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The effect of the number of aircraft noise events on sleep quality

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ABSTRACT

Background: Both the WHO and the EC recommend the use of L_{night} as the primary indicator for sleep disturbance. Still, a key question for noise policy is whether the prediction of sleep quality could be improved by taking the number of events into account in addition to L_{night}.

Objectives: The current paper investigates the association between sleep quality and the number of aircraft noise events. The first aim of this study was to investigate whether, for the purpose of predicting sleep quality measured by motility, the nummer of events is adequately represented in L_{night} for the purpose of predicting sleep quality measured by motility. The second aim was to investigate whether the number of events at a given L_{night} has an additional predictive value. In addition, it was explored whether the total number of events should be taken into account for the production of sleep quality, or only the number of events exceeding a certain sound pressure level.

Methods: This study is based on data of a field study among 418 people living within a range of 20 km from Amsterdam Airport Schiphol. The data from this study are well suited for this purpose, since for every subject both the number and the exposure level of events are available. Sleep quality was measured by motility, derived from actimeters worn on the wrist, and by self-reported sleep quality scored on a 11-point scale. Mixed linear regression models were built in a stepwise manner to predict sleep quality during a sleep period time.

Results: The results show that, given a certain equivalent noise level, additional information on the overall number of events does not improve the prediction of sleep quality. However, the number of events above L_{Amax} of 60 dB was related to an increase in mean motility, indicating lower sleep quality. No effect of number of events was found on self-reported sleep quality.

Conclusions: This study suggests that the number of events is more or less adequately represented in L_{night} and only the number of high noise level events may have additional effects on sleep quality as measured by motility. This may be viewed as an indication that, in addition to L_{night}, the number of events with a relatively high L_{Amax} could be used as a basis for protection against noise-induced sleep disturbance.

1. Introduction

Sleep disturbance due to night time noise is a major problem for public health. Sleep disturbance is assumed to lead to short- and long-term consequences for performance, well-being and health. It is therefore important to assess the impact of noise exposure on sleep at a population level [1]. The WHO Night Noise Guidelines for Europe [2] primarily refer to relationships between health and the equivalent noise exposure at the most exposed façade during the night (L_{night}). Both the WHO [2] and the EC [3] advise on the use of L_{night} as the primary indicator for sleep disturbance. L_{night} was proposed to be a suitable noise metric, providing a considerable degree of protection against noise during sleep. However, there are indications that some aspects of sleep disturbance are additionally dependent on the number [1], character [4,5] and distribution [4] of individual noise events over the night. Previous analysis [6] on survey data [7] around Schiphol Airport showed that an increase in the number of flights was adequately reflected in the equivalent sound levels as far as annoyance was concerned. However, for sleep disturbance this could be different. The Night Noise Guidelines for Europe [2] and the END [8] allow the possible use of both the maximum sound pressure level (L_{Amax}) and sound exposure level (SEL) in addition to L_{night} to predict sleep quality.

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A key question for policy is whether under certain conditions and from a public health point of view, limits to L_{night} offer sufficient protection against sleep disturbance or whether additional measurements should be applied to the equivalent sound limit levels. In order to answer these questions more insight is necessary into the influence of maximum levels and number of events during the night on the degree of sleep disturbance at a given equivalent sound level.

Associations with L_{Aeq} or L_{night} have been established for self-reported sleep disturbance, mean motility [10,11] and number of awakenings [1], but for instantaneous and short term effects such as (onset of) motility, awakening, cardiovascular responses and sleep stage changes, L_{Amax} or *SEL* seem to be more predictive [2]. Since instantaneous and short term effects may also contribute to a reduction in overall sleep quality such as measured by mean motility or number of awakenings, the prediction of sleep quality may be improved by additional information on the number or levels of individual events. Taking into account the number of noise events has been shown to lead to differential predictions of sleep disturbance at a given L_{night} in simulations [1]. Theoretically, a given equivalent sound level would cause the maximum level of sleep disturbance (e.g. the highest number of awakenings or highest mean motility) when consisting of a maximum number of sound events with L_{Amax} or sound exposure level (*SEL*) just above a certain threshold to evoke a response [3]. In literature no consensus has yet been reached about the use of *SEL* or L_{Amax} for predicting effects on sleep. A somewhat dated but extensive review representing over 20 years of research on noise-induced sleep disturbance by Pearsons et al. [11] found that *SEL* was a better predictor of awakenings than was L_{Amax}, although it was vice versa for sleep stage changes. A later extensive review of the literature by Berglund et al. [12] concluded that measures of L_{Amax} are better predictors of sleep disturbances than measures of average *SEL* of events. Although the best predictor may depend on the effect of interest as well as on the type of noise source, it seems that for the prediction of sleep quality, in particular instantaneous and short term effects such as motility and awakening, it may be advantageous to take into account either the sound exposure level or maximum level (*SEL*, L_{Amax}) of events.

