a single noise event (of duration less than about a minute) does not exceed 65 dB(A) at the location of the head of the speaker. Not incorporated in the considerations is the likelihood of a reduction in distance between speaker and listener and an increase of speech volume if a noisy event occurs. Since large inter-individual differences in speech volume exist this threshold for speech interruption has a large inter-individual variation. Taking the sound insulation to be 21 to 25 dB(A), the risk of interruption of speech indoors with speaker and listener at 1 m distance starts *on average* because of an outdoors noise event with SEL equal to 86 to 90 dB(A), measured at the façade of the dwelling. This implies that speech interruptions due to aircraft noise events mainly occur outdoors (in the garden, on the balcony) and indoors with windows opened.
Whether SEL or L_{Amax} of a noise event is a better indicator for speech interruption is unknown. For sure, a speech interruption that needs to last longer, e.g. due to passing of a long goods train, is more disturbing than a short interruption. For such situations, it is likely that a possible increased effect on annoyance is better assimilated by SEL than by L_{Amax}. Whether this also holds for aircraft noise events that are usually of shorter duration is debatable.

Adverse effects on activities during recreation time fall into two categories: effects on quiet activities, such as reading, studying, making crosswords and effects on activities for which it is important that relevant sounds are not masked, such as when listening to radio and television. For the latter activities the main effect is a decrease in intelligibility and the same principals as with speech intelligibility during face to face conversation are likely to hold. In this respect, the possibility to turn up the volume of the radio or television during aircraft noise events seems of limited practical value, since for comfortable listening conditions it is required that the volume is turned lower again after the noise event. This implies that the same model as for speech interruption during face to face conversation is applied. With respect to quiet activities, it is likely that people are more disturbed or distracted by noise events than by more continuous noise with the same overall level over longer observation periods. Unfortunately, it is unknown whether and how this affects annoyance in the long run. Therefore this subject will not be further elaborated.

Vibrations and also other environmental factors such as bad smell or soot may occur due to an event that also causes noise. These and other factors may contribute to increased feelings of disturbance and fear, which may in turn cause increased noise annoyance. This implies that events causing also other disturbances may have a disproportionate effect on noise annoyance. An example is an aircraft overflight, which causes noise and also vibrations of windows and objects in the dwelling.

For aircraft noise exposure there is a weak correlation between vibration annoyance and overall noise metrics (Passchier-Vermeer, 1998a). The correlation coefficient of the relationship of vibration annoyance with L_{Aeq24h} is 0.20. In a study about railway-induced vibration- and noise annoyance it is shown that vibration exposure during day-time has an extra effect on noise annoyance (Passchier-Vermeer and Zeichart, 1998b). Overall (railway) annoyance is affected by both noise and vibration exposure. Noise exposure explains 8% of the variance in total annoyance, vibration exposure 5% and the interaction between noise and vibration exposure 3%. However, to abate vibrations it is more effective to have regulations for vibrations in dwellings (and presumably also for low frequency noise) than to set limits to SEL or L_{Amax}. The same is applicable for bad smell and soot occurring in conjunction with noisy events.

If the noise of an event is considered to be *avoidable* it causes increased annoyance. The feeling that noise exposure occurs unnecessary, increases irritation about the noise. However, avoidable noise does not only give increased annoyance only if it is very loud. For abatement of avoidable noise, effective means are changes in attitude of the noise producer, local regulations to limit the use of sound sources at specific times, emission requirements and maintenance of these requirements.

It is therefore concluded that for awakening and speech interruption it is worthwhile to further elaborate the possibility of setting limits to parameters of noise events to limit extra effects on annoyance and sleep disturbance induced annoyance.

3.2 L_{Aeq}-measures and effects of single noise events

Since noise-induced awakenings and speech interruptions are functions of SEL (and L_{Amax}) of single noise events, these effects can be reduced by limiting SEL (or L_{Amax}) of these events. This section discusses whether such limits are necessary, considering the limitations imposed by L_{Aeq} on SEL or L_{Amax}. These limitations are more unambiguous for SEL than for L_{Amax}. In what follows, situations are considered in which aircraft noise events with the same SEL occur. The conclusions, however, are also applicable for situations in which aircraft noise events with different SEL values occur.
For a situation with aircraft noise events with the same SEL, the following equations apply (see Annex B):

(1a) $L_{Aeq} = SEL + 10 \lg N - 10 \lg T$
(1b) $SI(day) = 0.92\ SEL + 13.3 \lg N_{day} - 13.3 \lg T$ [4]

L_{Aeq} is assessed over a period T (in s), which usually is one year. SEL is the sound exposure level of the noise events and N the number of noise events during period T. SI(day) is an estimate of the German Störindex, if the day-time exposure factor is relevant. N_{day} is the number of aircraft

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[4] For SI(day + night) and SI see annex B. Although the equations are complicated, the implications are the same.

noise events in the period from 06 – 22 h and T is a year (365. 24.60.60 s). The equations (1a) and (1b) show that limits in terms of SI(day) or L_{Aeq} limit the number of events with high SEL (or L_{Amax}) values. The next section discusses the consequences of this limitation on the number of times an adverse effect occurs, if the risk for an effect increases with SEL. The calculations are limited to situations in which L_{Aeq} limits are in use. These conclusions, however, also hold for situations with SI as limiting overall value.

3.3 The maximal incidence for an effect

The incidence of an effect is the number of times an effect occurs during a given period.
A model is used which specifies the relationship between the risk of an effect induced by a noise event and SEL of the event. The model is a simplification of reality, since it is formulated such that the probability of a noise-induced effect during a period is independent of other noise events during that period. For example, in case of awakenings due to noise events during sleep period time, it is accepted that the probability of awakening due to a given noise event does not depend on other noise events during sleep period time. This is a reasonable assumption if the probability of noise-induced awakenings is small and the noise events are separated widely in time. However, in situations in which the noise events succeed each other so fast that an event still has an effect on e.g. sleep depth when the next event occurs, there will be an interaction which should not be ignored.

The model is specified such that the probability of a noise-induced effect is a function f of SEL of the event. Then, the expectancy of the number of times (n) the effect occurs is:
(2) $E(n;\ SEL) = N\ .\ f(SEL)$
N is the total number of noise events during the period under consideration.
By using equation (1a) N can be substituted by an expression in terms of SEL:
(3) $E(n;\ SEL) = 10^{(L - SEL + 10lgT)/10}\ .\ f(SEL)$,
with L_{Aeq} abbreviated to L. In the following calculations, L is a fixed chosen level. By differentiating E(n; SEL) to SEL and taking the result equal to 0, at the maximal (or minimal) to be expected number of noise-induced effects the following equation is obtained:
(4) $f'(SEL) = [(\ln 10)/ 10]\ .\ f(SEL)$.
With f'(SEL) the differentiated function of f(SEL). If the function f is known, this equation allows the assessment of SEL at which SEL E(n; SEL) is maximal (Passchier-Vermeer, 1994). By substituting this value of SEL in equation (3) for E(n; SEL) and for L the limit of L_{Aeq}, the maximal noise-induced incidence of the effect in the period under consideration is determined.

Assume, in order to be able to elaborate the foregoing line of thought, the occurrence of a noise-induced effect to be a linear function of SEL:
(5) $f(SEL) = a.SEL + b = a(SEL + b/a)$ if $SEL \geq .-b/a$

$F(SEL) = 0$ if $SEL < -b/a$
The effect starts to occur at SEL = -b/a: the threshold for that effect is –b/a.

From (4) and (5) it follows that the expected number of noise-induced occurrences of the effect is maximal if:

(6) $SEL = -b/a + 10/\ln 10 = -b/a + 4.3$ [dB(A)]

For this maximal incidence the following is applicable:

(7) $f(SEL) = 10a/\ln 10$

Equation (6) shows that if the probability of a noise-induced effect is a linear function of SEL, the SEL at which the maximal incidence occurs is only a function of the threshold of the effect (-b/a) and not a function of the increase of the probability of an effect (a) above the threshold. The value of SEL at which the maximal incidence occurs is 10/ln10 = 4.3 dB(A) above the threshold for that effect.

3.4 The maximal incidence for noise-induced awakenings during sleep period time

This section illustrates in which way a limit in terms of L_{Aeq} during the night limits the number of noise-induced awakenings.

Exposure effect relationship

The following equation is used for the relationship between the probability of noise-induced awakening and indoors SEL of noise events (Health Council of the Netherlands, 1997):

(8) $f(SEL) = 0.0018(SEL - 55)$ if SEL larger than 55 dB(A);
$f(SEL) = 0$ if SEL equal or less than 55 dB(A).

Night-time L_{Aeq} limit

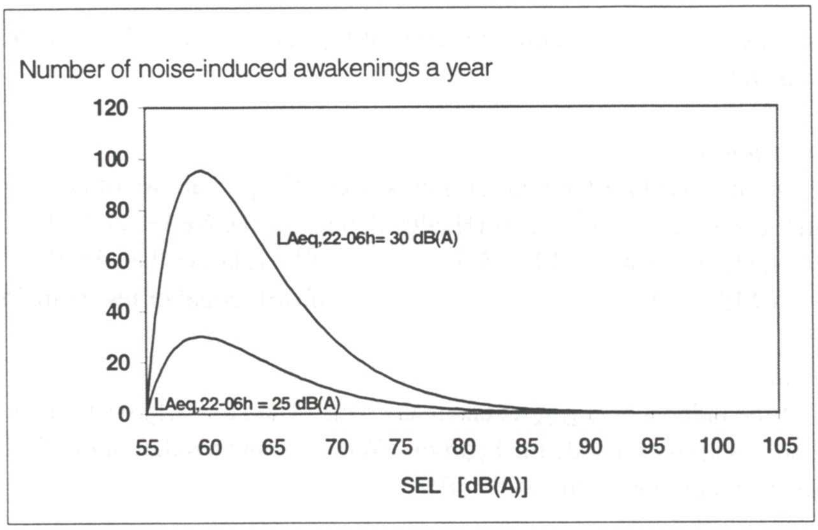
The limit of night-time indoors $L_{Aeq,22\text{-}06h}$ is taken as 25 dB(A) on a yearly basis. This limit is applicable to the noise exposure inside the bedroom. With a sound insulation of 25 dB(A), this value corresponds to an outdoors value of 50 dB(A).

Result

From equations (6) and (8) it follows that the maximum of the number of noise-induced awakenings is at SEL = 59.3 dB(A). By substitution in equation (3), the maximal incidence is 30.2 times a year. This implies that with 25 dB(A) as a limit of the indoors value of $L_{Aeq,22\text{-}06h}$, the number of noise-induced awakenings is limited to 30 times a year. Thirty noise-induced awakenings a year will happen in the most unfavourable case if all indoor SEL values are equal to 59.3 dB(A). Figure 1 gives the number of awakenings a year as a function of SEL, if $L_{Aeq,22\text{-}06h}$ is equal to 25 dB(A) on an annual basis and a probability of noise-induced awakenings as a function of SEL given in (8). SEL may have been adjusted for impulse, tonal or low frequency components. For SEL values not adjusted for these components, table 3 gives the number of noise events associated with the SEL values given in figure 1, to have a night-time $L_{Aeq,22\text{-}06h}$ of 25 dB(A) on an annual basis. For example, 333 noise events in a year (about once a night) with SEL (inside the bedroom) equal to 70 dB(A) result in $L_{Aeq,22\text{-}06h}$ of 25 dB(A) on an annual basis.

Adding a quadratic term to f(SEL) such that the same threshold for the effect is maintained, and with a doubling of the probability of noise-induced awakening at SEL = 73 dB(A) does give an increase in the SEL value with the maximal incidence of 1.6 dB(A) and an increase in the maximal incidence of noise-induced awakenings of 8 (25%) per year relative to the linear function elaborated in this section. Since there is on the basis of present knowledge no indication that a quadratic term as large as the chosen one will be necessary to meet the real situation, apparently the addition of a quadratic term does have only a slight effect on the maximal incidence of noise-induced awakenings.

Figure 1: *The number of noise-induced awakenings a year as a function of SEL. The relationship between SEL and the probability for noise-induced awakening is f(SEL) = 0.0018 (SEL-55). Each noise event does have an equal value of SEL. Therefore, if L_{Aeq} and SEL are specified, the number of noise events is fixed. In this figure $L_{Aeq,22\text{-}06h}$ is 25 dB(A) and 30 dB(A) respectively. If a limit of $L_{Aeq,22\text{-}06h}$ is chosen between 25 and 30 dB(A) the maximal incidence of noise-induced awakenings is for 26, 27, 28, en 29 dB(A) equal 38, 48, 60, en 76 times a year, respectively. SEL may have been adjusted for impulse, tonal or low frequency components.*



3.5 The maximal incidence of speech interruption

This chapter illustrates how a limit of $L_{Aeq,06\text{-}22h}$ limits the number of noise-induced speech interruptions.

