The sleep disturbance index – a measure for structural alterations of sleep due to environmental influences

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SUMMARY

Sleep disturbances caused by noise and other environmental influences are usually rather moderate but have a rather typical pattern with reduced times in slow-wave-sleep (SWS) and in REM-sleep, with delays of sleep onset and of the first occurrence of SWS, with prolonged wakefulness after sleep onset and sleep stage S1 as well as an increase of the number of wake periods longer than 3 minutes. This paper presents a newly developed sleep disturbance index (SDI) that constitutes a reliable and valid indicator of physiological sleep quality. It was developed on the basis of the 7 aforementioned sleep parameters derived from polysomnograms recorded during an undisturbed night of 38 men and 28 women (19-34 yrs, reference sample).

Reliability was ascertained by application of the SDI to a quiet night of 82 persons of the same age from two other laboratory studies. Validity was verified by significantly higher index-values indicating more disturbed sleep, that were determined for noisy nights of 50 persons (25 men, 25 women, 19-28 yrs) and for the first night in the laboratory of 62 persons (37 men, 25 women, 19-34 yrs) as compared with quiet reference nights of the respective sample. Further the index-values increased with age as determined with polysomnograms from 193 participants observed in the laboratory and 56 persons observed in a field study whose age varied between 18 and 68.

INTRODUCTION

Nocturnal noise provokes sleep disturbances which in turn cause after effects, i.e. subjectively degraded sleep quality and impairments of mood and performance. The physiological alterations that are derived from the polysomnogram are usually described by an ensemble of various parameters where only a few are significant. Based on a literature review and the analysis of our own studies 7 variables were identified which were frequently observed to alter during noisy nights, however, not necessarily simultaneously. Instead, some studies revealed mainly reductions of SWS or of REM-sleep or an increase of the time awake either by prolonged sleep onset latency or by intermittent wakefulness (e.g. Eberhardt 1987; Griefahn 1986).

This paper describes the development of a sleep disturbance index (SDI) which allows a reliable estimate of physiological sleep quality. It bases on data recorded during quiet nights of young persons. Validity was tested by within-subject comparisons between the index-values calculated for quiet nights on one hand with the index-values determined for noisy nights and for the first night in the laboratory on the other hand and further by relating the index-values recorded in quiet nights to age.

DEVELOPMENT OF THE SLEEP DISTURBANCE INDEX, SDI

Data base

The polysomnograms (PSG, 2 EEG, 2 EOG, 1 EMG) used for the development and for the validation of the sleep disturbance index were taken from six experimental studies (Studies I-VI) and a field study (Study VII) performed at the Institute for Occupational Physiology at Dortmund Technical University (IfADo) and at the Institute of Aerospace Medicine of the German Aerospace Center (DLR). The same methods were applied in all these studies and the PSG were evaluated according to Rechtschaffen and Kales (1968).

- Studies I-III: 58 persons (19 male, 29 female, 19-28 yrs) observed in the laboratory (Griefahn et al. 2006a, b), where a first night for habituation was followed by a sequence of four consecutive nights (bedtime 2300 to 0700 h) in each of two or three consecutive weeks. Apart from 8 persons who slept in quiet throughout, one quiet (reference) night was randomly arranged with three noisy nights each week where either aircraft-, rail- or road traffic noise was applied with equivalent noise levels of 39, 44 or 50 dBA. (From those persons who participated in more than one study, only the observation in the first study in which he/she participated was considered for this analysis.)
- Study IV with 9 men (19 – 34 yrs) concerned night sleep after experimental work shifts in the afternoon.
- Study V: 128 persons (53 men, 75 women, 19-65 yrs) observed in the laboratory during 13 consecutive nights from 2300 to 0700 h (Basner & Samel 2005). While 16 persons slept in quiet throughout, 112 persons were exposed to aircraft noise during the 3^{rd} to 11^{th} night. The individual average of the 2^{nd} and the 12^{th} night were used for the analysis.
- Study VI: 65 persons (31 men, 34 women, 18-8 yrs) whose sleep was recorded in the laboratory during 11 consecutive nights from 2300 to 0700 h (Basner et al. 2006a). After a habituation night aircraft, rail and/or road traffic noise was presented during 8 nights within which a reference night without noise exposure was systematically interspersed.
- Study VII: 58 residents (25 men, 33 women, 19-61 yrs) living in the vicinity of an airport with heavy nocturnal traffic load (Basner et al. 2006b). Their sleep was recorded during 9 consecutive nights in their own bedrooms. Bedtimes varied according to the participants' habitual sleep times. The 6^{th} night (Saturday night) with the lowest number of flyovers was used for the calculation of the SDI.