This paper investigates the association between sleep quality and the number of noise events based on available data from a field study among 418 people by Passchier-Vermeer et al. [10]. Previously, relationships were presented from this study between night-time aircraft noise exposure and motility for three time scales (instantaneous levels, sleep period and long term). Both *SEL* and L_{Amax} of aircraft noise events as measured inside the bedroom were found to be related to instantaneous (onset of) motility (measured by actimetry), and behavioural awakening (button push). Furthermore, sleep onset latency (SOL) and mean motility over a sleep period as measured by actimetry were shown to be associated with L_{Aeq}, while long term mean motility was associated with L_{night}. Of these measures, mean motility (both per night and over longer periods) and sleep onset latency (per night) were positively associated with indicators of subjective sleep quality and/or perceived awakenings, health complaints and adverse sleep effects. The data from this study are well suited for the present purpose, since for every subject aircraft noise exposure was measured inside the bedroom for several nights, on the basis of which both the number and the level of events could be derived. The analysis focuses on mean motility as an objective measure for sleep quality. Additionally, self-reported sleep quality is included to see whether possible effects observed on motility are also found on subjective sleep quality. The first aim of this study was to investigate if the number of events is adequately represented in L_{night} for the purpose of predicting sleep quality measured by motility. The second aim was to investigate whether, given $L_{night,}$ the number of events has an additional predictive value. It is further explored whether, for the prediction of sleep quality, the events exceeding a certain sound level should be taken into account rather than the overall number of events.

2. Methods

2.1. Data

As part of the health impact assessment around Amsterdam Airport Schiphol commissioned by the Netherlands Ministry of Housing, Spatial Planning and the Environment and in close collaboration with the Netherlands Institute for Public Health and the Environment (RIVM), a study was performed among 418 adults residing at various distances from Schiphol airport in the period of November 1999 to April 2001. The objective was to derive exposure–response relationships for night time noise effects and to estimate the prevalence of noise related sleep disturbance at a population level.

2.2. Respondents

Candidates for participating in the study were recruited by mail. The request to participate and a leaflet with information about the tasks of a subject were sent to 3000 addresses. Of these, about 540 candidates showed interest in participating, and 440 potential candidates were chosen for an intake visit and further consultation. After this intake visit 22 persons decided not to take part in the study. All 418 subjects that actually started participation completed the study. At the end of participation subjects received vouchers to the value of €113. Subjects participated from a Monday evening until a Friday morning 11 days later. After subjects agreed to participate in the study, he/she filled out an extensive questionnaire. Participation in the study encompassed the following tasks at each of the 11 participation days:

- Filling out a morning and evening diary on a laptop.
- Performing a reaction time test on a laptop before going to bed.
- Filling out a sleepiness scale five times during day and evening and wearing a watch which produced a noise signal at the times the sleepiness scale had to be filled out.
- Wearing an actimeter (CNT, type AW4, weight about 50 g) monitoring body movements continuously (with the exception of periods of bathing and swimming during study participation), and indicating bedtime and wakeup times by pressing a marker on the actimeter.
- The subjects in this study were exposed to usual night-time aircraft noise in their bedroom. Ages varied between 18 and 81 years, 50% of the subjects were male, 6% lived less than 1 year in the present neighbourhood, 44% over 15 years and the remaining 50% between 1 and 15 years.

2.3. Locations

The study was carried out successively at 15 locations within a distance of 20 km from Schiphol, selected mainly on the basis of modelled night time (23:00–06:00) aircraft noise exposure (see Fig. 1). Other selection criteria pertained to road and railway noise, degree of urbanization and type of dwelling. Two control locations were selected because of their presumed absence of night time aircraft noise to ensure a wide range of different aircraft exposures. The other locations had various degrees of night time aircraft noise exposure, from relatively few aircraft at night up to the highest exposure in residential areas close to Schiphol Airport. At each location, the study took place during two subsequent intervals