Exposure effect relationships
There are no proven relationships between speech interruption due to a noise event and SEL or L_{Amax} of such an event. Hereafter a tentative relationship is presented to show how a limit of $L_{Aeq,06\text{-}22h}$ limits the number of noise-induced speech interruptions. The relations are based on data about speech level (vocal effort) at 1 m from a speaker and speech level required for sentence intelligibility as a function of background level (Heusden et al., 1979; Plomp, 1986). It is as-

sumed that *on average* decrease in speech intelligibility and speech interruption starts at 55 dB(A) and is complete at 75 dB(A). The variance in the slope and the intercept for an individual depend on individual variations in speech level, speech quality, willingness to speak louder and other individual aspects of the speaker and its surrounding.

The following tentative relationships for the probability of speech interruption during a noise event and SEL of the noise event will be applied:

$f(SEL) = 0.05(SEL - 65)$ if SEL is between 65 en 85 dB(A);
$f(SEL) = 1$ if SEL is larger than 85 dB(A);
$f(SEL) = 0$ if SEL is smaller than 65 dB(A).

Conversations usually only take place during a part of the time. Let z be the probability that a person takes part in a conversation. The probability of speech interruption is then:

$f(SEL) = 0.05z(SEL - 65)$ if SEL is between 65 en 85 dB(A);
$f(SEL) = z$ if SEL is larger than 85 dB(A);
$f(SEL) = 0$ if SEL is smaller than 65 dB(A).

Limit
The limit of outdoors $L_{Aeq.06\text{-}22h}$ (L) is 55 dB(A).

Result
By a method similar to the one applied in the calculation of maximal noise-induced awakenings it is calculated how a limit of L limits the number of speech interruptions. The calculations are more complicated, mainly because it has to be taken into account that people speak at various locations inside and outside the dwelling, with different shielding from outside noises. Let p_G be the probability of being indoors with windows closed and assume a sound insulation of 25 dB(A), let p_O be the probability of being indoors with windows partly opened and assume the sound insulation to be 15 dB(A), and assume that the rest of the time is spent outdoors (without sound insulation). The starting point is a person who is always at home. It is also assumed that conversation is independent of the location of the speaker and listener.

The maximal incidence of noise-induced speech interruptions is the sum of the expected maxima for each of three situations: outside, inside with closed windows and inside with partly opened windows. To be able to calculate the maximal incidence, values for z (probability of conversation), p_G (probability of being indoors with windows closed) and p_O (probability of being indoors with windows partly opened) have to be chosen. This determines the probability of being outdoors, which is $1 - (p_G + p_O)$. Assume for the calculations in this example that $z = 0.10$, $p_G = 0.75$ and $p_O = 0.22$. The probability of being outdoors between 06 and 22 hours is therefore equal to 0.03 (which is on average about half an hour a day).
From equations (5) and (6) it follows that the maximal incidence of noise-induced speech interruptions is for SEL = 69.3 dB(A). The maximum number of speech interruptions when outdoors is found by substituting $10 \lg T = 58.0$ ($= 10 \lg [0.03 \times 365 \times 16 \times 60 \times 60]$), L = 55 and SEL = 69.3 in equation (3), assuming z = 0.10: E(n; SEL) = 504. By substituting $10 \lg T = 66.65$ ($= 10 \lg [0.22 \times 365 \times 16 \times 60 \times 60]$), L = 40 and SEL = 69.3 dB(A), the maximal incidence of noise-

induced speech interruption for indoors with windows partly opened is found: E(n; SEL) = 117. By substituting 10 lg T = 72.0 (= 10 lg [0.75 x 365 x 16 x 60 x 60]), L = 30 and SEL = 69.3, the maximal incidence for speech interruption indoors with windows closed is found: E(n; SEL) = 40. Therefore, in this example with a limit of $L_{Aeq,06\text{-}22h}$ outdoors of 55 dB(A), the maximal incidence of noise-induced speech interruption becomes 661 (= 504 + 117 + 40) per year, assuming all suppositions are correct. This implies about 13 noise-induced speech interruptions a week, with about three-quarters of them during conversation outside the dwelling.

3.6 The maximal incidence of an effect on intelligibility of speech produced by radio and television

This section illustrates how a limit of $L_{Aeq,06\text{-}22h}$ equal to 55 dB(A) outdoors limits the number of times an adverse effect occurs on the intelligibility of speech produced by television or radio. The same model as used in section 3.5 with respect to speech interruption in a face to face conversation is applied. Therefore, the following tentative relationships for a probability of such an adverse effect during a noise event and SEL of the noise event are used:

$f(SEL) = 0.05(SEL - 65)$ if SEL is between 65 en 85 dB(A);
$f(SEL) = 1$ if SEL is larger than 85 dB(A);
$f(SEL) = 0$ if SEL is smaller than 65 dB(A).

Listening to radio or television usually only takes place during a part of the time. Let z be the probability that a person performs these activities. The probability of an adverse effect on intelligibility is then:

$f(SEL) = 0.05z(SEL - 65)$ if SEL is between 65 en 85 dB(A);
$f(SEL) = z$ if SEL is larger than 85 dB(A);
$f(SEL) = 0$ if SEL is smaller than 65 dB(A).

By the same method as applied in the calculation of maximal noise-induced speech interruptions it is calculated how a limit of L limits the number of times an adverse effect on intelligibility of speech produced by radio or television occurs.

The maximal incidence of such a noise-induced effect is the sum of the expected maxima for each of the following two situations (assuming people do not listen to radio or television outdoors): inside with closed windows and inside with partly opened windows. To be able to calculate the maximal incidence, values for z (probability of listening to radio and television), p_G (probability of being indoors with windows closed) and p_O (probability of being indoors with windows partly opened) have to be chosen. Assume for the calculations in this example that z = 0.15, $p_G = 0.75$ and $p_O = 0.22$.

From equations (5) and (6) it follows that the maximal incidence of a noise-induced effect on intelligibility is for SEL = 69.3 dB(A). The maximum number of times an effect occurs for situations with windows partly opened is found by substituting 10 lgT = 66.65 (= 10 lg [0.22 x 365 x 16 x 60 x 60]), L = 40, z = 0.15 and SEL = 69.3 dB(A): E(n; SEL) = 176. By substituting 10 lg T = 72.0 (= 10 lg [0.75 x 365 x 16 x 60 x 60]), L = 30, z = 0.15 and SEL = 69.3, the maximal incidence for an effect in situations with windows closed is found: E(n; SEL) = 60. Therefore, in this example with a limit of $L_{Aeq,06\text{-}22h}$ outdoors of 55 dB(A), the maximal incidence of a noise-induced effect on intelligibility of speech produced by radio or television is 236 times a year, assuming all suppositions are correct.

3.7 Outline to decide about an additional limit for SEL or L_{Amax} with respect to sleep disturbance

3.7.1 Introduction

This section discusses the question whether it is necessary to limit SEL or L_{Amax} in addition to a limit already in existence in terms of L_{Aeq}. The decision of an introduction of a limit for SEL or L_{Amax} to limit the occurrence of a certain adverse noise-induced effect can be made according to the general outline given in section 3.7.2. The outline has been formulated for a noise-induced effect on sleep and on the basis of an already existing limit for $L_{Aeq,22\text{-}06h}$ on an annual basis. The outline can easily be adapted to speech interruption and decrease in intelligibility of speech produced by radio or television and to other overall noise metrics. In section 3.7.3 the general outline is illustrated with an example.

3.7.2 Outline

1. Assume that L is the limit for $L_{Aeq,22\text{-}06h}$, assessed for instance on the basis of the relationship between $L_{Aeq,22\text{-}06h}$ and subjectively experienced sleep quality and other considerations.

2. Assess from investigations what the relationship is between the probability of an effect induced by a noise event and SEL of the event.

3. Assess SEL for which the number of occurrences of the noise-induced effect E(n; SEL) is maximal by solving the following equation:

   $$f'(SEL) = (\ln 10)/\ 10]\ f(SEL).= 0.23\ f(SEL)$$

   If the probability of a noise-induced effect is a linear function of SEL:

   $$f(SEL) = a.SEL + b,$$

   then E(n; SEL) is maximal if

   $$SEL = -b/a + 4.34.$$

   f(SEL) is then equal to 4.34a

4. Assess the maximum of the number of noise-induced effects by substituting the limit L, SEL from step 3, and f(SEL) in:

   $$E(n;\, SEL) = 10^{(L - SEL + 70.2)/10} f(SEL).$$

   (70.2 is based on 365 nights with T = 8 hours a night)

5. Decide which number of noise-induced effects Z is acceptable.

6. Compare the maximum found in step 4 with Z. If this maximum is larger than Z (which implies that the situation is not acceptable) either L is lowered or SEL is limited.

7. The new limit value for L (L') or a limit for SEL is calculated by solving the equation, either for SEL or L:

   $$Z = 10^{(L - SEL + 70.2)/10} f(SEL)$$

   A prerequisite constraint is: f(SEL) > 0 is, which implies for a linear relationship that SEL > -b/a.

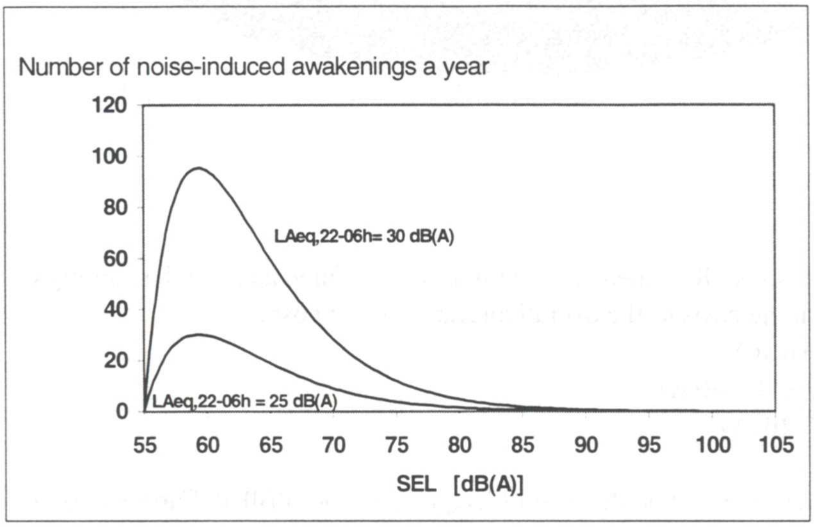
3.7.3 Example

Hereafter an example is given for noise-induced awakenings with a chosen value of Z (maximal allowed number of noise-induced awakenings a year) and $L_{Aeq,22\text{-}06h}$. In figure 3 the example is illustrated by a graphical presentation.

- Step 1. Assume the overall limit $L_{Aeq,22\text{-}06h} = 30$ dB(A);
- Step 2. Selected adverse noise-induced effect: awakening with f(SEL) = 0.0018(SEL – 55);
- Step 3. (Figure 2 gives the number of noise-induced awakenings a year as a function of SEL for L = 30 dB(A).) The number of awakenings is maximal at SEL = 59.3 dB(A);
- Step 4. E(n;SEL) = 96;
- Step 5. Assume Z = 30;
- Step 6. E(n;SEL) > Z
- Step 7. By solving the equation it is shown that with L' = 25 dB(A) the maximal number of noise-induced awakenings is 30 per year. If L is lowered to 25 dB(A), a limit for SEL is superfluous. Assume that L is kept at 30 dB(A). By solving the equation, SEL is equal to 55.6

dB(A) [5]. To meet the requirement L = 30 dB(A), the number of events with SEL=55.6 should not exceed 28840 a year, which is 79 events per night. This SEL value is an indoor value. With windows closed and a sound insulation of 25 dB(A), the corresponding outdoor SEL value is about equal to 80 dB(A) [6].

Figure 2: The number of noise-induced awakenings a year as a function of SEL. The relationship between SEL and the probability for noise-induced awakening is f(SEL) = 0.0018 (SEL-55). Each noise event does have an equal value of SEL. In this figure two curves are presented L_{Aeq}*(22-06) = 25 dB(A) and 30 dB(A) respectively. SEL at which the maximum number of awakenings occurs is the same for both curves: 59.3 dB(A). These maximal values are for* L_{Aeq}*(22-06) = 25 dB(A) 30 awakenings per year and for* L_{Aeq}*(22-06) = 30 dB(A) 96 awakenings per year. SEL may have been adjusted for impulse, tonal or low frequency components.*



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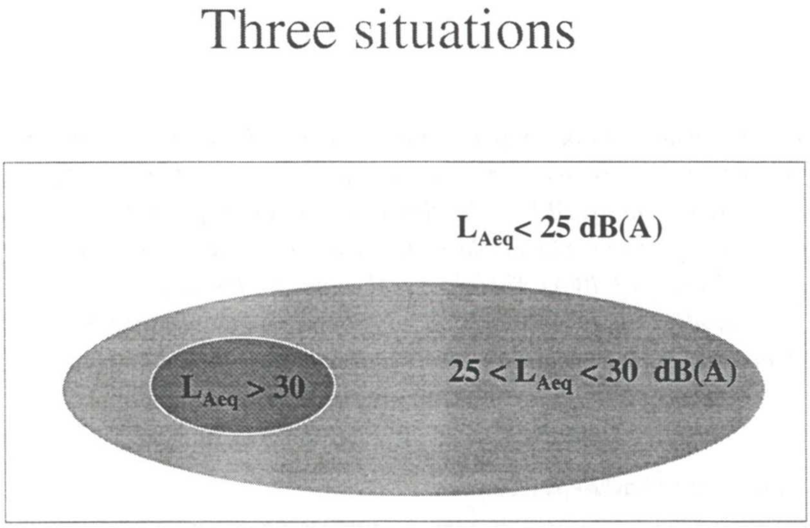
[5] Mathematical there is a second solution (see figure 2). This solution is a limit value of SEL that has to be exceeded. This second solution for SEL is equal to 69.6 dB(A) and it concerns 1140 noise events a year, which is about 3 per night. Such type of limit value is in practice not manageable.