Frequently ascertained alterations of sleep in noisy nights

Due to a literature review and the studies performed at IfADo and DLR (> 300 participants, ≈ 4 000 nights) the following alterations were frequently though not necessarily simultaneously ascertained during nights with noise exposure:

(1) prolongation of sleep onset latency (SOL), i.e. minutes from the start of the observation period and the first epoch of sleep stage S1,
(2) increase of latency to slow-wave-sleep (SWSL) i.e. minutes from sleep onset to the first occurrence of SWS,
(3) increase of wakefulness after sleep onset (WASO), i.e. minutes awake from sleep onset to final awakening,

(4) increase of the number of periods awake of more than three minutes (W3min),
(5) increase of the time spent in sleep stage S1 (in minutes),
(6) decrease of the time spent in SWS (in minutes),
(7) decrease of the time spent in REM-sleep (in minutes).

Remark: Sleep stage S2 was not regarded as alterations might be related to alterations of the time spent in stage S1 and/or in SWS and/or in REM-sleep.

Principal component analysis

Sixty-six quiet reference nights of 38 male and 28 female participants (Studies I-IV) were chosen for the development of the SDI. The seven parameters listed above were derived from each PSG and submitted to a principal component analysis, after some of them had been transformed to their natural logarithms (log) or square roots (SQRT) for a better approximation to normality. The first principle component (PC1, Table 1) with the highest eigenvalue of > 2 explained about 35 % of the variance and was the only component where the times spent in SWS and in REM-sleep loaded negatively and all the others positively thus meeting the criteria derived from the literature analysis and allowing to interprete the PC1 as an indicator of 'disturbed sleep' where higher values indicate worse and lower values better sleep.

Table 1: Results of the principal component analysis with means and standard deviations (SD) of the (transformed) 7 variables. PC: principal component

Variable	*mean*	*SD*	*Scores of the principal components*						
			PC1	*PC2*	*PC3*	*PC4*	*PC5*	*PC6*	*PC7*
(1) log (WASO)	3.27	0.46	0.326	-0.311	-0.196	0.005	0.274	-0.049	1.539
(2) SQRT (minutes in S1)	4.28	1.29	0.110	-0.109	0.599	0.653	0.530	0.081	-0.204
(3) Minutes in SWS	68.69	26.15	-0.279	-0.262	0.289	-0.329	0.017	1.005	0.611
(4) Minutes in REM	113.99	22.16	-0.167	0.370	-0.453	0.457	0.569	0.561	0.296
(5) log (SOL + 0.5)	2.59	0.88	0.177	0.424	0.207	-0.638	0.736	0.046	-0.088
(6) log (SWS-latency + 0.5)	2.74	0.29	0.224	0.472	0.205	0.166	-0.795	0.503	0.538
(7) SQRT (W3min-events)	0.88	0.72	0.315	-0.251	-0.251	-0.040	-0.000	0.827	-1.154
Eigenvalue			2.469	1.282	1.200	0.847	0.540	0.440	0.222
explained variance			0.353	0.183	0.171	0.121	0.077	0.063	0.032

The SDI was then calculated while using the (transformed) values x_i of the seven input variables, the sample means (AM_i) and standard deviations (SD_i) with the scores of the first principle component ($PC1_i$) as follows

$$SDI = \sum_{i=1}^{7} PC1_i \times \frac{x_i - AM_i}{SD_i}$$

The index was thus standardized to the mean value 0 and the standard deviation 1 for the base sample with undisturbed sleep in the laboratory.

RELIABILITY OF THE SLEEP DISTURBANCE INDEX

To test its reliability the SDI was applied to the quiet nights of 82 persons of the same age whose sleep was recorded in Studies V and VI. Mean and standard deviation (-0.07 ± 1.06) did not significantly differ from the respective data of the reference sample (p = 0.66).