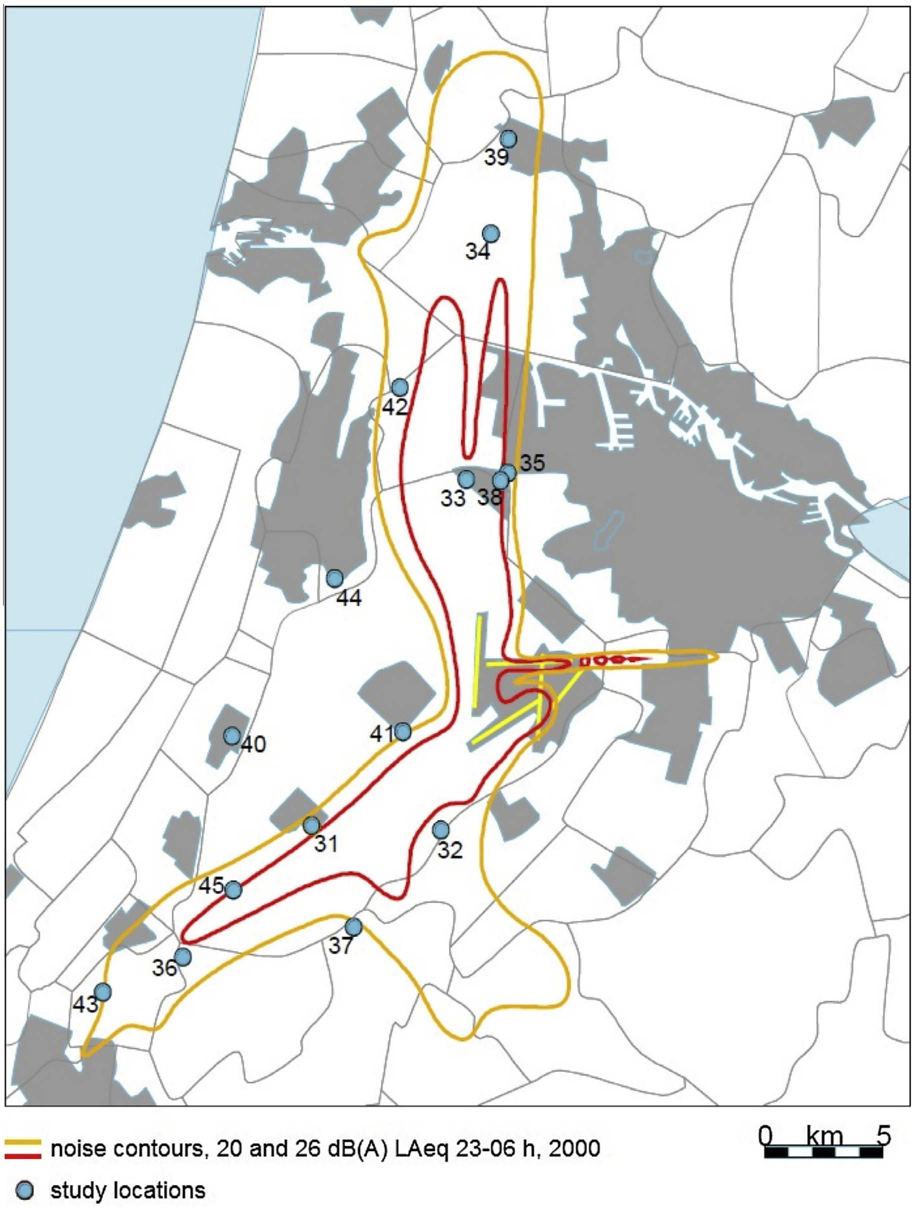

Fig. 1. Map of Amsterdam Airport Schiphol noise contours and study locations.

with 11 nights. Data were available for 414 respondents, with a maximum of eleven nights each. In total 4048 respondent-nights were collected with exposure measures and sleep characteristics. Location summaries are given in Table 1, the overall distribution of aircraft events across the time period of the night is shown in Table 2.

2.4. Sleep quality measures

Sleep quality in this study was assessed by motility and self-reported sleep quality. Motility, the term used for accelerations of the body or body parts during movements, was measured by actimeters worn on the wrist. Actimetry has been used to monitor sleep disturbance in several large field studies with subjects sleeping at home exposed to the usual aircraft, road traffic or railway noise [9,13–17], relating night-time noise exposure to motility measures. Motility measures such as total sleep time, time of falling asleep and wake-up time have been validated by comparing the outcomes with polysomnography, showing reasonable agreement [18]. Other measures of motility used in this study are the instantaneous motility, defined as the probability of motility or the probability of onset of motility in a fixed time interval of 15-s, and the mean probability of motility during the intervals within one sleep period time. In the current study mean probability of motility is given as the percentage of the total sleep time where motility was detected, derived from 15-s interval measures of motility.