[6] According to Ollerhead (1992) an outdoor SEL of 80 dB(A) corresponds to outdoor L_{Amax} of 69 dB(A). With a sound insulation of 25 dB(A) (windows closed), this outdoor value corresponds to an indoor of 44 dB(A).

Figure 3 Three situations in the vicinity of an airport, specified by $L_{Aeq.22\text{-}06h}$.



The example can also be illustrated as given in figure 3. Three areas in the vicinity of an airport can be specified on the basis of the overall aircraft noise exposure:

1. $L_{Aeq.22\text{-}06h} > 30$ dB(A);
2. $25 < L_{Aeq.22\text{-}06h} < 30$ dB(A);
3. $L_{Aeq.22\text{-}06h} < 25$ dB(A).

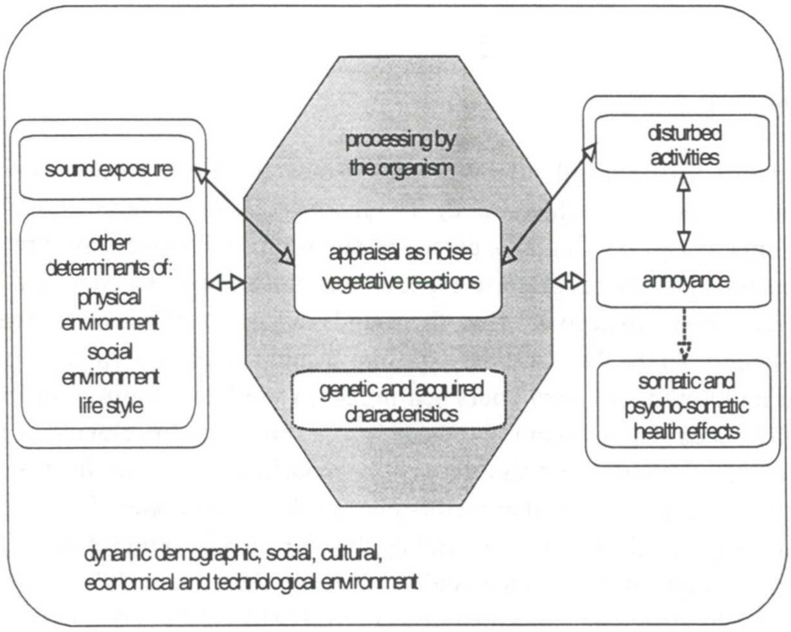
In area 1 the restriction based on the overall $L_{Aeq.22\text{-}06h}$ is not fulfilled. Further actions as a result of this infringement are necessary. In area 2 the requirement for overall $L_{Aeq.22\text{-}06h}$ is fulfilled There should, however be a limit to SEL to protect the population for too many noise-induced awakenings. To limit this number of awakenings in the population in that area, it should be required that SEL of any aircraft noise event should not exceed 55.6 dB(A). In area 3 requirements with respect to overall $L_{Aeq.22\text{-}06h}$ and SEL are both fulfilled. No specific action is required.

4 Present state of knowledge of noise-induced adverse effects on health

4.1 Introduction

A conceptual model to discuss health effects of environmental noise exposure is presented in Figure 4 (Passchier-Vermeer, Passchier, 2000). The model considers effects on health and quality of life as the outcome of a processing by a person of environmental noise exposure, such as aircraft noise exposure. The effects of noise exposure can not be understood by only taking physiological mechanisms into account. E.g., the sounds in a disco are music for the dancers but noise for the neighbours. In the first case the exposure would not be annoying, but is expected to contribute to hearing loss; for the neighbours hearing loss would be most improbable, but annoyance would certainly occur among them. Exposure, processing and effect take place within the economic and social environment and all three will be modified by societal factors. Furthermore, lifestyle and concurrent exposure to other factors play a role. An example of the former was given above. An example of the latter is the finding that the perceived presence of aircraft crash risk has been found to augment annoyance (and vice versa) (Reijneveld, 1994). This processing of noise is influenced by the genetic and acquired characteristics of the organism. E.g., some people have a specific sensitivity to noise and will be more susceptible to one or all of the effects than others. Examples of societal factors that determine the adverse effects associated with noise exposure are insulation of houses, noise level related depreciation of house prices and the individual and societal appreciation of the activities generating the noise.

Figure 4 Model of the interaction of sound with the organism and the occurrence of effects on health and quality of life.



4.2 Assessment of health effects

4.2.1 Introduction

The Committee on Noise and Health, an international committee of the Health Council of the Netherlands, assessed in 1994 the health effects of environmental and occupational noise exposure (Health Council of the Netherlands, 1994; see also Passchier-Vermeer, 1993). It rated the evidence in terms of categories used by the International Agency on the Research of Cancer (IARC Monographs, 1997) as sufficient, limited, inadequate and lacking. In the report also observation thresholds are presented for those adverse health effects for which sufficient evidence was considered to be available. The observation threshold for an effect has been defined in the report as the lowest noise exposure value at which on average the effect has been observed in well-designed epidemiological studies. An observation threshold concerns an average population of adults or an average population otherwise specified, such as babies of women exposed to noise during pregnancy. This definition implies that in the course of time the observation threshold of an effect may have to be lowered if that is supported by new information from epidemiological studies.

In this chapter, the 1994 Health Council report is taken as a starting point. More recent reviews (IEH (Institute for Environment and Health), 1997; Berglund, 1996; Morrell, Taylor, Lyle,1997; Porter, Flindell, Berry, 1998; Shaw,1996; Thompson, 1996;Job,1996), and papers presented at the meeting of the International Commission on the Biological Effects of Noise in Sydney, Aus-

tralia (Carter, 1998), were used to extend the 1994 evaluation. In general the more recent reviews and papers concur well with the conclusions of the Health Council, if we take a rating of 'inconclusive' as equivalent to the Health Council's 'limited'. With respect to some effects there appear to be differences of opinion: ischaemic heart disease, hypertension and congenital effects. This will be further discussed below.
In Table 5 information is given about the adverse effects related to environmental and occupational noise exposure that have been examined in epidemiological studies. The table is adapted from table 1 of the 1994 Health Council report. The changes concern the noise metric in which the observation thresholds for hypertension and ischaemic heart disease were originally given[7]. Also the observation threshold for awakening by a single noise event was lowered by 5 dB(A). Finally, it has been added that the observation threshold for sleep pattern changes is below 60 dB(A) (expressed in outdoors $L_{Aeq,night}$).
Several of the health end points are not specific to noise exposure. In fact, as was mentioned above and in accordance with the conceptual model of Figure 4, factors that apparently modify the effects of noise exposure may also affect health in a similar way as noise exposure. Situations exist where it difficult to identify primary and modifying factors.

The following sections will highlight the main aspects of the data on environmental noise exposure presented in Table 5.

4.2.2 Noise-induced hearing impairment

Hearing impairment is an increase in hearing threshold level (ISO 1999, 1990). International Standard ISO 1999 gives a method to estimate noise-induced hearing impairment in populations exposed to continuous, intermittent and impulse noise during working hours. Noise exposure is characterised by the equivalent sound level over an 8 hours working day ($L_{Aeq,8h}$). Since the method specified in ISO 1999 is the only universally adopted method to estimate occupational noise-induced hearing impairment, attempts have been made to assess whether this method is applicable also to hearing impairment due to environmental noise, including leisure time noise. The results of various studies strongly suggest that the ISO 1999 procedure can also be accepted for environmental and leisure time noise exposures of adults and older children, provided the exposures are not too extreme and the exposures are expressed in $L_{Aeq,24h}$ (as now exposure during the full 24 hours day is of importance) instead of $L_{Aeq,8h}$ (Health Council of the Nether-

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[7] The conversions are between the day-time equivalent sound level and DNL. For most situations with higher environmental noise exposures, day- and night-time exposures are highly correlated. For road traffic noise, the average difference between day- and night-time equivalent sound levels is about 8 dB(A). This implies that the difference DNL- $L_{Aeq,24h}$ is about 2 dB(A), and the difference between the daytime equivalent sound level and DNL about –1 dB(A). For aircraft noise exposure the noise metric used in the relevant study has been converted to DNL directly. This resulted in an estimated observation level of 70 dB(A). Also taking into account the accuracy with which the observation thresholds for hypertension and ischaemic heart disease could be established, for those noise-induced effects DNL is taken equal to the daytime equivalent sound level in the case of road traffic noise and 70 dB(A) in case of aircraft noise exposure. This resulted in the 70 dB(A) given in table 5.

lands, 1994; WHO, 1980, 2000; Passchier-Vermeer, 1993; Passchier-Vermeer, Vos, Steenbekkers, 1998; Smoorenburg, 1998; Struwe, Jansen, Schwarze, Schwenzer, Nitzsche, 1996; Babisch, Ising 1989; Pfander, Bongartz, Brinkmann, Kietz, 1980; Ising, Hanel, Pilgramm, Babisch, Lindthammer,1994; Passchier-Vermeer, 1991). This implies that exposure to environmental noise with $L_{Aeq.24h}$ values below 70 dB(A) does not cause hearing impairment in the large majority of people (over 95%), even in case of life time exposure[8]. It should be borne in mind, however, that there are no large-scale epidemiological studies that investigated noise-induced hearing impairment in the general population that do support this proposition. Also, data from animal experiments indicate that young children may be more vulnerable in acquiring noise-induced hearing impairment than adults (Passchier-Vermeer, 1991). For impulsive (shooting) noise with $L_{Aeq,24h}$ over 80 dB(A), studies on temporary threshold shifts suggest the possibility of an increased risk for impulse noise-induced hearing impairment in adults (Smoorenburg, 1998).
At very high instantaneous sound levels mechanical damage to the outer and the inner ear may occur. Occupational limits for such types of exposures have been set equal to the observation threshold for this effect at a peak sound pressure level of 140 dB (European Council, 1986). For adults, it is plausible that a similar threshold applies with respect to exposure to environmental and leisure time noise. In the case of children, however, also taking into account their habits while playing with noisy toys, peak sound pressure levels above 120 dB may cause mechanical damage to the hearing organ (Passchier-Vermeer, 1991). Peak sound pressure levels of noisy toys of 120 dB correspond to L_{Amax} of about 20 dB(A) lower. With respect to low-flying aircraft a value of L_{Amax} of about 115 dB(A) should not be surpassed to avoid hearing damage in the child's ear (Spreng, 1989).

4.2.3 Annoyance

Noise annoyance is a feeling of resentment, displeasure, discomfort, dissatisfaction or offence when noise interferes with someone's thoughts, feelings or actual activities. It is as yet impossible to predict noise annoyance of the individual person due to the large variety of (partly unknown) endogeneous and exogeneous characteristics that affect annoyance (cf. Figure 4). However, on a population level relationships between noise annoyance and noise exposure have been elucidated, together with several effect modifying factors. Annoyance in populations is evaluated by using questionnaires. Exposure-effect relationships have been derived for exposure to the three main types of traffic noise: road, and railway traffic and aircraft. The most recent and comprehensive relationships are shown in Figure 5 (Miedema, Vos, 1998). The relationships pertain to populations that have been chronically exposed to noise at the given levels for periods of time of more than a year. The effect is specified as the percentage of the population that is highly annoyed by a specific environmental noise. Highly annoyed are those persons that respond to a question about the degree of annoyance in the worst 28% of the possible range of answer

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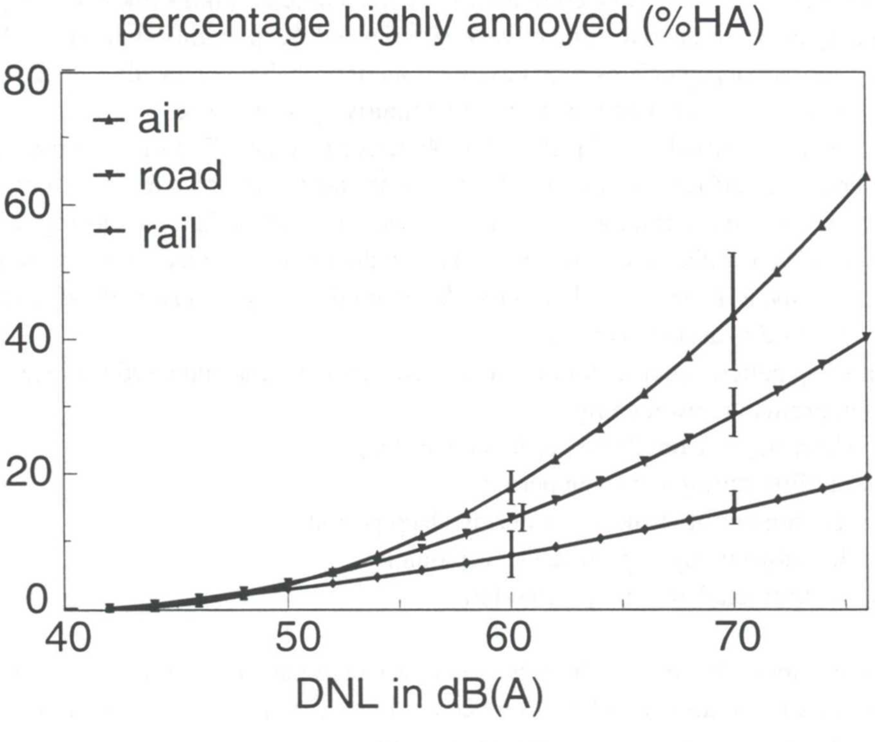
[8] A $L_{Aeq.8h}$ value of X dB(A) corresponds to a $L_{Aeq.24h}$ value of X - 5 dB(A). Therefore the exposure-response relationships of ISO 1999 that are expressed in $L_{Aeq.8h}$, should be shifted with 5 dB(A) to be applicable to environmental exposures expressed in $L_{Aeq.24h}$.

categories[9]. The noise exposure is expressed in DNL, assessed in front of the facade of dwellings. The relationships depicted in Figure 5 demonstrate that annoyance induced by the different modes of transport —air, road, rail— differs at the higher exposure levels. Taking the statistical variations within and between the various studies into account it was shown that aircraft noise is statistically significantly more annoying than road traffic noise and that railway noise is less annoying.