VALIDITY OF THE SLEEP DISTURBANCE INDEX

The validity of the index was tested with regard to noise-induced sleep disturbances, to the First-night effect (Agnew et al. 1966), and to age-related alterations of sleep.

Noise-induced sleep disturbances

Table 2 presents means and standard deviations of the SDI and of the seven parameters that contributed to its development for 50 persons who slept in either of Studies I-III, separately for all (quiet) reference nights and all noisy nights. Each individual parameter revealed significant alterations into the expected direction ($p < 0.05$) and this was reliably reflected by the highly significant increase of the SDI during noisy as compared to quiet nights.

Table 2: Means and standard deviations (SD) of the SDI and 7 sleep parameters for quiet (reference) and noisy nights of 25 men and 25 women (19-34 yrs). Wilcoxon Test. **: p ≤ 0.01, ***: p ≤ 0.001

Dependent variables	**Quiet nights**		**Noisy nights**		
50 participants	mean	± sd	mean	± sd	p
Sleep onset latency	19.7	±13.2	23.7	±12.2	***
Latency to SWS	16.5	±7.8	20.3	±12.5	***
WASO	29.1	±14.3	37.1	±14.9	***
Periods awake > 3 min	1.1	±1.1	1.7	±1.4	***
Time in S1	18.4	±10.1	21.0	±12.0	**
Time in SWS	70.5	±24.9	64.3	±24.9	**
Time in REM-sleep	112.4	±17.7	107.2	±17.5	**
Sleep disturbance index	-0.12	±1.07	0.48	±0.97	***

Table 3 shows a more detailed analysis of the noise effects of Study I, where the sleep of 12 women and 12 men, 19-28 years of age was recorded during 4 consecutive nights each of 3 consecutive weeks. During 3 nights each week the participants were exposed either to noise emitted from aircraft, from rail or from road traffic with equivalent noise levels of 39, 44, or 50 dBA. Means and standard deviations are listed separately for the total of 3 nights each spent in quiet and under the impact of the 3 equivalent noise levels irrespective of the type of noise. The seven single parameters altered as expected and the SDI increased significantly under each of the 3 noise levels. There was, however, no gradual increase with noise levels. The SDI was instead almost equally increased under the impact of 39 and 44, but much more under the impact of 50 dBA.

Table 3: Means and standard deviations (SD) of the SDI, SEI and 7 sleep parameters calculated from Study I (IfADo) for 3 nights each spent in quiet (reference) and under the impact of 3 equivalent noise levels (12 men, 12 women, 19-28 yrs). Wilcoxon Two-Sample Test for the comparison of quiet with noisy nights. *: p ≤ 0.05, **: p ≤ 0.01, ***: p ≤ 0.001

Dependent variables	**Quiet nights**		**L_{Aeq} = 39 dBA**		**L_{Aeq} = 44 dBA**		**L_{Aeq} = 50 dBA**	
	mean	± sd	mean	± sd	mean	± sd	mean	± sd
Sleep onset latency	21.8	±12.7	23.3	±12.8	24.5	±14.9	23.5	±12.1
Latency to SWS	17.7	±9.5	22.5	±17.0 *	19.5	±9.6	24.6	±22.4 ***
WASO	30.0	±13.4	36.5	±17.1**	36.0	±17.8*	41.7	±20.2***
Periods awake > 3 min	1.3	±1.2	1.9	±1.5**	1.9	±1.5 **	1.9	±1.6 **
Time in S1	19.2	±7.2	21.9	±9.8*	23.4	±10.4 **	24.8	±10.0 ***
Time in SWS	73.3	±25.6	69.6	±29.1	68.0	±26.0 *	66.0	±26.1
Time in REM-sleep	107.0	±14.2	102.2	±16.3	100.6	±19.9	99.4	±16.9 **
Sleep disturbance index	0.03	±0.95	0.52	±1.24 ***	0.44	±1.27 **	0.80	±1.11 ***

First night effect

Table 4 presents means and standard deviations calculated for the first nights in the laboratory of 62 persons (37 men, 25 women, 54 participants from studies I-III, 8 from study IV)) and for the first (quiet) reference night. Despite the same acoustic conditions each single parameter indicated, though not always significantly, a worse sleep quality in the first as compared to the first quiet nights. The SDI was slightly negative during quiet and significantly ($p < 0.001$) higher during the first night.