Self-reported sleep quality was measured with a 11-point scale questionnaire which had to be completed every morning during participation. The wording of the question was: ‘How well did you sleep last night?’, with extreme answering categories labelled: 0 = very bad, 10 = very well. The 11-point scale was transformed into a 0–100 scale where 0 means good and 100 means bad sleep quality.

Also, as a control variable in the analysis and as a variable on which to base the individual exposure, the Sleep period time (SPT, in hours) was calculated from bedtime and wakeup time actimeter marker data.

Table 1
Locations, number of respondents and mean of exposure characteristics during the sleep period time.

Location	Label	Number of respondents	Number of nights	L_{Aeq} indoor (by aircraft)	Average SEL indoor	Number of events
Nieuw-Vennep	31	28	298	16.3	50.2	10.6
Rijsenhout	32	27	286	19.1	52.7	11.4
Zwanenburg	33	27	269	19.3	50.6	22.7
Assendelft	34	26	259	20.7	55.1	11.6
Halfweg A	35	27	294	25.4	56.2	23.1
(Buiten)Kaag	36	25	268	24.1	55.3	20.7
Leimuiden	37	27	272	20.4	54.9	12.1
Halfweg B	38	27	288	27.5	56.5	31.0
Krommenie	39	24	256	24.6	54.2	26.0
Hillegom*	40	28	197	9.8	49.7	2.8
Hoofddorp	41	30	327	24.9	58.9	12.0
Spaarndam	42	30	175	13.3	52.7	3.3
Warmond	43	30	316	22.6	53.4	20.7
Haarlem*	44	29	242	10.5	50.9	2.0
Abbenes	45	29	301	23.9	55.7	20.6
Total		414	4048	20.8	54.0	16.1

Control sites are marked*, labels refer to the locations given in Fig. 1.

Table 2
Distribution of events across the night.

Time of night	%	% per hour
Before 23:00	1.1	1.1
Between 23:00 and 0:00	4.0	4.0
Between 0:00 and 6:00	37.8	6.3
Between 6:00 and 7:00	26.6	26.6
After 7:00	30.5	15.3

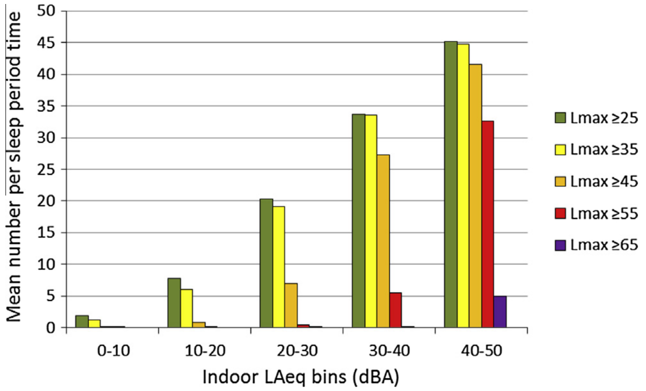

Fig. 2. Mean number of events per sleep period time (using different cut-off values) by indoor L_{Aeq}.

2.5. Noise exposure measures

To assess night-time aircraft noise exposure of subjects, noise was measured between 22:00 and 09:00 using indoor noise monitors in the bedroom of each subject and one outdoor noise monitor. The noise monitors stored the equivalent sound level using a slow time constant (1 s). Aircraft noise events were identified by comparing the noise and time data from the indoor and outdoor noise monitors with information obtained from the aircraft identification system at Schiphol (FANOMOS). For each identified event, both L_{Amax} and *SEL* (indoors) were calculated, the latter defined as the (A-weighted) equivalent sound level during the time that the noise level was between L_{Amax} and L_{Amax} −10 dB, normalized to 1 s. For each individual sleep period time (*SPT*), the number of aircraft noise events, the L_{Aeq} indoors caused by aircraft noise, and the arithmetic mean of the indoor *SEL* values of aircraft noise events were calculated. Fig. 2 shows the mean number of events per sleep period time.