Figure 5 Relationships between the percentage highly annoyed and DNL for air, road and railway traffic noise. Each curve has been derived by a multilevel analysis of all studies for which original data were available. The vertical bars at 60 and 70 dB(A) represent 95%-confidence intervals (bar at 60 dB(A) for 'road' has been displaced by 0.5 dB(A) for clarity).



Environmental noise exposure is only one of the factors that contributes to noise annoyance, albeit a significant one. The degree of annoyance experienced by an individual, but also on a population level can in practice differ considerably from the exposure-response relationships presented in Figure 5, because of the influence of so-called non-acoustical factors. Important

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[9] In the various surveys on which the exposure-response relationships of Figure 5 are based, various measuring scales were used to assess the responses to annoyance questions. The procedures for converting the different measuring scales to a common one is discussed in Miedema and Vos, 1998.

non-acoustical effect-modifying factors are anxiety, fear of the noise source and the feeling that the noise could be avoided. These effect-modifying factors have been identified in multivariate analyses of population data (Job,1996; Lercher, 1998;Guski, 1999; Job, 1999; Miedema, Vos, 1999; Stallen, 1999).

4.2.4 Sleep disturbance

Sleep is a recovery process that is essential for humans to function properly. Besides, people like to sleep and usually consider a good night's sleep to be an important aspect of an individual's quality of life. Deleterious health effects are expected from chronic noise-induced interference with sleep, as it impairs the functions of sleep, such as brain restoration, and the provision of a period of respite for the cardiovascular system (Horne, 1990; Carter, 1998*)*. Apart from the physiological aspects of a noise-induced reduction of sleep quality, night-time noise exposure of sufficient intensity is also related to subjectively experienced sleep quality (Öhrström, 1991). Also, reduced sleep quality interferes with daytime functioning, having an adverse effect on mood next day and possibly also on vigilance and cognitive performance.
Sleep quality can be quantified by subjective and objective methods. The most commonly applied subjective methods are self-reporting using sleep logs or diaries, and, to a lesser extent, behavioural observations. The most commonly used objective methods are EEG recordings and actimetry. Usually in field studies on noise-induced sleep disturbance subjects wear watch-like actimeters for movement detection at their wrist. Sleep quality may be adversely affected by:

- changes in the cardiovascular system
- changes in sleep pattern, such as an increased sleep latency time and a reduced sleep period
- time through premature awakening
- changes in sleep stages from deeper to less deep sleep
- increase in motility during the sleep period
- increase in the number of awakenings during sleep period
- changes in the subjectively experienced sleep quality
- changes in the hormonal and immune system.

Present knowledge about the relationships between awakening and exposure to single noise events indicates that habituation or adaptation occurs. From the epidemiological studies there appears to be sufficient evidence for a causal relationship between the exposure to night-time noise and changes in sleep pattern and sleep stages, awakenings, changes in subjective sleep quality, changes in heart rate and changes in mood the next day (Health Council of the Netherlands, 1994). Observation thresholds for these effects are given in Table 5. Evidence for other effects is limited (hormone levels and performance the next day) or inadequate (immune system). With respect to research into the effects of night-time aircraft noise on hormone levels, the laboratory and pseudo-field investigations by Maschke and co-workers are of interest (Maschke et al., 1992, 1995a, 1995b, 1996). He showed that test subjects exposed to 64 aircraft noise events per night with an indoor L_{Amax} equal to 55 dB(A) (SEL equal to 69 dB(A)) – which corresponds to an indoor $L_{Aeq,night}$ 43 dB(A) - had increased levels of adrenaline in the morning urine. In the Hamburger Night-time Aircraft Noise Study cortisol levels of 16 participants (sleeping in their own home in the vicinity of the airport) were analysed for 6 weeks. Aircraft noise exposure was through loudspeakers in the bedroom and participants were exposed each night from 0 - 4 h to 32 aircraft noise events with L_{Amax} equal to 65 dB(A) (SEL equal to 77 dB(A)), which corresponds to an estimated indoor $L_{Aeq,4h}$ of over 50 dB(A)! From the test results promising adaptation models have been postulated. These models, however, need further verification in laboratory and ultimately in field studies, in order to be a basis for regulations.

Exposure-response functions have only been derived from field studies for some of the effects of night-time noise exposure, among others for reduction of subjective sleep quality and increase in number of awakenings during sleep period time. The relationship between the risk of awakening and exposure to night-time environmental noise is only established for single noise events, with exposure specified by the indoor SEL values of the events (see also chapter 3 and Annex B). Aircraft noise exposure conforms to this description. This exposure effect relationship is different from the one used by Griefahn (1976) to specify maximal allowable night-time noise exposures. In the method used by Griefahn to derive these maximal allowable night-time noise exposures, events with L_{Amax} below 53 dB(A) (SEL equal to approximately 67 dB(A)) were not taken into account. More recent research result do show the observation level to be a SEL value of 55 dB(A) (approximately an L_{Amax} equal to 38 dB(A) for aircraft noise events).
In 1997 an international group of experts, convened by the Health Council of the Netherlands, assessed the observation threshold for awakening due to single noise events at a lower indoor SEL value of 55 dB(A) (Table 5) instead of 60 dB(A) (Health Council of the Netherlands, 1997).This change reflected the improved knowledge of the transfer functions of SEL values measured outdoors to indoor SEL values in some of the underlying studies.
Apart from the direct effects of night-time noise on sleep, various authors point to the importance of the impact of sleep disturbance on quality of life, including somatic health and annoyance (Vallet, 1998). Babisch reported larger overnight changes in epinephrine levels in subjects reporting high disturbance of sleep than in those without severe complaints (Babisch, Fromme, Beyer, Ising, 1996). Another study showed that psycho-social wellbeing of subjects exposed to high levels of road traffic noise was not related to daytime noise exposure, but to night-time equivalent sound level in the bedroom and to subjectively experienced sleep quality (Öhrström, 1991).

Although recently several field studies have started (Passchier-Vermeer, Vos, Gils, Miedema, et al., 1999) or have been completed (Fidell, Howe, Tabachnick, et al., 1998; Griefahn, Mehnert, Moehler, Schuemer-Kohrs, Schuemer, 1996; Fidell, Howe, Tabachnick, et al., 1995; Fidell, Pearsons, Tabachnick, et al., 1995) there still is an urgent need for a tested model on sleep disturbance, environmental noise exposure and secondary effects, in which causal and modifying factors and their mutual relations have been assessed.

4.2.5 Noise-induced stress-related health effects

The reactions to a stressor can be of a psychological (feelings of fear, depression, sorrow), behavioural (social isolation, aggression, excessive use of alcohol, tobacco, food, drugs) and somatic nature (cardiovascular, gastrointestinal, respiratory illnesses). A large number of laboratory experiments have shown noise-induced temporal changes in the cardiovascular system. These findings led to several investigations into possible long-term effects associated with noise exposure, such as stress-related cardiovascular disorders. In addition some research has been carried out regarding effects on the hormone and immune system. Also effects from environmental noise on reproduction and development were studied.

Research into the chronic effects of long-term exposure to noise is complicated because cardiovascular and biochemical changes are non-specific and a number of factors may also cause these changes. In research projects these factors have to be controlled for. For cross-sectional studies it is difficult to obtain appropriate information about past noise exposure and longitudinal studies are time- and money consuming. Also, people intervene in their own situation, e.g. by moving from a noisier surrounding to quieter places. This may result in 'noise proof' populations that are exposed to the higher noise levels. Furthermore there are large individual differences in susceptibility. Not withstanding these complications, statements on the relationship between noise exposure and cardiovascular disease appears possible from meta-analyses of the available epidemiological data.

Cardiovascular effects in adults
Epidemiological environmental noise studies on changes in blood pressure and increased risk for ischaemic heart disease in adults are mainly limited to the effects of road traffic noise, with the exception of a Netherlands study on the effects of aircraft noise in the vicinity of Schiphol (Knipschild, 1977; Knipschild, 1976). In general these studies demonstrate no obvious effects from noise exposure on the mean diastolic and mean systolic blood pressure, but do show effects in terms of an increase of the percentage of people with hypertension (including those who use medication for hypertension). The observation threshold for hypertension is estimated to correspond to a DNL value of 70 dB(A) for environmental noise exposure. The Schiphol study showed effects from aircraft noise exposure to start at an Ke (Kosten Unit) value of about 40, which corresponds with a DNL value of over 65 dB(A). The Health Council of the Netherlands suggested in 1994 the same observation threshold for ischaemic heart disease as for hypertension (Table 5). The relative risk (compared to populations with low environmental noise exposure) for both hypertension and ischaemic heart disease for exposure levels above the observation thresholds are estimated to be about 1.5 [10].

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[10] Although the relative risk for hypertension and ischaemic heart disease at exposures above the observation threshold are both equal to 1.5, this does not imply that the noise-induced increase in persons with such disease are equal. E.g., in the Netherlands about 10% of the adult population is hypertensive or is using medication for hypertension. There are no data on the prevalence of ischaemic heart disease in the Netherlands, but data on the admission to hospitals (including death) due to ischaemic heart disease give 0.5%. This implies that the noise-induced increase in hypertensives is 20 times as large as the noise-induced increase in admission to hospitals due to ischaemic heart disease.

In 1997 a Chinese study was carried out among a large sample of over 20 000 residents in rural communities. The results show that self-reported exposure to noise (unfortunately exposure was not assessed objectively) is an important determinant of systolic and diastolic blood pressure (Xu, Niu, Christiani, et al., 1997). Of special interest are the outcomes of the longitudinal study on the effect of road traffic noise exposure on the incidence of ischaemic heart disease (Babisch et al., 1988, 1993, 1996, 1998). In this Caerphilly and Speedwell study, two cohorts of about 2 500 middle-aged men in the UK were recruited to study the predictive power of already known and new risk factors for ischaemic heart disease. Noise measurements were performed in each of the streets where subjects lived. Even in the highest noise exposure class DNL did not exceed 70 dB(A). The statistical analysis on the relationships between incidence of ischaemic heart disease (classified in a standardised way) and environmental noise exposure was controlled for potentially confounding factors. The average annual incidence rate of ischaemic heart disease appeared to be 1.4% during the second phase of the study (six years follow up, mean age of the men 57 years). If orientation of the living and the bedroom, window opening habits and years of residence over 15 years were taken into account, the relative risk for incidence of ischaemic heart disease of the highest exposed group relative to the group exposed to levels between 50 and 55 dB(A) turned out to be 1.6, which appeared to be statistically not significantly different from 1.0 at the 5% level ($P<0.10$). This study fits in with the earlier evaluation that above levels of 70 dB(A) there is sufficient evidence for a noise exposure related effect, and provides no support for lowering the observation level of 70 dB(A) for ischaemic heart disease.
Only few epidemiological studies considered biochemical and immunological effects (Babisch, Ising, Elwood, Sharp, Bainton, 1993; Babisch, Gallacher, Elwood, Ising, 1988; Babisch, Ising, Gallacher, Sweetnam, Elwood, 1998). More recently, overnight resting levels of epinephrine and norepinephrine levels were assessed in a study of middle-aged women living in Berlin (Babisch, Fromme, Beyer, Ising, 1996). Significantly elevated levels of norepinephrine were found in women whose bedroom faced a busy street (more than 20 000 vehicles a day) and epinephrine levels were also higher in women reporting high disturbance of communication and sleep under closed window conditions.