Table 4: Means and standard deviations (sd) of the SDI, SEI and 7 sleep parameters calculated from Studies I-IV (***IfADo***) for first (habituation) nights and quiet nights of 37 men and 25 women, 19 to 34 years of age. Wilcoxon Two-Sample Test for the comparison of first nights with the first following night quiet nights. *: p ≤ 0.05, **: p ≤ 0.01, ***: p ≤ 0.001

Dependent variables	**Quiet nights**		**1st night**		
62 participants	mean ±	sd	mean ±	sd	p
Sleep onset latency	22.5	±20.3	33.3	±24.7	***
Latency to SWS	16.2	±6.5	21.0	±22.5	
WASO	30.4	±21.5	40.1	±25.4	**
Periods awake > 3 min	1.0	±1.2	2.2	±2.1	***
Time in S1	19.4	±11.9	20.3	±12.1	
Time in SWS	68.3	±27.3	63.7	±25.8	
Time in REM-sleep	108.1	±23.5	89.5	±28.8	***
Sleep disturbance index	-0.01	±1.22	0.75	±1.35	***

Alteration with age

Noise-induced alterations of sleep are non-specific. As similar alterations occur with increasing age (e.g. Griefahn 1985), the SDI was supposed to correlate significantly with age. To test this, the SDI was applied to Studies V-VII where the age of the participants varied in a wider range (18-68 yrs).

Table 5 shows the statistical parameters calculated for age and for the SDI together with the respective correlation coefficients that are highly significant for each of the 3 samples, though much lower for the field study. According to Figure 1 the SDI increased gradually with age.

Table 5: Means, standard deviations (sd), minima and maxima of the age and the sleep disturbance index values calculated for a quiet night ascertained in Studies V, VI, VII performed at DLR, ***: p ≤ 0.001

	N	**Age**				**SDI**				**Corr.**
Study		mean	± sd	min -	max	mean	± sd	min -	max	SDI:age
V	128	38	± 13	19 -	65	0.47	±1.22	-2.1	-4.3	0.50 ***
VI	65	39	± 13	18 -	68	0.46	±1.15	-1.9	-3.6	0.56 ***
V+VI	193	38	± 13	18 -	68	0.46	±1.20	-2.1	-4.3	0.52 ***
VII	58	37	± 12	19 -	61	0.53	±1.04	-1.5	-4.4	0.33 ***