2.6. Statistical analyses[2]

Following earlier studies [19,20], the relative impact of the noise level *L* of events and the number *N* of its occurrence on effect variables (*Y*) was expressed as the ratio of regression coefficients B_N/B_L taken from:

$$Y = B_0 + B_L L + B_N \log N + B_t \log(T)$$

B_0 is the regression coefficient for the intercept, B_L and B_N are the regression coefficients for sound exposure level (average *SEL*) and number (*N*) of noise events, respectively. The ratio between the two ($k = B_N/B_L$) indicates the relative importance of number compared to level, and is called the decibel-equivalent number effect. It equals 10 in the equal-energy indices (e.g. L_{Aeq}), meaning that a tenfold increase in number corresponds to a 10 dB increase in *SEL*. B_t is the regression coefficient for time across which noise is measured (*T*), in this case the sleep period time (*SPT*). Mixed linear regression models, with respondent ID as random factor, were built in a stepwise manner for mean motility and self-reported sleep quality.

In addition, both mean motility and self-reported sleep quality were predicted from L_{Aeq} as the basic prediction variable. Mixed linear regression models, with respondent ID as random factor to account for highly correlated observations between nights within subjects, were built in a stepwise manner, controlling for sleep period time, age (centred on mean age), age squared, and gender. Effects of age [9] and gender [21] on sleep have been observed before, and sleep period time was included in the model to adjust for the possibility that a longer sleep period is associated with both sleep quality and exposure characteristics.

Subsequently, the additional predictive value of number of events was investigated, meanwhile exploring the importance of the L_{Amax} of the events. Number of events exceeding a certain cut-off value was added to the model with L_{Aeq} as the basic prediction variable, controlling for possible confounders. Subsequently, the cut-off values for the number of events as predictor variable were increased with steps of 5 dB L_{Amax} to explore a possible threshold. The model fits were presented using the −2 Log Likelihood (−2 LL), where a smaller value indicates a better fit. The significance of the differences between the models was calculated using chi-squared values. All analyses were done with the Statistical Package SPSS (version 20).

3. Results

3.1. Descriptives

Table 3 shows the descriptive statistics for the variables used in the analyses. Table 4 shows the descriptive statistics for the number of events above a certain cut-off score as used in the cut-off model. The L_{Amax} values ranged from 26 dB to 84 dB (correlating highly with *SEL*, Pearson $R = 0.94$). The first cut-off point included all events above 25 dB, thereby including all events. The highest

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[2] Although the method used by Miedema et al. [6] is in principle also very appropriate to quantify the tradeoff between number of events and sound level, this analysis did not give reliable estimates for the trade-off parameters, because the relationship between exposure level during the sleep period and mean motility was not strong enough for a stable optimization of the parameters

Table 3
Descriptive statistics for variables in the analyses.

	N	Minimum	Maximum	Mean	Std. Dev.
Dependent variables					
Mean motility (%)	4013	0.06	28.01	3.65	1.88
Self-reported sleep quality (0 = very well – 100 = very bad)	3991	4.55	95.45	32.68	18.46
Predictor variables					
L_{Aeq} indoor by aircraft during sleep period	4012	0.1	48.5	20.8	8.9
Average SEL indoor during sleep period	4048	38.0	78.0	54.0	5.6
Number of events during sleep period	4048	1	109	16.1	17.1
Sleep period time (SPT) in hours	4048	1.6	12.1	7.3	1.2
Age	414	18	81	45.7	14.7
Gender	414	Male (0) 207 (50%)	Female (1) 207 (50%)		

Table 4
Descriptive statistics for the number of events above a certain cut-off value of L_{Amax}. For each cut-off value of L_{Amax} are given: the average and maximum number of events per night (*Mean* and *Max # events per night*); total number of events exceeding cut-off value over all respondent nights (*Sum of # over all nights*); the% of the number above a certain cut-off value with regard to the total number of events (# events (%)); the number of exposed nights; and the% exposed of the total number of nights.

L_{Amax}cut-off	Mean # events per night	Max # events per night	Sum of # events over all nights	# events (%)	Number of exposed nights	% of exposed nights
⩾25 dB	16	109	64,995	100	4048	100
⩾30 dB	16	109	64,557	99.3	4045	99.9
⩾35 dB	15	109	60,296	92.8	3940	97.3
⩾40 dB	12	108	47,555	73.2	3602	89.0
⩾45 dB	7	104	29,848	45.9	2934	72.5
⩾50 dB	4	103	14,479	22.3	2014	49.8
⩾55 dB	1	103	5376	8.3	1058	26.1
⩾60 dB	0	62	1536	2.4	390	9.6
⩾65 dB	0	28	327	0.5	114	2.8
⩾70 dB	0	4	33	0.1	23	0.6

cut-off point was set to 70 dB, above which only a very low number of respondents and events was observed.