Cardiovascular effects in children
This subject has been considered in detail in Passchier-Vermeer, 2000. Two early cross-sectional studies showed higher systolic and diastolic blood pressure in school children exposed to very high road traffic noise levels (Karsdorf et al., 1968) or very high aircraft noise levels at school (Cohen et al., 1980) than children not exposed or with minor exposure to these noise sources. Karsdorf et al. (1968) measured blood pressures of 13 to 16 years old secondary school children in the first five hours after beginning of class. The results show an increase with age in the (statistically significant) differences in systolic and diastolic blood pressure between noise exposed children and children not exposed to loud road traffic noise at school. Unfortunately, known effect-modifying factors (body weight, smoking, social class, diet, alcohol use) have not been taken into account. Therefore, it is largely unknown whether the actual noise exposure caused (all of) the effect reported. Cohen et al. (1980) measured rested blood pressure in advance of the beginning of school. His study shows unambigiously that rested blood pressure and noise exposure at school are associated. Cohen et al. (1981) re-examined children from the first investigation again one year later. Of the 262 children from the first investigation, only 163 took part in

the second investigation. It turned out that a large proportion of the aircraft noise exposed children with higher blood pressure did not participate in the second investigation. The analysis of the attrition sample of the longitudinal study did not show any effect of noise exposure, testing session, or interactions between noise exposure and testing session on either systolic or diastolic blood pressure. Lercher (Lercher, 1992) examined 796 school children living close to or far from highways. The study does not only consider noise exposure, but also other environmental factors, such as exposure to lead. The results are presented as percentages of children with a systolic blood pressure over 120 mm Hg, with a diastolic blood pressure over 80 mm Hg or with cholesterol levels over 176 mg/dl. Blood pressure measurements were mostly performed in the morning from 9 to 12 hours. The results observed are contradictory to the hypothesis of higher values in the higher noise exposed children, and this contradiction remains if effect-modifying factors are taken into account. More recently Slovakian researchers studied 1542 3-7 year old children from kindergartens (Regecova et al., 1995). They estimated the road traffic noise exposures at the kindergartens and at the homes of the children. The children were classified according to these two noise exposures in four groups (road traffic noise with equivalent sound levels below or above 60 dB(A)): 1 quiet kindergarten and quiet home, 2 quiet kindergarten and noisy homes, 3 noisy kindergarten and quiet homes, 4 noisy kindergarten and noisy homes. Measurements on blood pressure and heart rate were performed in the morning (8.30 to 12.00 hours). The authors observed significantly higher systolic and diastolic blood pressure and lower heart rate in groups 3 and 4 compared to group 1 and 2, after control for age, weight, and height. The differences in mean systolic and diastolic blood pressures of the various groups were lower in the youngest age group and increased with age. Although the study is carefully designed, the possibility exist that social class can, in part, explain the differences observed (see also Lercher et al., 1998).
In the Munich airport study, schoolchildren were examined in the years Munich airport moved from one to another location (Hygge et al., 1996; Evans et al., 1998). One location was situated close to the 'old' airport and the other close to the 'new' airport. The cross-sectional part of the study showed a, not statistically significant ($P = 0.08$), higher systolic blood pressure in children highly exposed at school (Evans et al., 1995). Children were matched on socio-economic characteristics. In the study also neuro-endocrine indices of chronic stress (urinary cortisol levels and levels of epinephrine and norepinephrine) were examined. Overnight resting levels of epinephrine and norepinephrine levels were significantly higher in the children exposed to aircraft noise at the old Munich airport in comparison to the control group. There were no differences in cortisol levels. After the move of the airport, overnight resting levels of epinephrine and norepinephrine levels rose significantly among children living under the flight paths of the new airport. There was, again, no effect on cortisol levels. The overall conclusion is that only the cross-sectional study of Cohen et al. (1980) showed that aircraft noise exposure (as specified at school) is statistically significant associated with increase in systolic and diastolic blood pressure. In the Munich study, noise-induced increase in epinephrine and nor-epinephrine levels could be established. These results can best be considered as part of a stress response of children to their noisy (school) environment. With respect to adaptation, the data presented by Karsdorf and by Regecova on road traffic noise show an increase with age in the differences in blood pressure between noise-exposed and not exposed children (no adaption), whereas all data on aircraft noise exposure show decreasing differences with duration of exposure (adaptation). If possible effect-modifying factors would not have played a role, this would imply that children physiologically adapt to a certain degree to aircraft noise, but not to road traffic noise. It should be pointed out, however, that this does not imply that the child also adapts to aircraft noise exposure in all other aspects nor that long term consequences or other effects are therefore absent.

Effects on the unborn child
In view of data from older studies, it is not improbable that high levels of aircraft noise (DNL over 62 dB(A)) to which pregnant women are exposed, gives a small reduction in birth-weight. In a more recent study of 200 Taiwanese women, noise exposure was measured by personal noise dosimeters on three occasions during pregnancy (Wu, Chen, Lai, Ko, Shen, Chang, 1996). Noise exposure turned out not to be related to birth-weight, after adjustment for social class, smoking and alcohol use, maternal weight gain in pregnancy, gender of the child and duration of pregnancy. Older and more recent investigations do not show statistically significant effects of occupational or environmental noise exposure of pregnant women on the course of pregnancy and congenital defects of babies, with the exception of high frequency hearing damage associated with high occupational noise exposure.

4.2.6 Effects on performance

From laboratory experiments there is overwhelming evidence that the presence of uncontrollable noise can significantly impair cognitive performance. Noise is able to induce learned helplessness, increase arousal, alter the choice of task strategy, and decrease attention to the task. Noise may also affect social performance, mask speech and other relevant sound signals, impair communication and it may distract attention from relevant social clues. Already at low levels adverse acute effects have been assessed. Performance on a task involving motor and monotonous activities is sometimes not decreased, but on the contrary enhanced (Hygge et al., 1998).

Effects in children
For over thirty years epidemiological studies have shown that school children, when exposed to high levels of traffic noise, do show impairments in performing cognitive tasks (railway noise: Bronzaft et al., 1975; aircraft noise: Cohen et al., 1980; road traffic noise: Karsdorf et al., 1968). The best documented noise effect is that on reading acquisition (Green et al., 1982; Evans, 1997). Close to twenty studies have found indications of a negative relationship between noise exposure and reading acquisition. There are fewer studies of noise effects on other aspects of cognitive processing, such as long term memory, attention, and motivation of children. The most ubiquitous memory effects occur when complex, semantic materials are probed: several studies on long term or acute noise exposure have found adverse effects of aircraft noise exposure on long term memory for complex, difficult materials.
The studies which have examined possible links between noise exposure and attentional deficits among children show different results. Several investigators found an effect of long term noise exposure on the performance of a visual search task or of an auditory sustained attention task, while other researchers did not. Various variables may moderate the relations between long term noise exposure and performance on a sustained attention task. Of interest is the finding that young children from noisy homes were less distracted by auditory signals during a visual matching task than children from quiet homes. It was also found that compared to children attending quiet schools a visual coding task was performed better under acute noise conditions by children attending noisy schools whereas they did worse on the task when performing it under quiet conditions. These and other findings suggest that attentional deficits related to long term noise exposure in children occur since children learn how to ignore auditory stimuli (gate out distraction) as a way to cope with chronic noise. Unfortunately this tuning out process may over-

generalise so that children learn to tune out not only noise, but also relevant other auditory signals such as speech.
Some studies showed that children highly exposed to environmental noise for prolonged periods of time are less motivated when placed in situations where task performance is dependent on persistence. The motivational deficits in children related to long term noise exposure have been considered in the light of the learned helplessness theory. Prolonged exposure to uncontrollable stimuli has been shown across a wide variety of conditions, including noise, to induce feelings and behaviours indicative of helplessness. As the child continues to struggle unsuccessfully with an uncontrollable adverse stimulus, it eventually learns that it is helpless to do anything about the situation, as manifested by feelings of hopeless and reduced persistence. Like in adults, this effect is strongly mediated by personal characteristics of the child.
More recently two longitudinal studies were carried out (Evans et al., 1995, 1998; Hygge et al., 1996; ; Hygge et al., 1998;Haines et al., 1998). In the Munich airport study (a longitudinal intervention study), reading comprehension and long term memory were impaired in children around the old Munich airport and reading comprehension improved after the closing of the airport. At the same time, it deteriorated in children subjected to the aircraft noise exposure near the new Munich airport. Recently, in the UK a field study with annually repeated tests was carried out to assess whether the association between aircraft noise exposure and reading comprehension was mediated through sustained attention and whether it was confounded by social deprivation and language spoken at home (Haines et al., 1998). The 340 children that participated were aged about 9 to 10 years. They visited a school classified either as a high noise school ($L_{Aeq,schoolhours}$ over 66 dB(A)) or as a low noise school ($L_{Aeq,schoolhours}$ less than 57 dB(A)). There appeared to be a high correlation between noise at school and the aircraft noise exposure at home. The results show that on average reading comprehension of children attending the high noise schools was poorer at both measuring times compared with that of children from the low noise schools. Sustained attention, only measured at follow-up, was poorer in the children at the high noise schools than in the children at the low noise schools. Sustained attention did not play a significant role in the explanation of the relation between reading comprehension and aircraft noise exposure. However, if adjustments were made for age, main language spoken at home and social deprivation, the differences between children from high and low noise schools in reading comprehension failed significance.

5 Responses to the questions

With respect to aircraft noise-induced annoyance, the following specific questions have been derived from the preparatory paper by UBA:

1. Is there a difference in the correlation for the relationship between the Störindex and aircraft noise-induced annoyance and that relationship with L_{Aeq}- based metrics?

2. Which values of a L_{Aeq}- based metric (such as DNL) correspond with the Störindex values equal to 67 and 75 dB(A)?

3. Is it possible to give an indication of adjustments for aircraft noise events during winter-, spring- and autumn- time, relative to aircraft noise events during summer-time?

With respect to the other adverse noise-induced health effects, it concerns the following questions:

4. Given the values of the Störindex equal to 67 and 75 dB(A) (or the corresponding L_{Aeq}-based metric values), which other adverse noise-induced health effects are to be expected above these levels?

5. Given the values of the Störindex equal to 67 and 75 dB(A) (or the corresponding L_{Aeq}-based metric values), is it advisable to put a limit to the characteristics of single aircraft noise events? For which other adverse noise-induced health effects would this be appropriate and what should be the limiting SEL or L_{Amax} value?

These questions are answered in the following.

1. The analysis of the Amsterdam Airport Schiphol study (a survey carried out in 1996) shows that the correlation of the Störindex and aircraft noise annoyance is the same as the correlation of L_{Aeq}-based overall metrics (with an adjustment of 10 dB(A) to the night-time aircraft noise events during the period 22 – 6 h) and aircraft noise annoyance. Three of the four older British and American surveys (reported between 1967 and 1970) show the same trend: minor and statistically not significant differences ($\alpha = 5\%$, tested two-sided) between correlation coefficients of Störindex and annoyance score and DNL (or LDEN) and annoyance score. Only the second phase of the USA Tracor Survey gives a statistically significant higher correlation between Störindex and annoyance than between DNL and LDEN and annoyance. The final conclusion of the analyses is that Störindex, DNL and LDEN perform equally well in predicting annoyance due to aircraft noise exposure. In this conclusion more weight is given to the results of the Amsterdam Airport Schiphol study than to the results of the second phase of the Tracor Survey. The main reasons are: the Amsterdam Airport Schiphol study was carried out recently, and therefore incorporates the characteristic features of modern

aviation. Also, the number of respondents in the Amsterdam Airport Schiphol study is much larger than in the second phase of the Tracor Survey. Finally, the noise data of the Amsterdam Airport Schiphol study are much more detailed, since it consists of characteristics of each aircraft noise event separately and in the second phase of the Tracor Survey average values of characteristics are given for classes of aircraft noise events.

2. By using the data of the Amsterdam Airport Schiphol study, a regression analysis has been performed to assess the linear relationships between DNL on the one hand and the metrics Störindex, SI(day), and SI(day + night) on the other hand. Two calculations have been carried out: with corrected and with uncorrected SEL values. The results are given in table 7. From these equations the following correspondence between SI and DNL is derived:

	Data with uncorrected SEL	Data with corrected SEL	Average value
SI = 67	DNL = 65.1 dB(A)	DNL = 64.4 dB(A)	64.8 dB(A)
SI = 75	DNL = 72.2 dB(A)	DNL = 71.3 dB(A)	71.8 dB(A)

Therefore SI = 67 corresponds to DNL = 65 dB(A) and SI = 75 with DNL = 72 dB(A).

3. The data in the database do not permit to assess an indication of adjustments for aircraft noise events during winter-, spring- and autumn- time, relative to aircraft noise events during summer-time.

4. In the response to the second question it was shown that SI values equal to 67 and 75 correspond to DNL values of 65 and 72 dB(A) respectively. Table 5 shows that with respect to hypertension, ischaemic heart disease, and performance of children at school, a DNL value of 72 dB(A) is just above the observation threshold of 70 dB(A) for each of these three effects [11] and a DNL value of 67 dB(A) is below these thresholds. Therefore a limit of DNL = 72 dB(A) does not exclude an increased risk of hypertension, and ischaemic heart disease, and a decrease in performance of children at school due to aircraft noise exposure.