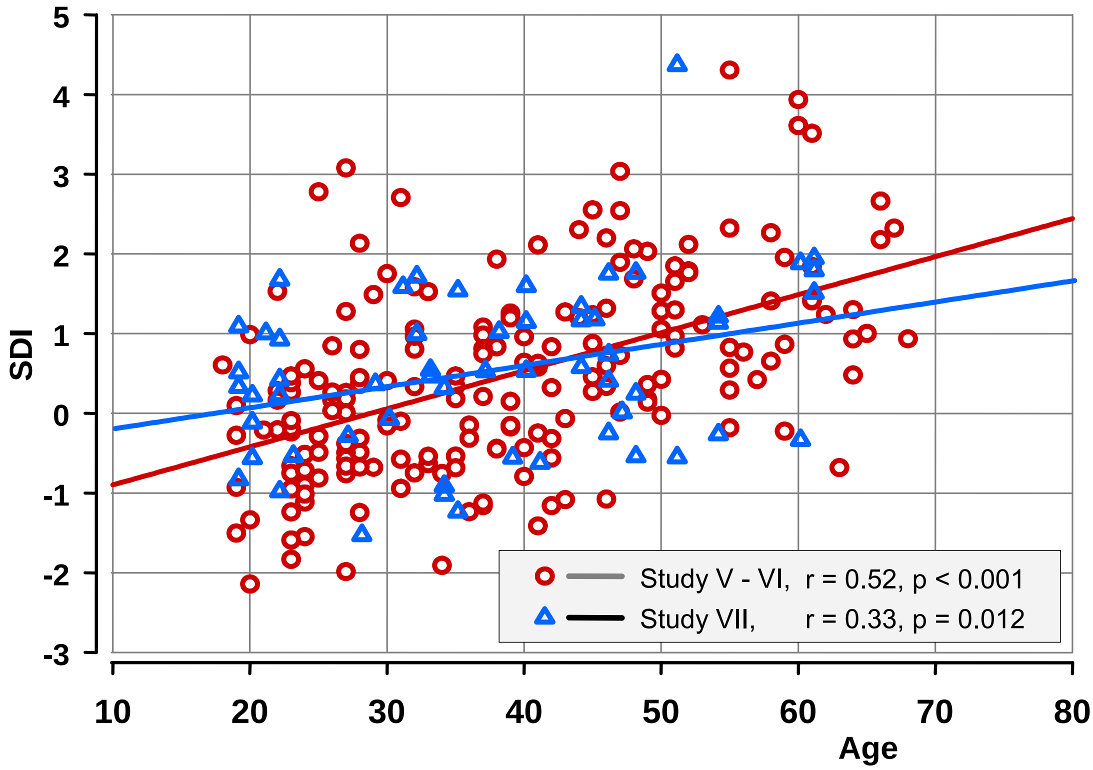

Figure 1: SDI related to age. Blue regression line: SDI of 193 persons (18-68 yrs), observed in the laboratory, red regression line: SDI determined from 58 persons (19-61 yrs), observed in the field

DISCUSSION

Development of the sleep disturbance index

A sleep disturbance index was developed using 7 sleep parameters that frequently alter under the impact of noise. These variables were derived from polysomnograms recorded during an undisturbed night of a rather homogenous sample of 38 men and 28 women (19-34 yrs). As the respective nights were preceded by at least a habituation night, the participants were then sufficiently adapted to the technical equipment and their sleep was regarded as normal (Griefahn & Gros 1986). After transformation (log, SQRT), the variables were submitted to a principal component analysis where the first principal component explained 35 % of the variance. The respective scores were used for the calculation of the index. The percentage of explanation might perhaps be increased to some degree by the inclusion of further variables, but this would then increase the number of variables that are not independent of each other and complicate the interpretation of the results.

The application of the index to various groups and conditions indicate the reliability and the validity of the index.

Reliability. To test its reliability the SDI was calculated for the quiet nights of 82 persons of similar age whose sleep was recorded in the laboratory at the DLR (Studies V and VI). As the SDI did not differ significantly from that of the reference sample the index is regarded as reliable.

Validity. The index was standardized to a mean of 0 and a standard deviation of 1. Negative values indicate therefore better and positive numbers worse sleep. Positive values were expected under the impact of noise, during the first night in the laboratory as well as with increasing age.

Effects of noise on sleep. Using the nights recorded in Studies I-III the SDI clearly revealed higher values during noisy as compared to quiet nights. One would have expected that sleep disturbances and thereby the SDI increase gradually with the equivalent noise level, a metric that indicates the total acoustic energy over a defined time period (here the bedtime, 23-7 h). But though the highest noise level evoked the strongest increase of the SDI (Table 3) the response did not differentiate between both the lower noise levels. This is supported by other studies that clearly disqualify the equivalent noise level as a reliable predictor of sleep disturbances (Basner et al. 2006b; Eberhardt 1987; Griefahn et al. 2006b; Öhrström & Rylander 1982).

First-night-effect. The 'first-night-effect', initially described by Agnew et al. (1966) indicates a less restorative sleep during the first night in experimental studies not only in the laboratory but also in field studies (e.g. Griefahn & Gros 1986). Sleep in the first night is usually characterized by a prolonged time to fall asleep and to reach SWS, by a shorter time in SWS and in REM-sleep as well as by an increase of the time awake and of the number of sleep stage changes. This night was evaluated here to test the validity of the SDI which was significantly greater than during the quiet nights, thus not only confirming the 'first-night-effect' but also the validity of the SDI.

Alterations with age. As the alterations of sleep evoked by noise are non-specific and rather diffuse, similar alterations were expected with increasing age (e.g. Griefahn 1985). Accordingly, the SDI correlated significantly ($p < 0.01$) with the age of the 193 participants observed in Studies V and VI. The correlation coefficient dropped, however, from $r = 0.52$ ($p < 0.001$) in the laboratory studies to a still significant coefficient of 0.33 ($p = 0.012$) in the field study with 58 residents near an airport (Study VII). Several facts might have contributed to the lower coefficient. First, the participants adhered to their usual bedtimes that varied not only between but also within one and the same person. Second, the acoustic load varied between the residents who lived at different distances to the runway and thereby under the impact of a different number of flyovers with different noise levels.

