Proceedings of 20th International Congress on Acoustics, ICA 2010

23–27 August 2010, Sydney, Australia

A night noise index on the basis of the integration of awakening potential

Toshihito Matsui (1), Tomoya Takashima (1), Junta Tagusari (1) and Kozo Hiramatsu (2)

(1) Graduate School of Engineering, Kyoto University, Kyoto 615-8540, Japan
(2) Kyoto University, Kyoto 606-8501, Japan

PACS: 43.50.Qp

ABSTRACT

Existing community noise indices are mostly proposed to predict community response, especially annoyance response, based on the information of sound level being correlated with the response. As to night noise, indices such as SEL, L_{Amax} and L_{night} have been used to evaluate sleep disturbance due to noise as well as adverse health effects probably caused by the sleep disturbance without firm evidence for using these indices. This paper proposes a noise index based on neuro-physiological facts of awakening process. The recent neuro-physiology has revealed that wakefulness and sleep are dominated by the nuclei in the brainstem where the potential causing awakening is considered to be integrated. From this evidence, a night noise index, $N_{\mathrm{awake,year}}$, was derived on the basis of integration of awakening potential. The potential as a function of sound level was estimated from the existing dose-response relationship between SEL and the percentage of awakening due to a single noise event. The developed index gives the total number of awakenings per year, and would cover a wide-range of the number of noise events during night time. Simulated calculation of awakening due to night noise showed that the index, Nawake,year, had a sufficiently linear relationship with the number of night-time awakenings, while L_{night} brought about remarkable variation in the relationship. Some examples of the application of Nawake,year are presented on the basis of the sound level measurements of traffic noise.

INTRODUCTION

A number of studies have been carried out in laboratories and fields on noise-induced sleep disturbance, where SEL, L_{Amax} and L_{night} are widely used to evaluate nighttime noise. These noise indices, however, might be inappropriate because they are not based on neuro-physiological facts of awakening process but mainly applied for the practical reasons.

From the viewpoint of the neuro-physiology, wakefulness and sleep are found to be dominated by the nuclei in the brainstem. Circadian and homeostatic drives control the activities of the nuclei, and a sleep-awake switch is characterized by mutual inhibition between the nuclei. Recent studies have developed some mathematical models[1, 2] based on the neurophysiology which enable an explanation of the periodic circadian oscillation of sleep and awake, and the switch of sleep-awake reaction due to external stimuli.

Simulated calculations[3] based on the mathematical model of the brainstem revealed that the brainstem does not integrate sound energy of external stimuli but integrates awakening potential of external stimuli and that time constant for integrating the potential was about 10–100 when the lag system of first-order was assumed. These results suggest that the existing night noise index, SEL, L_{Amax} and L_{night}, are not appropriate to evaluate awakening response.

In this study, a night noise index was developed based on the neuro-physiological facts mentioned above. The index can be calculated from the records of sound level fluctuation during nighttime and shows the expected number of awakening (or percentage of awakening) per year. The index would cover a wider-range of night noise events because of its neurophysiological background.

NEURO PHYSIOLOGICAL MODEL OF AWAKENING

Based on the neuro-physiology, a number of mathematical models have been proposed on the sleep-awake switch in the brainstem. Wakefulness and sleep are found to be dominated by the nuclei called AAS (ascending arousal system) in the brainstem and VLPO (ventrolateral preoptic) nucleus in the hypothalamus. Phillips and Robinson[1, 2] adopt the physiological mechanism into a neuronal population model. Only the MA (monoaminergic) nuclei in AAS which are activated while wakefulness, and the VLPO nuclei which are inactivated while wakefulness, were modeled to establish a simple mathematical model. Although the ultradian rhythm was neglected, this model enables to make quantitative evaluation of the sleep-awake switch including a brief awakening due to external stimuli[4]. The schematic diagram of this model is shown in Figure 1.

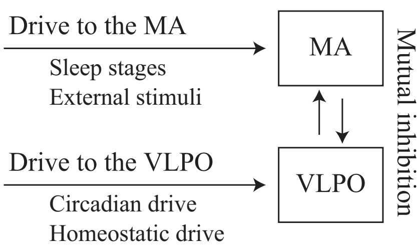

Figure 1: The schematic diagram of the Phillips-Robinson model. The MA nuclei and the VLPO nuclei are activated by the external drives related to sleep stages, external stimuli, circadian and homeostatic drives. There is a mutual inhibition between the MA and the VLPO which characterises the sleep-awake switch.

Based on the Phillips and Robinson model, the neuro-electrical thresholds of awakening were calculated as a function of the duration of the external stimuli. The thresholds were converted into sound level on the basis of an existing laboratory experiment[5].