Some notes should be made with regard to the explorative cut-off models. First, the number of the events per respondent night is not normally distributed, particularly in the higher cut-off value range, since in most nights only a relatively low number of events occurred. Second, for some of the cut-off values the (log) number of events correlated rather highly with L_{Aeq}, but not above around 0.70. Therefore, it was deemed acceptable to combine the number of events and L_{Aeq} in the same model. Third, one outlier was found within the mean motility data. However, omitting this outlier from the analysis did not lead to different results and therefore it was decided to leave it in.

3.2. The relative effect of indoor SEL and number of events on mean motility

The stepwise linear regression model for mean motility with *SEL* and number of events is shown in Table 5. The results show the independent effects of the average *SEL* values and the logarithm of the number of events (*LogNumber*) on mean motility.

Average *SEL* is positively associated with mean motility in each model shown in Table 5. Also *LogNumber* added in model 2 shows a positive relation with mean motility. The k value for this model is 0.150/0.016 = 9.375, which is very close to the k value of 10 implicit in L_{Aeq}. However, with the addition of the logarithm of sleep period time (*LogSPT*) in model 3, *LogNumber* is no longer related with mean motility, which makes the calculation of k here not meaningful anymore. The positive relation of sleep period time with mean motility indicates that longer sleep time is an important predictor of increased mean motility.

3.3. The relative effect of indoor SEL and number of events on self-reported sleep quality

The stepwise linear regression model for self-reported sleep quality with *SEL* and number of events is shown in Table 6. This model tests the effect of *SEL* and number of events on the quality

Table 5
Stepwise linear regression model for mean motility with *SEL* and number of events. The association of each variable with mean motility is shown by B (unstandardized regression coefficient). The k value shows the ratio between the coefficients B of *LogNumber* and *SEL*. The −2 LL shows the fit for each model. The −2 LL of each model was compared with the −2 LL of its previous model. Significant differences between the −2 LL values were determined using chi-squared values.

	Model 0B	Model 1B	Model 2B	Model 3B
Intercept	3.658***	2.664***	2.692***	−0.375
Average SEL indoor		0.019**	0.016**	0.019**
LogNumber			0.150**	−0.048
LogSPT (Sleep period time)				3.598***
k			9.38	−2.53
−2 Log Likelihood	14,377	14,376	14,371	14,270*

*** Significant at the 0.001 level (2-tailed).
** Significant at the 0.01 level (2-tailed).
* significant at the 0.05 level (2-tailed).

Table 6
Stepwise linear regression model for self-reported sleep quality with *SEL* and number of events. The association of each variable with self-reported sleep quality is shown by B (unstandardized regression coefficient). The *k* value shows the ratio between the coefficients B of *LogNumber* and *SEL*. The −2 LL shows the fit for each model. The −2 LL of each model was compared with the −2 LL of its previous model. Significant differences between the −2 LL values were determined using chi-squared values.

	Model 0B	Model 1B	Model 2B	Model 3B
Intercept	32.438***	24.816***	24.580***	30.902***
Average SEL indoor		0.142*	0.163*	0.154*
LogNumber			−1.050	−0.669
LogSPT (Sleep period time)				−7.211
k			−6.44	−4.34
−2 Log Likelihood	33,907	33,906	33,902	33895*

*** Significant at the 0.001 level (2-tailed).
* Significant at the 0.05 level (2-tailed).

of sleep measured on a 0–100 scale. Note that this scale is reversed to match with mean motility, so high scores on the sleep quality scale represent a low sleep quality and low scores represent high sleep quality.

Model 1 shows that higher average *SEL* is related to lower self-reported sleep quality. *LogNumber* is not related to self-reported sleep quality in any of the models, therefore the *k* values for these models are not meaningful. Also, *LogSPT* shows no significant association to self-reported sleep quality.

3.4. Exploring the importance of L_{Amax} for the effect of number of events on mean motility

The importance of the L_{Amax} of events for their effect on mean motility is explored by stepwise addition of the number of events exceeding certain cut-off points to the base model of L_{Aeq} on mean motility. The L_{Aeq} model is shown in Table 7.

L_{Aeq} is positively related to mean motility in model 1 shown in Table 7, but after the addition of *SPT* in the model it is no longer significant. As in Table 5, *SPT* shows a positive effect, indicating that longer sleep time is associated with increased mean motility. Furthermore, the square of age is positively related to mean motility, meaning that people who are further away from the mean age show higher mean motility.