Limitations. The sleep disturbance index developed here was designed to evaluate rather moderate sleep disturbances as caused by noise and other environmental influences. It reliably indicates worsening and improvement of sleep but cannot substitute the subtly differentiated evaluation required for clinical purposes. As it is true for many other indices, the condensation of different (weighted) variables to a single number, might mask possible causal relations, e.g. between physiological alterations and after-effects. Additional calculations performed with the data from Study I revealed for instance a better correlation of subjectively evaluated sleep quality ($r = 0.29$, $p < 0.001$) with the SDI than with most of the 7 included variables.

The SDI was developed on the basis of nights with an exactly 8 h time in bed. The significant correlation between the SDI and age in the field study indicates its possible suitability for different bed times. The coefficient between SDI and age was, however, lower than calculated for the laboratory studies (0.33 vs 0.52). The SDI calculated for the 26 persons of the same age category as of the reference sample (19-34 yrs) was for the night from Saturday to Sunday 0.21 ± 0.87, which differed not significantly ($p = 0.34$) from the SDI of the reference sample (0 ± 1). The respective bed times varied, however, between 5.7 and 10.5 hours (8.56 ± 0.88 h).

Application. However, specific alterations of only 2 or 3 sleep parameters are not likely for sleep disturbances evoked by noise, by other environmental influences or for the alterations that accompany increasing age. These disturbances are rather moderate and diffuse, i.e. determined by complex alterations of several parameters that are well reflected by the SDI.

Studies on the effects of environmental influences on sleep performed in different laboratories are often difficult to compare as most authors tend to focus their reports mainly on significant alterations, where it is often not clear, whether variables that are not mentioned are not affected or not even considered for evaluation. The application of the SDI would therefore facilitate the comparability of studies.

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References

Agnew H W Jr, Webb W B, Williams R L (1966). The first night effect: An EEG study of sleep. Psychophysiology 2: 263-266.

Basner M, Samel A (2005). Effects of nocturnal aircraft noise on sleep structure. Somnologie 9: 84-95.

Basner M, Elmenhorst EM, Maaß H, Müller U, Quehl J, Vejvoda M, Samel A (2006a). Single and combined effects of air, road and rail traffic noise on sleep. In: Institute of Noise Control Engineering of the USA (ed): Proceedings of Internoise 2006, Dec 3-6, Honolulu, Hawaii, USA (10 pp.). CD-ROM.

Basner M, Isermann U, Samel A (2006b). Aircraft noise effects on sleep: Application of the results of a large polysomnographic field study. J Acoust Soc Am 119: 2772-2784.

Eberhardt JL (1987). The influence on sleep of noise and vibrations caused by road traffic. Akademisk avhandling. Lund: Bloms Boktrycheri AB.

Griefahn B (1985). Schlafverhalten und Geräusche. Feld- und Laboruntersuchungen über Straßenverkehr, EEG-Analyse, Literaturauswertung. Stuttgart: Enke.

Griefahn B (1986). Grenzwerte nächtlicher Belastbarkeit durch Straßengeräusche. Appl Acoust 19: 265-284.

Griefahn B, Gros E (1986). Noise and sleep at home, a field study on primary and after-effects. J Sound Vibr 105: 373-383.

Griefahn B, Marks A, Robens S (2006a). Noise emitted from road, rail and air traffic and their effects on sleep. J Sound Vibr 295: 129-140.

Griefahn B, Marks A, Basner A (2006b). Awakenings related to noises from various traffic modes. In: Institute of Noise Control Engineering of the USA (ed): Proceedings of Internoise 2006, Dec 3-6, Honolulu, Hawaii, USA (10 pp.). CD-ROM.

Öhrström E, Rylander R (1982). Sleep disturbance effects of traffic noise – a laboratory study on after effects. J Sound Vibr 84: 87-103.

Rechtschaffen A, Kales A (eds.) (1968). A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects. Los Angeles, CA: BIS/BRI, UCLA.