   With respect to sleep disturbance, observation thresholds have been expressed in SEL and $L_{Aeq.night}$. To consider possible changes in sleep pattern (increased latency time, reduced sleep period time, earlier awakening in the morning), subjective sleep quality and the after-effect mood next day, $L_{Aeq.night}$ and not DNL would have to be considered. In the following discussion $L_{Aeq.night}$ has been converted to $L_{Aeq.night}$ [12] by using the average difference between day- and night-time aircraft noise exposure values obtained from an analysis of the TNO database (Health Council of the Netherlands, 1997). By approximation DNL values of 65 and 72 dB(A) correspond to $L_{Aeq.night}$ values of 56 and 63 dB(A) respectively. Obviously (see table 5), the observation threshold of 40 dB(A) outdoors for subjective sleep quality is exceeded to a large extent in both cases. The observation thresholds for sleep pattern changes and decreased mood next day are at any case exceeded by the higher limit value. It can also not be

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[11] It is assumed that DNL and $_{LAeq.school}$ are about equal.

[12] Assume $L_{Aeq.night}$ to be 8 dB(A) below $L_{Aeq.day}$. Then, $L_{Aeq.night}$ of 56 dB(A) implies DNL = 65 dB(A) and $L_{Aeq.night}$ of 63 dB(A) implies DNL = 72 dB(A).

excluded that there is an adverse effect on sleep pattern and mood next day at the lower limit value, given the fact that for these two effects the observation threshold is specified as below a $L_{Aeq,night}$ of 60 dB(A).

With respect to changes in heart rate and sleep stages and increase in number of awakenings during sleep period time, the observation threshold is expressed in indoor SEL of a single aircraft noise event. If all aircraft noise events have indoor SEL values below such an observation threshold the risk for an effect is absent. The outdoor $L_{Aeq,night}$ (assuming the sound insulation to be 25 dB(A)) (with night equal to 8 hours) from one aircraft noise event with SEL at the observation threshold is equal to SEL + 25 – 44.5 dB(A). This corresponds to outdoor $L_{Aeq,night}$ observation threshold values of 35 dB(A) for awakening, 15 dB(A) for sleep stage changes and 20 dB(A) for changes in heart rate [13].

Not mentioned by the Health Council of the Netherlands (table 5) are observation thresholds for speech interruption and for decreased intelligibility of speech produced by radio or television. In chapter 3 tentative observation thresholds for these effects are set at SEL equal to 65 dB(A), measured at the location of the head of the listener. For activities only performed indoors with windows closed, the observation threshold in terms of outdoor $L_{Aeq,day}$ (with day equal to 16 hours) is 42 dB(A).

5. In chapter 3 it is made plausible that, in addition to an overall limit of aircraft noise exposure expressed e.g. in DNL, a limit for single aircraft noise events may be feasible with respect to limiting the number of awakenings during sleep period time, the number of speech interruptions and the number of times intelligibility of speech produced by radio or television decreased. If such effects are never allowed to occur, the maximum allowable aircraft noise event is specified by the observation threshold. If there is a limit set to the number of times a specific effect may occur, the models given in chapter 3 allow the calculation of a maximum overall value below which this maximum number of effects will not occur. If the overall level would be reduced to that value a limit for single aircraft noise events would not be necessary. If, however, the overall level is not changed, then there is a range of overall levels for which an additional limit of single aircraft noise events may be feasible. The following is an example with respect to awakening during sleep period time. Assume two limits for outdoor $L_{Aeq,night}$ are considered: 56 and 63 dB(A). Assume 25 dB(A) sound insulation during each night, then these outdoor values correspond to indoors values of 31 and 38 dB(A), respectively. From the model given in chapter 3 it follows that the maximum number of awakenings for indoor $L_{Aeq,night}$ equal to 31 and 38 dB(A) is 121 and 601 times a year, respectively. Assume 125 awakenings a year is considered acceptable from the viewpoint of public health. Then reducing the limit of the overall aircraft noise exposure, expressed in $L_{Aeq,night}$, from 38 to 31 dB(A) would make a limit for single aircraft noise events not necessary. If such reduction is not enforced, for the situations with $L_{Aeq,night}$ between 31 and 38 dB(A), SEL (or L_{Amax})

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[13] This does not at all imply that any aircraft noise exposure above these values does have an impact on the functions mentioned. Only for the worst case the statement is valid.

of single aircraft noise events should be limited to meet the requirements with respect to number of awakenings. This limit should according to chapter 3 be an indoor SEL equal to 55.6 dB(A). This value corresponds to an outdoor SEL value of 80.6, which is about equal to a value of L_{Amax} of 69 dB(A) outdoors. It should be stressed that such a limit for SEL or L_{Amax} is necessary only for the situations with $L_{Aeq,night}$ between 31 and 38 dB(A), and not for noisier and less noisy situations. From a practical point of view it is questionable whether such a relatively low value of L_{Amax} is feasable.

6 Summary

With a view to a possible change in the German aircraft noise exposure regulations, TNO Prevention and Health carried out a project by order of the Umwelt Bundesambt (UBA). The project has been executed in the framework of the Umweltforschungsplan 1999, Forschungs- und Entwicklungsvorhaben 299 51 255, thema "Umweltqualitatsziele zum Schutz vor schädlichen Umwelteinwirkungen durch Fluglärm". The aim of the project is to obtain scientific results that can be used in a decision about future aircraft noise exposure regulations in Germany. UBA formulated questions regarding overall aircraft noise exposure metrics, and consequences for specified adverse aircraft noise-induced effects on public health, if specific limits are exceeded. Questions were also formulated regarding the usefulness of limits of the maximal sound level or the SEL value of single aircraft noise events, in addition to overall limits. At present, in Germany, the so-called Störindex is used as the descriptor of aircraft noise exposure. The Störindex (SI) is the maximum of an index (SI(day)) for aircraft noise events during the day (06 – 22 h) and an index (SI(day + night)) for all aircraft noise events with an off-set of 5 to 1 for events occurring in the period 22 – 6 h. The German regulations do not specify a limit for single aircraft noise events.

The following adverse noise-induced effects on public health have been considered:

- Annoyance;
- Somatic health;
- Speech disturbance;
- Recreation disturbance;
- Sleep disturbance.

Annoyance
With respect to questions related to annoyance, two sets of data have been (re)analysed:

- Dataset Amsterdam Airport Schiphol study (TNO-PG and RIVM, 1998). This dataset contains information about aircraft noise annoyance and about the distribution of sound levels outside the dwelling of respondents (described with SEL) of all aircraft noise events during a year. In the study a sample was drawn from dwellings within a circle around Schiphol with a radius of 25 km. The sample was stratified according to noise load and distance to the airport. A total of 11 812 respondents (response rate: 39 %) returned the mail questionnaire. The questionnaires of 10 495 respondents have been analysed, because 1 317 respondents were excluded for obvious reasons;
- TNO database with data of over 60 000 respondents of over 50 socio-acoustic surveys. This database has already been used for specifying exposure-effect relationships between noise annoyance and noise exposure, also for aircraft noise. Also, the influence of effect-modifying factors have been established by analysing this data. The database includes four datasets that have been used in this report to compare the strengths (in terms of correlation coefficients) of the relationships between annoyance and Störindex, and between annoyance and L_{Aeq}-based metrics. These four datasets are: USA Four Airport Survey (phase I of Tracor Survey) (1967) (3 499 respondents), USA Three Airport Survey (phase II of Tracor Survey) (1969) (2 828

respondents), USA Small City Airports Survey (small City Tracor Survey) (1970) (1 112 respondents), and Heathrow Aircraft Noise Survey (1967) (4 515 respondents).

The results are:

- The analysis of the data of the Amsterdam Airport Schiphol study shows that the correlation coefficient of the Störindex and aircraft noise annoyance is statistically not significant different ($\alpha = 5\%$, tested two-sided) from the correlation coefficients of L_{Aeq}-based overall metrics and aircraft noise annoyance. Among the L_{Aeq}-based overall metrics considered are the optimal metric, which gives the highest correlation with aircraft noise annoyance, and the L_{Aeq}-based metric with an adjustment of 10 dB(A) to the night-time aircraft noise events during the period 22 – 6 h. Three of the four British and American surveys show the same trend: minor and statistically not significant differences ($\alpha = 5\%$, tested two-sided) between correlation coefficients of the Störindex and annoyance score and correlation coefficients of DNL (day-night level) or LDEN (day-evening-night level) and annoyance score. Only the second phase of the USA Tracor Survey gives a statistically significant higher correlation between the Störindex and annoyance than between DNL and LDEN and annoyance. The final conclusion of the analyses is that Störindex, DNL and LDEN perform equally well in predicting annoyance due to aircraft noise exposure. In this conclusion more weight is given to the results of the Amsterdam Airport Schiphol study than to the results of the second phase of the Tracor Survey. The main reasons for this weighting are: the Amsterdam Airport Schiphol study was carried out recently, and therefore incorporates the characteristic features of modern aviation. Also, the number of respondents in the Amsterdam Airport Schiphol study is much larger than in the second phase of the Tracor Survey. Finally, the noise data of the Amsterdam Airport Schiphol study are much more detailed, since they consist of characteristics of each aircraft noise event separately while in the other surveys, including the second phase of the Tracor Survey, average values of characteristics are given for classes of aircraft noise events;
- The present German regulations uses two exposure limits (Störindex equal to 67 and 75, respectively). On the basis of data of the Amsterdam Airport Schiphol study, the relationship between the Störindex and DNL has been established. According to this relationship, the values of the Störindex equal to 67 and 75 correspond to DNL values of 65 and 72 dB(A), respectively.

Other adverse health effects

The Committee on Noise and Health, an international committee of the Health Council of the Netherlands, assessed in 1994 the health effects of environmental and occupational noise exposure. The report presents observation thresholds for those adverse health effects for which evidence for a relationship with noise exposure was considered sufficient. The observation threshold for an effect was defined in the report as the lowest noise exposure at which for an average population the effect has been observed in well-designed epidemiological studies. In this report, the 1994 Health Council report has been taken as a starting point and more recent reviews and results of more recent surveys have been used for an up-date of the 1994 evaluation. In general the more recent reviews and papers concur well with the conclusions of the Health Council, if a rating of 'inconclusive' is taken as equivalent to the Health Council's 'limited'. From the updated information the conclusions are given in table 8 with the following remarks:

- With respect to hypertension, ischaemic heart disease, and performance of children at school, a DNL value of 72 dB(A) (equal to a Störindex of 75) is just above the observation threshold of 70 dB(A) for each of these three effects and a DNL value of 67 dB(A) is below these thresholds. Therefore a limit of DNL = 72 dB(A) does not exclude an increased risk of hypertension, and ischaemic heart disease, and a decrease in performance of children at school due to aircraft noise exposure, for those exposed to aircraft noise with DNL over 70 dB(A);

- With respect to the various aspects of sleep disturbance, observation thresholds for some noise-induced effects have been expressed in the overall metric $L_{Aeq,night}$ and for other effects in the SEL value of single noise events. Therefore, to consider possible changes in sleep pattern (increased latency time, reduced sleep period time, earlier awakening in the morning), subjective sleep quality and the after-effect mood next day, not the consequences of a limit of DNL of 67 and 72 dB(A) would have to be considered, but those of the corresponding $L_{Aeq,night}$ values. In situations with aircraft noise exposures in the higher DNL range, $L_{Aeq,night}$ is on average about 8 dB(A) lower than DNL. Therefore, DNL values of 65 and 72 dB(A) approximately correspond on average with $L_{Aeq,night}$ equal to 56 and 63 dB(A), respectively. The observation threshold for subjective sleep quality of $L_{Aeq,night}$, which is equal to 40 dB(A), is exceeded to a large extent by both $L_{Aeq,night}$ values of 56 and 63 dB(A). The observation thresholds for sleep pattern changes and decreased mood next day, which is *below* $L_{Aeq,night}$ of 60 dB(A), is at any case exceeded by the higher $L_{Aeq,night}$ limit value. It can also not be excluded that there is an adverse effect on sleep pattern and on mood next day at the lower limit value of 56 dB(A), given the fact that the observation threshold for these two effects may be lower than 56 dB(A);
- The observation threshold for changes in heart rate and sleep stages, increase in number of awakenings during sleep period time, is expressed in *indoor* SEL of a single aircraft noise event. If all aircraft noise events have indoor SEL values below the observation threshold for an effect, the probability of that noise-induced effect is zero. The *outdoor* $L_{Aeq,night}$ (assuming the sound insulation to be 25 dB(A)) (with night equal to 8 hours) from one aircraft noise event with SEL at the observation threshold of the effect is equal to 35 dB(A) for awakening, 15 dB(A) for sleep stage changes and 20 dB(A) for changes in heart rate. Therefore, these overall levels might be considered as overall observation thresholds for these effects. However, this does not at all imply that any aircraft noise exposure above these values does have an impact on the functions mentioned. Only for the worst case the statement is valid. It is obvious that the two limits of $L_{Aeq,night}$ values of 56 and 63 dB(A) are well above these worst case overall observation thresholds;
- Not mentioned by the Committee on Noise and Health are observation thresholds for speech interruption and for decrease in intelligibility of speech produced by radio or television. In this report tentative observation thresholds for these effects are set at SEL equal to 65 dB(A), measured at the location of the head of the listener. Then, the observation threshold for these activities performed indoors with windows closed, is in terms of DNL equal to 43 dB(A), assuming a sound insulation of 25 dB(A). The values of DNL equal to 65 and 72 are above this value of 43 dB(A).