Results for the additional effects of the number of events exceeding L_{Amax} cut-off points from 25 to 70 dB on mean motility are summarized in Table 8.

The model shows no effects on motility for the number of events exceeding the cut-off points of ⩾25 dB (all events) up to ⩾55 dB. For cut-off points starting from ⩾60 dB, an increase in the number of events is associated with an increase in motility (at a given L_{Aeq}). In these cases, the −2 LL values show that the additional effect of the number of events leads to a significantly better model fit compared to the basic L_{Aeq} model in Table 7.

Table 8
Cut-off value method for mean motility. The additional effect is shown of the number of events exceeding a certain cut-off value, when added to the full L_{Aeq} model on mean motility. For each cut-off value, the regression coefficient *B* and model fit using the −2 LL is shown. The −2 LL scores are compared to the −2 LL scores of the full L_{Aeq} model (14158) and tested for significant difference using chi-squared values.

Number of events above L_{Amax} cut-off	*B*	−2 Log Likelihood
⩾25 dB	−0.001	–
⩾30 dB	−0.001	–
⩾35 dB	−0.001	–
⩾40 dB	0.001	–
⩾45 dB	0.002	–
⩾50 dB	0.005	–
⩾55 dB	0.011	–
⩾60 dB	0.056***	14145***
⩾65 dB	0.154***	14137***
⩾70 dB	0.876***	14135***

*** Significant at the 0.001 level (2-tailed).

3.5. Exploring the importance of L_{Amax} of events on self-reported sleep quality

Also for self-reported sleep quality the importance of the L_{Amax} of events was explored using L_{Aeq} as the basic model. The effect of L_{Aeq} on self-reported sleep quality is shown in the Table 9.

L_{Aeq} is shown not to be significantly related to self-reported sleep quality. *LogSPT* and *Gender* are related to self-reported sleep quality, with longer sleep time associated with increased self-reported sleep quality and female respondents reporting lower sleep quality than male respondents. No effect of age was found. Number of events was not found to have additional predictive value with any of the cut-off values applied.

4. Discussion

The first aim of this study was to investigate if the number of events is adequately represented in L_{night} for the purpose of

Table 7
Stepwise linear regression model for mean motility with L_{Aeq}. The association of each variable with mean motility is shown by B (unstandardized regression coefficient). The −2 LL shows the fit for each model. The −2 LL of each model was compared with the −2 LL of its previous model. Significant differences between the −2 LL values were determined using chi-squared values.

	Model 0 B	Model 1 B	Model 2 B	Model 3 B
Intercept	3.658***	3.406***	1.908***	1.627***
L_{Aeq} indoor		0.013***	0.006	0.006
SPT (Sleep period time)			0.224***	0.218***
Age				0.004
Age^2				0.001***
Gender (0 = male, 1 = female)				–
−2 Log Likelihood	14,377	14,266***	14,161***	14,158

*** Significant at the 0.001 level (2-tailed).

Table 9
Stepwise linear regression model for self-reported sleep quality with L_{Aeq}. The association of each variable with self-reported sleep quality is shown by B (unstandardized regression coefficient). The −2 LL shows the fit for each model. The −2 LL of each model was compared with the −2 LL of its previous model. Significant differences between the −2 LL values were determined using chi-squared values.

	Model 0 B	Model 1 B	Model 2 B	Model 3 B
Intercept	32.438***	31.734***	35.391	30.974***
L_{Aeq} indoor		0.0357	0.0487	0.0514
SPT (Sleep period time)			−0.538*	−0.591*
Age				–
Age^2				–
Gender (0 = male, 1 = female)				3.161***
−2 Log Likelihood	33,907	33,620***	33,616	33,606*

*** Significant at the 0.001 level (2-tailed).
* Significant at the 0.05 level (2-tailed).

predicting sleep quality measured by motility. To gain insight into this, the decibel-equivalent number effect *k* was determined, defined as the ratio between the estimates for the number and for the level effect. This proved to be around 10 for the prediction of sleep quality measured by motility in the unadjusted model, meaning that the effect of a tenfold increase in the number of events corresponds to that of a 10 dB increase in *SEL*, as is implemented in L_{Aeq} and L_{night}. However, no effect of number of events was found after correction for sleep period time, which was associated with higher motility. Consistent with sleep quality measured by motility, self-reported sleep quality was found to decrease with increased average *SEL*, although no effect of the number of events was found. In contrast to sleep quality measured by motility, self-reported sleep quality improved with a longer sleep time, suggesting that the perception of sleep quality is partly dependent on the duration of sleep. The results above suggest that the number of events is more or less adequately represented, or even slightly overrepresented, in L_{night}.