Limit of a single aircraft noise metric in addition to overall aircraft noise exposure limits
In the report a model is elaborated to consider whether it is useful to limit the maximal sound level (L_{Amax}) or SEL of single aircraft noise events to limit specific adverse health effects, if there is already an overall limit (based on metrics such as the Störindex or $L_{Aeq,night}$) that restricts L_{Amax} or SEL of single aircraft noise events. A possible limit of single aircraft noise event characteristics is considered with respect to the following three adverse noise-induced effects:

- awakening;
- interruption of conversation due to assumed decrease of intelligibility;
- effect on listening to radio and television.

For each of these three effects a linear relationship between the probability of an effect and SEL is assumed. The probability of an effect is zero at the observation threshold for that effect. (E.g. for awakening this observation threshold is indoors SEL equal to 55 dB(A).) The model shows that if an overall limit is not exceeded, there is a worst case situation with a maximal possible number of times the specific adverse noise-induced effect occurs. This worse case situation occurs if all aircraft noise events have a SEL value that is 4.3 dB(A) above the observation threshold for the effect. (E.g., with respect to number of noise-induced awakenings, in the worst case situation the SEL of each aircraft noise event is equal to 59.3 dB(A). If the indoors $L_{Aeq,22\text{-}06h}$ is equal to 31 dB(A) for each night of a year, in the worst case on average 120 awakenings per year per person will occur in the exposed population. All other situations with indoor $L_{Aeq,22\text{-}06h}$ equal to 31 dB(A) will result in fewer awakenings per year.)

The report describes a stepwise procedure to decide about the introduction of a limit for SEL or L_{Amax} to limit the occurrence of a certain adverse noise-induced effects if an overall limit already exists. The procedure has been formulated for a noise-induced effect on sleep and on the basis of an already existing limit for $L_{Aeq,22\text{-}06h}$ on an annual basis. The procedure can be easily adapted to speech interruption and decrease in intelligibility of speech produced by radio or television and to other overall noise metrics. The general procedure is illustrated with an example for noise-induced awakenings. To be able to decide whether it is appropriate to consider a limit for SEL or L_{Amax}, first the maximal allowable number of a specific noise-induced effect over a specified period of time must be chosen. If for a specific overall limit the number of times the noise-induced effect occurs in the worst case situation is less than the number of maximal allowable noise-induced effects, it is not necessary to limit SEL in order to limit the specific noise-induced effect. If the number of times the noise-induced effect occurs in the worst case situation is higher than the number of maximal allowable noise-induced effects, either the overall limit must be reduced or an additional limit for SEL or L_{Amax} of single aircraft noise events must be introduced. This limit for SEL or L_{Amax} will need to be below the observation threshold for the effect plus 4.3 dB(A).

In the report the following example is given with respect to noise-induced awakenings during sleep period time. Assume the limit for outdoor $L_{Aeq,night}$ is 56 or 63 dB(A). Assume the sound insulation is 25 dB(A) during each night, then these outdoor values correspond to indoor values of 31 and 38 dB(A), respectively. From the model it follows that the maximum numbers of awakenings for indoor $L_{Aeq,night}$ equal to 31 and 38 dB(A) are 120 and 600 times a year, respectively. Assume 125 awakenings a year is considered acceptable from a viewpoint of public health. There are no requirements for SEL or L_{Amax} in case the overall limit, expressed in $L_{Aeq,night}$, is 31 dB(A). If the limit is equal to 38 dB(A), then reducing this limit from 38 to 31 dB(A) would make a limit for single aircraft noise events superfluous. If such a reduction in overall level is not enforced, then three areas in the vicinity of an airport can be specified on the basis of the overall aircraft noise exposure:

1 $L_{Aeq,22\text{-}06h} > 38$ dB(A);
2 $31 < L_{Aeq,22\text{-}06h} < 38$ dB(A);
3 $L_{Aeq,22\text{-}06h} < 31$ dB(A).

In area 1 (closest to the airport) the restriction based on the overall $L_{Aeq,22\text{-}06h}$ is not fulfilled. Further actions as a result of this infringement are necessary. In area 2 the requirement for overall $L_{Aeq,22\text{-}06h}$ is fulfilled. There should, however be a limit to SEL (or L_{Amax}) to protect the population for too many noise-induced awakenings. To limit this number of awakenings in the population in that area, it should be required that indoor SEL of any aircraft noise event should not exceed 55.6 dB(A). This value corresponds to an outdoor L_{Amax} of about 70 dB(A). It should be stressed that such a limit for SEL or L_{Amax} is necessary only for the situations with $L_{Aeq,night}$ between 31 and 38 dB(A), and not for noisier and less noisy situations. In area 3 requirements with respect to overall $L_{Aeq,22\text{-}06h}$ and SEL are both fulfilled. No specific action is required.

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Tables

Table 1 *The average number of aircraft noise events in a year per SEL class (corrected and uncorrected values) for respondents in the Amsterdam Airport Schiphol study. The average numbers are given for two periods of the day (06 –22 h and 22 – 06 h) and if respondents are weighted and not weighted for selective non-response in the study.*

Midpoint of SEL class in dB(A)		06 – 22 h		22 – 06 h	
Uncorrected SEL values	Corrected SEL values	No weighting	Weighting	No weighting	Weighting
69	76	15 424	15 275	751	754
74	79	13 276	13 145	652	644
79	82	11 618	11 261	658	630
84	86	8 504	7 937	429	403
89	89	2 946	2 693	128	116
94	92	779	727	24	23
99	95	213	194	5	5
104	99	17	16	1	1
109	102	2	2	0	0

Table 2 *In the first row optimal values for the parameters p and q, the trade-off parameter α and the night-time adjustment $W_{22\text{-}06h}$ = 10 lg $w_{22\text{-}06h}$, if $W_{06\text{-}22h}$ = 0 (see eqs 1, 2, and 3), together with their 95 % confidence intervals. In the last column the resulting correlation coefficient r is given. In the second row optimal values and the resulting r if α is set equal to 1. In the third row the values of p, q and r from a linear regression analysis if α = 1 and $W_{22\text{-}06h}$ = 10. In the last three rows the values of p, q and r from a linear regression analysis if SI(day), SI(day + night) and SI are taken as noise metrics. Each cell gives the results of four analyses, namely, upper left: no weight for selective non-response & no SEL correction; upper right: no weight & SEL correction; lower left: weight for selective non-response & no SEL correction; lower right: weight & SEL correction. The results are based on 10 495 respondents in NET-371 with a valid annoyance score.*

Restrictions	$W_{22\text{-}06h}$		α		P		q		r	
None	11.3 ± 1.8	11.3 ± 1.8	0.81 ± 0.11	1.24 ± 0.17	2.85 ± 0.26	2.85 ± 0.26	6.1 ± 1.1	6.9 ± 1.7	0.317	0.317
	12.7 ± 1.9	12.7 ± 1.9	0.87 ± 0.11	1.34 ± 0.18	2.48 ± 0.23	2.48 ± 0.23	24.2 ± 3.8	26.5 ± 6.0	0.295	0.295
α = 1	13.8 ± 1.4	9.4 ± 1.3	1	1	2.50 ± 0.14	3.14 ± 0.18	30.7 ± 1.4	36.7 ± 1.2	0.316	0.316
	10.0 ± 1.4	8.6 ± 1.2	1	1	2.29 ± 0.14	2.82 ± 0.18	34.3 ± 1.6	38.1 ± 1.2	0.294	0.293
α = 1 $W_{22\text{-}06h}$ = 10 (DNL)	10	10	1	1	2.43 ± 0.14	3.14 ± 0.18	29.9 ± 1.5	36.9 ± 1.1	0.311	0.316
	10	10	1	1	2.20 ± 0.14	2.82 ± 0.18	31.6 ± 1.5	38.1 ± 1.1	0.289	0.292
Model SI (day)					2.03 ± 0.12	2.47 ± 0.15	22.8 ± 3.3	32.9 ± 2.0	0.300	0.303
					1.81 ± 0.12	2.18 ± 0.14	24.6 ± 3.5	34.1 ± 3.8	0.275	0.277
Model SI(day + night)					3.42 ± 0.13	2.65 ± 0.16	16.3 ± 1.3	34.4 ± 3.4	0.314	0.308
					2.82 ± 0.13	2.37 ± 0.15	18.8 ± 2.3	35.7 ± 3.7	0.290	0.285
Model SI					2.12 ± 0.12	2.68 ± 0.16	24.2 ± 1.0	35.3 ± 3.4	0.307	0.317
					1.89 ± 0.13	2.38 ± 0.15	25.8 ± 3.4	36.5 ± 3.7	0.282	0.291

Table 3 *Additional information to figure 1. Number of noise event with a given SEL in the bedroom resulting in a L_{Aeq}(22-06) of 25 dB(A) on an annual basis. SEL has not been adjusted for impulse, tonal, or low frequency components.*

SEL in the bedroom (in dB(A))	Number of noise events a year
55	10 520
60	3 327
65	1 052
70	333
75	105
80	33
85	11
90	3
95	1

Table 4 Correlation coefficients between annoyance score and Störindex, DNL and LDEN for four socio-acoustic surveys.

Survey	Number of respondents	Correlation coefficient for the relationship with as noise metric		
		Störindex	DNL	LDEN
Heathrow Aircraft Noise Survey (1967)	4 515	0.347	0.349	0.349
USA Four-Airport Survey (phase I of Tracor Survey) (1967)	3 499	0.421	0.431	0.433
USA Three-Airport Survey (phase II of Tracor Survey) (1969)	2 828	0.258	0.211	0.205
USA Small City Airports Survey (phase III of Tracor Survey) (1970)	1 112	0.444	0.429	0.430

Table 5 Long term effects that have been related to exposure to noise and classification of the evidence for a causal relationship between noise and effect. The last three columns contain information on the observation threshold of an effect for which the causal relationship with noise exposure (second column) is judged to be 'sufficient'.

Effect	Classification Of evidence[a]	Situation[b]	Observation threshold		
			Metric	Value in dB(A)	Indoors/ Outdoors[c]
Hearing impairment	Sufficient	Occ	$L_{Aeq,8h}$	75	In
		Env	$L_{Aeq,24h}$	70	In
		Occ unb	$L_{Aeq,8h}$	<85	In
Hypertension	Sufficient	Occ ind	$L_{Aeq,8h}$	<85	In
		Env	DNL	70	Out
Ischaemic heart disease	Sufficient	Env	DNL	70	Out
Biochemical effects	Limited	Occ			
		Env			
Immune effects	Limited	Occ			
		Env			
Birth weight	Limited	Occ			
		Env air			
Congenital effects	Lack	Occ			
		Env			
Psychiatric disorders	Limited	Env air			
Annoyance	Sufficient	Occ off	$L_{Aeq,8h}$	<55	In
		Occ ind	$L_{Aeq,8h}$	<85	In
		Env	DNL	42[d]	Out
Absentee rate	Limited	Occ ind			
		Occ off			
Psycho-social well-being	Limited	Env			
Performance	Limited	Occ envt			
	Sufficient	School	$L_{Aeq,school}$	70	Out

			Observation threshold		
Sleep disturbance, changes in:					
sleep pattern	Sufficient	Sleep	$L_{Aeq,night}$	<60	Out
Awakening	Sufficient	Sleep	SEL	55	In
sleep stages	Sufficient	Sleep	SEL	35	In
subjective sleep quality	Sufficient	Sleep	$L_{Aeq,night}$	40	Out
heart rate	Sufficient	Sleep	SEL	40	In
hormone levels	Limited	Sleep			
Immune system	Inadequate	Sleep			
mood next day	Sufficient	Sleep	$L_{Aeq,night}$	<60	Out
Performance next day	Limited	Sleep			

a Classification of evidence of causal relationship between noise and health.

b occ = occupational situation, ind = industrial, off = office, env = living environment, sleep = sleep period time, unb = unborn: exposure of pregnant mother, school = exposure of children at school.

c Value relates to indoor or outdoor noise assessment.

d The observation threshold is about 12 dB(A) lower for environmental impulse noise.

Table 6 Data about the linear relationship between DNL and SI, SI(day), and SI(day = Night), obtained from the Amsterdam Airport Schiphol study.

Correlation coefficient r	Best fitting first order regression line	
	Uncorrected SEL values	Corrrected SEL values
0.96	SI(day) = -9.0 + 1.21 DNL	
0.99	SI(day + night) = -8.4 + 1.09DNL	
0.97	SI = -6.5 + 1.129DNL	
0.93		SI(day) = -6.5 + 1.13 DNL
0.995		SI(day + night) = -7.4 + 1.14 DNL
0.99		SI = -7.1 + 1.151 DNL

Table 7 Probability of adverse noise-induced effects on public health. A + sign indicates that it is likely that the effect is induced by aircraft noise exposure. A – sign indicates that it is likely that a noise-induced effect is absent.