These results are not in line with the expectation of an influence of the number of events on sleep quality based on instantaneous relationships [1–3]. However, the number of events did have an effect on motility consistent with L_{night} before correction for sleep period time. This correction was done since a higher number of noise events for a longer sleep period time does not necessarily mean a noisier night or a higher density of events. Possibly, however, the observed strong positive association between sleep period time and mean motility masked the effect of number of events. A reason for the higher mean motility with longer sleep time may be that the chance of motility increases over time after falling asleep, as was found in other analyses on the same data [9], as well as in a study on the effect of road and rail traffic noise on sleep quality measured by motility [10]. Alternatively, it may partly be due to the sleep period overlapping with periods of high traffic densities in the morning, or increased sleep period time may even be a consequence of sleep fragmentation due to noise, in which case adjusting for sleep period time could lead to an overcorrection, masking effects of noise on motility. Furthermore, regarding self-reported sleep quality, a longer sleep time may have partially compensated for any adverse effects of number of events.

Secondly, it was investigated whether, given L_{Aeq} during the sleep period, the number of events has an additional predictive value. The prediction of mean motility based on L_{Aeq} was slightly better than the prediction based on average *SEL* and number of events combined, suggesting that uncoupling *SEL* and number of events leads to a loss of information, since the effect of number of events is not independent of the level of these events [e.g. 2,26]. In line with this, it was explored whether for the prediction of sleep quality the total number of events should be taken into account, or only the number of events exceeding a certain sound level. L_{Amax} thresholds were found ranging from 32 dB to 42 dB for evoking sleep related responses [2], and previous event-based analyses on the present dataset found a threshold of 32 dB for motility [2,3,9]. Theoretically, a given equivalent sound level would be expected to cause the highest mean motility when consisting of a maximum number of sound events with L_{Amax} roughly 5 dB above this threshold [3,27]. In contrast, the present results indicate that only the number of events exceeding 60 dB L_{Amax} is related to an increase in mean motility at a given L_{Aeq}, suggesting that particularly the loudest events should be limited for better sleep quality (see also [22]). Since sleep related responses may be found at much lower L_{Amax} levels, limiting the number of events above 60 dB L_{Amax} only seems to be beneficial as a protection measure in addition to L_{night}. Nevertheless, these results suggest that sleep quality may improve by reducing the number of events exceeding 60 dB L_{Amax}, rather than to lower the overall number of events.

Additionally, mean motility was related to age, with respondents of around the mean age showing lower mean motility than both younger and older respondents, which is in good agreement with results of Passchier-Vermeer et al. [9,10]. Furthermore, lower self-reported sleep quality was found in women than in men, which was also found in earlier studies [23,24, see also 2] and is possibly partly caused by phases in female biological cycles [25].

In this study, L_{Aeq} was used as a proxy for L_{night}. However, it should be kept in mind that the exposure measure (L_{Aeq} inside the bedroom during sleep period time) used here is very much related to the individual sleeping pattern of the respondents and can therefore not be directly compared to L_{night} or other time of day related exposure measures. Furthermore, it should be noted that the associations between noise exposure and sleep quality are quite weak, since obviously there are many other factors that may influence the individual sleep quality. However, in this study the focus is on improving the prediction of sleep quality from noise. Also, since the sample used in this report cannot be viewed as a random sample from the population in terms of exposure, the results have to be regarded as indicative and cannot be generalized to a larger population not living in the vicinity of Schiphol Airport. Besides, in this study only the effect of the number of air traffic noise events on sleep quality is investigated. It is expected that the number of other traffic noise events have different effects on sleep disturbance [3] which cannot be derived from this study. Nevertheless, the present findings suggest that, to reduce motility as a proxy for restless sleep, it may help to prevent the occurrence of events with high maximum levels in addition to reducing L_{night}.

5. Conclusions

This study suggests that the number of events is more or less adequately represented in L_{night} and only the number of high noise level events may have additional effects on sleep quality as measured by motility. This may be viewed as an indication that, in addition to L_{night}, the number of events with a relatively high L_{Amax} could be used as a basis for protection against noise-induced sleep disturbance.

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