Effect	Long-term aircraft noise exposure with	
	DNL = 65 dB(A) Störindex = 67	DNL = 73 dB(A) Störindex = 75
Hearing impairment	-	-
Hypertension	-	+
Ischaemic heart disease	-	+
Annoyance	+	+
Performance of school children	?	+
Sleep disturbance, changes in:		
sleep pattern	?	+
Awakening	+	+
sleep stages	+	+
subjective sleep quality	+	+
heart rate	+	+
mood next day	?	+

Appendix A Terms, definitions, and equations

1 SEL (sound exposure level) is defined by:

(1) $SEL = 10.\lg \int 10^{L(t)/10}\,dt$ [dB(A)]

in which: - L_t the sound level (in dB(A)) at time t

- t in s

2 $L_{Aeq.T}$ (equivalent sound level over time T) is defined by:

(2) $L_{Aeq.T} = 10 * \lg 1/T \int 10^{L(t)/10}\,dt$ [dB(A)]

For single noise events, such as aircraft noise events

(3) $L_{Aeq,T} = 10 * \lg [(1/T) \sum_i 10^{SEL(i)/10}]$ [dB(A)]

in which: - SEL(i) SEL of event i

3 The following description is assumed to hold for aircraft noise events: the sound level L_t increases linear until it reaches its maximum according to:

$L_t = a * t$ [dB(A)]

in which a is the increase of the sound level with time [dB(A)/s] and t the time [s] from the onset of the event. After its maximum $L_t = L_{Amax}$ at time $t = t_{max}$ the sound level decreases until $L_t = 0$ at $t = 2 * L_{Amax}/a$ according to:

$L_t = 2 * L_{Amax} - a * t$ [dB(A)]

Substituting this in (1) gives:

$SEL = 10 * \lg 2 * \int^{tmax} 10^{at/10}\,dt$ [dB(A)]

Integration gives:

$SEL = 10 \lg [20/(a \ln 10)(10^{LAmax/10} - 1)] =$

$= 10 * \lg (20/\ln 10) - 10 \lg a + 10 * \lg(10^{LAmax/10} - 1)$ [dB(A)]

Since $10^{LAmax/10} >> 1$ it follows that:

$SEL = L_{Amax} - 10 \lg a + 9.4$ [dB(A)]

a is specified by:

$a = 10/[1/2\ t(-10)]$ [dB(A)/s]

in which: - period t(-10) [s] is the period during which the sound level is between L_{Amax}- 10 and L_{Amax}

Substitution gives:

(4) $SEL = L_{Amax} + 10 \lg t(-10) - 3.6$ [dB(A)]

4 SEL(-10)is defined by:

$SEL(-10) = 10 * \lg \int 10^{L(t)/10}\,dt$ [dB(A)]

with integration over the period in which the sound level is between $L_{Amax} - 10$ and L_{Amax},

Integration gives:

SEL (-10) = $10 \lg [20/(a \ln 10)(10^{LAmax/10} - 10^{(LAmax-10)/10})]$ [dB(A)]
SEL and SEL(-10) have the following relationship:
SEL (-10) = SEL + $10^{*} \lg (1 - 10^{-10/10})$ [dB(A)]
Since $10^{*} \lg (1 - 10^{-10/10})$ is equal to – 0.46, it follows that:
(5) SEL(-10) = SEL – 0.46 [dB(A)]
For practical applications it is therefore irrelevant whether assessments are made in terms of SEL or SEL(-10) of aircraft noise events.

5 Störindex (SI) is defined by:
(6) Störindex = maximum of SI(day) and SI(day + night)
in which:
(6a) SI(day) = Störindex (day) = $13.3 \lg [\sum_i g(i)\,(1/T)\,t(i)\,10^{LAmax(i)/13.3}]$
in which: - T = 365*24*60*60 s
- g(i) = 1.5
- LAmax(i) written as L_{Amax} of event i
- t(i) written as t(-10) of event i
- summation over a year of all events during 06 – 22 h [14].
(6b) SI(day + night) = Störindex (day + night)
= $13.3 \lg [\sum_i g(i)\,(1/T)\,t(i)\,10^{LAmax(i)/13.3}]$
in which: - g(i) = 1 for all events i during 06 – 22 h
- g(i) = 5 for all events i during 22 – 06 h

6 $L_{Aeq.\alpha}$ (equivalent sound level with trade-off α) for aircraft noise events during period T is defined by:
(7) $L_{Aeq.\alpha} = 10 \lg [(1/T) \sum_i 10^{\alpha SEL(i)/10}]$ [dB(A)]
with (i) referring to the i-th noise event

7 Relationship between $L_{Aeq.\alpha}$ and SI
Substitution of SEL from (4) in (7) gives:
$L_{Aeq.\alpha}$ $= 10 \lg 1/T \sum_i 10^{\alpha[(LAmax(i) + 10 \lg ti(-10) - 3.6]/10.} =$
$= 10 \lg (10^{-3.6\,\alpha/10})/T \sum_i 10^{\alpha(LAmax(i)/10}\, t(i)^{\alpha}.=$
$= 10 \lg (10^{-3.6\,\alpha/10})/T \sum_i t(i)\, 10^{\alpha(LAmax(i)/10}\, t(i)^{\alpha - 1}$
$L_{Aeq.\alpha}$.can be replaced by:
(8) $L_{Aeq.\alpha} = 10 \lg (10^{-3.6\,\alpha/10})/T \sum_i t(i)\, 10^{\alpha(LAmax(i)/10}\, k(i)$
in which - $k(i) = t(i)^{\alpha - 1}$
If α is taken equal to 0.75, then $10^{\alpha[(LAmax(i)/10} = 10^{(LAmax(i)/13.3}$ and the first two factors after the sum sign have the format of the Störindex. These two terms, however, have to be multiplied by k(i) which for $\alpha = 0.75$ varies with t(i) for the range of SEL values relevant for aircraft noise events in the vicinity of airports. If α is taken equal to 0.69

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[14] The German regulations specify the Störindex for the noisiest six month of the year.

(and with four decimals 0.6875), k(i) is constant and in $L_{Aeq,\alpha=0.69}$ the Störindexfactor of each noise event is then multiplied by the same value, irrespective of SEL of the aircraft noise event. This is shown below. There is one approximation to be made by taking the formula specified by Ollerhead (1992). The following formula was derived for aircraft noise events in the vicinity of airports:

(9) $SEL = 0.8\,L_{Amax} + 25$

According to (4):

$10\,\mathrm{lg}\,t(-10) = SEL - L_{Amax} + 3.6$

Substitution of L_{Amax} gives:

$10\,\mathrm{lg}\,t(-10) = SEL - (SEL - 25)/0.8 + 3.6 = -0.25\,SEL + 34.85$

Therefore: $t(-10) = 10^{(-0.025SEL + 3.485)}$ and from this it follows:

$k(i) = 10^{(-0.025SEL(i) + 3.485)(\alpha - 1)}$

Substitution of k(i) in (8) gives:

$L_{Aeq,\alpha} =$

$= 10\,\mathrm{lg}\,[(10^{-3.6\,\alpha/10}) \sum_i (t(i)/T)\, 10^{\alpha LAmax(i)/10}\; 10^{(-0.025SEL(i) + 3.485)(\alpha - 1)}] =$

$= 10\,\mathrm{lg}\,10^{-3.6\,\alpha/10} + 10\,\mathrm{lg}\,[\sum_i(t(i)/T))\, 10^{0.75LAmax(i)/10}\; 10^{(\alpha - 0.75)LAmax(i)/10}\; 10^{(-0.025SEL(i) + 3.485)(\alpha - 1)}]$

$= 10\,\mathrm{lg}\,10^{-3.6\,\alpha/10} + 10\,\mathrm{lg}\,[\sum_i (t(i)/T)\, 10^{LAmax(i)/13.3}\, 10^{(\alpha - 0.75)LAmax(i)/10 + (-0.025SEL(i) + 3.485)(\alpha - 1)}]$

$= 10\,\mathrm{lg}\,10^{-3.6\,\alpha/10} + 10\,\mathrm{lg}\,[\sum_i \text{störindexfactor} * 10^{(\alpha - 0.75)LAmax(i)/10 + (-0.025SEL(i) + 3.485)(\alpha - 1)}]$

in which - störindexfactor of event i equal to $(t(i)/T)\, 10^{LAmax(i)/13.3}$

$L_{Aeq,\alpha}$ can be rewritten as:

$L_{Aeq,\alpha} = 10\,\mathrm{lg}\,10^{-3.6\,\alpha/10} + 10\,\mathrm{lg}\,[\sum_i \text{störindexfactor} * r(\alpha)]$

in which - $r(\alpha) = 10^{(\alpha - 0.75)LAmax(i)/10 + (-0.025SEL(i) + 3.485)(\alpha - 1)}$

and - $T = 365*24*60*60$ s.

$r(\alpha)$ is constant if the exponent of $r(\alpha)$ is constant for each value of SEL (i) (and corresponding LAmax(i), see equation (9)). The exponent of $r(\alpha)$ is equal to $(\alpha - 0.75)LAmax(i)/10 + (-0.025SEL(i) + 3.485)(\alpha - 1)$.

Substitution of LAmax(i) (equation 9) in the exponent of $r(\alpha)$ and replacing SEL(i) by SEL gives:

exponent of $r(\alpha) = (\alpha - 0.75)(SEL - 25)/8 + [-0.025SEL + 3.485](\alpha - 1) =$

$= (\alpha - 0.75)*SEL/8 - (\alpha - 0.75)/8 - 0.025SEL(\alpha - 1) + 3.485(\alpha - 1) =$

$= [(\alpha - 0.75)/8 - 0.025\,(\alpha - 1)]\,SEL - (\alpha - 0.75)/8 + 3.485(\alpha - 1).$

This exponent is constant for each SEL if $(\alpha - 0.75)/8 - 0.025\,(\alpha - 1) = 0$

This is applicable if $\alpha = 0.6875$.

The constants in the relationship of $L_{Aeq,\alpha=0.69}$ and SI are calculated as follows:

$L_{Aeq,\alpha} = 10\,\mathrm{lg}\,[(10^{-3.6\,\alpha/10}) + 10\,\mathrm{lg}\,[\sum_i \text{störindexfactor} * 10^{(\alpha - 0.75)LAmax(i)/10 + (-0.025SEL(i) + 3.485)(\alpha - 1)}]$

In which $T = 365*24*60*60$ s

$L_{Aeq,0.69} = -3.6*0.69 + 10\,\mathrm{lg}\,0.134 + 10\,\mathrm{lg}\,[\sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}] =$

$= -11.21 + 10\,\mathrm{lg}\,[\sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$

Form this it follows:

$(L_{Aeq,0.69} + 11.21)/10 = 10 \lg [\, \sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$ and by multiplication with a factor 13.3:

$1.33\, (L_{Aeq,0.69} + 11.21) = 13.3 \lg [\, \sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$

In equation (6a) the Störindex (day) has been defined as

Störindex (day) = $13.3 \lg [\, \sum_i g(i)\, (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$

with T = 365*24*60*60 s and g(i) = 1.5 and summation of all events during 06 – 22 h.

Since 13.3 lg 1.5 is equal to 2.34:

Störindex (day) = $2.34 + 13.3 \lg [\, \sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$

By substitution of $13.3 \lg [\, \sum_i (1/T)\, t(i)\, 10^{LAmax(i)/13.3}]$ by $1.33\, (L_{Aeq,0.69,day} + 11.21)$, it follows:

Störindex (day) = $2.34 + 1.33\, (L_{Aeq,0.69,day} + 11.21)$ and therefore:

(10) Störindex (day) = $1.33\, L_{Aeq,0.69,day} + 17.25$,

with
- T = 365*24*60*60 s in $L_{Aeq,0.69,day}$
- summation in $L_{Aeq,0.69,day}$ over all events during 06 – 22 h

(11) Störindex (day + night) = $13.3 \lg [10^{(LAeq\ 0.69,day + 11.21)/10} + 5*10^{(LAeq\ 0.69,night + 11.21)/10}]$

with
- T = 365*24*60*60 s in $L_{Aeq,0.69,day}$

  summation in $L_{Aeq,0.69,day}$ over all events during 06 – 22 h,

  summation in $L_{Aeq,0.69,night}$ over all events during 22 – 06 h.

8 Equations for situations with all SEL values of aircraft noise events equal

From equation (3) the following equation can be derived:

(12) $L_{Aeq} = SEL + 10 \lg N - 10 \lg T$

From equation (7) the following equation can be derived:

(13) $L_{Aeq,\alpha} = \alpha\, SEL + 10 \lg N - 10 \lg T$

In equation (10) SI(day) has the following equation:

(14) $SI(day) = 1.33\, L_{Aeq,0.69} + 17.25$

By substituting equation (14) with α equal to 0.69 it follows:

$$\begin{aligned} SI(day) &= 1.33\, (0.69\, SEL + 10 \lg N_{day} - 10 \lg T) \\ &= 0.92\, SEL + 13.3 \lg N_{day} - 13.3 \lg T \end{aligned}$$

In equation (11) SI(day + night) has been specified. By substituting equation (14) with α equal to 0.69 for both day and night it follows:

(15) $SI(day + night) = 0.92\, SEL + 13.3 \lg (N_{day} + 5\, N_{night}) - 13.3 \lg T$

Finally, SI has been defined in equation (6) by:

(16) SI = maximum SI(day) and SI(day + night)