The calculated threshold level of awakening gave the following results;

- The brainstem does not integrate the sound energy of external stimuli but integrates awakening potential of external stimuli.
- The brainstem integrates the potential with a lag system of first-order and a time constant of 10–100 seconds approximately.
- The threshold levels of awakening due to short-duration noises are extremely high and $L_{\max}$ and SEL both give over-estimates.
- The index SEL gives over-estimates even for long-duration noises, because the brainstem integrates the awakening potential with a time constant of 10–100 seconds.

These results suggest that L_{night} also gives over/under estimates in the evaluation of awakening response.

DEVELOPPMENT OF NIGHT NOISE INDEX

Awakening risk due to a single noise event

A night noise index was developed based on the above mentioned results of the simulated calculation of Phillips and Robinson model. Firstly, dose-response relationship of awakening due to a single noise event is derived from the results with some assumptions.

The neuro-electrical external stimuli to the brainstem, $E(t)$ [mV], is assumed to be a function, f, of the sound stimuli as follows:

$$E(t) = f(L(t)), \tag{1}$$

where $L(t)$ [dB] is the indoor sound level fluctuation of a single noise event, and t shows time in second.

The external stimuli, $E(t)$, is approximately integrated in the brainstem with a lag system of first-order. The integrated potential at t_0, $\overline{E}(t_0)$ is expressed by

$$\overline{E}(t_0) = \int_{-\infty}^{t_0} e^{-(t_0-t)/\tau} E(t)\, dt, \tag{2}$$

where τ is a time constant (10–100 seconds) of the lag system.

Most of traffic noise during nighttime is considered to be a single event because of less traffic volume. If the duration of the noise event is relatively shorter than the time constant of the brainstem, τ, the maximum value of $\overline{E}(t)$ due to the single noise event can be approximated to

$$\overline{E}_{\max} \sim \int_{-\infty}^{\infty} E(t)\, dt. \tag{3}$$

The awakening risk would be correlated with the value of $\overline{E}_{\max}$, and the dose-response relationship on awakening should be expressed as a function of $\overline{E}_{\max}$. Introducing a function, g, which shows the dose-response relationship between percentage of awakening and $\overline{E}_{\max}$, the percentage of awakening due to a single noise event, P_{single}, is formulated as

$$\begin{aligned} P_{\text{single}} &= g\left(\overline{E}_{\max}\, dt\right) \\ &= g\left(\int_{-\infty}^{\infty} E(t)\, dt\right). \end{aligned} \tag{4}$$

Assuming that the function g has linearity (additivity), The expression of P_{single} can be transformed into

$$\begin{aligned} P_{\text{single}} &= \int_{-\infty}^{\infty} g\left(E(t)\right) dt. \\ &= \int_{-\infty}^{\infty} g\left(f(L(t))\right) dt. \end{aligned} \tag{5}$$

This equation is simplified by substituting $R(L(t))$ for $g(f(L(t)))$,

$$P_{\text{single}} = \int_{-\infty}^{\infty} R(L(t))\, dt, \tag{6}$$

where the function, $R(L(t))$ [/sec], is interpreted as a unit risk of awakening per second at $L(t)$ [dB].

The function, $R(L(t))$, should be determined by a field study or a laboratory experiment. In this study, an existing dose-response relationship on awakening was employed for the estimation of the function, $R(L(t))$.

Passchier-Vermeer[6] reported a dose-response relationship between behavioural awakening and SEL of a single noise event. The percentage of awakening, $p_{\text{awake,single}}$ [%], is expressed by

$$p_{\text{awake,single}} = -0.564 + 1.909 \times 10^{-4} \times (SEL_{\text{indoor}})^2 \tag{7}$$

where SEL_{indoor} is the sound exposure level of an aircraft noise event in the bedroom and is available from 54 dB to 90 dB.

The following power function was assumed as $R(L(t))$;

$$R(L(t)) = a(L(t) - b)^c, \tag{8}$$

where the symbols a and c are constants and b is a threshold level of awakening risk. A least-square method was applied to determine the constants using Eq. (7) and Eq. (6), where linearly increasing and decreasing single noise events with the slope of ± 1 dB/sec were assumed in the simulated calculation of Eq. (6). The constant b was set to 45 dB, because the threshold SEL of 54 dB in Eq. (7) is converted to 45 dB in L_{Amax} with the above mentioned noise envelope.

The formula of $R(L(t))$ [/sec] as a function of indoor sound level $L(t)$, is obtained as

$$R(L(t)) = 9.3 \times 10^{-5} \times (L(t) - 45)^{0.15}. \tag{9}$$

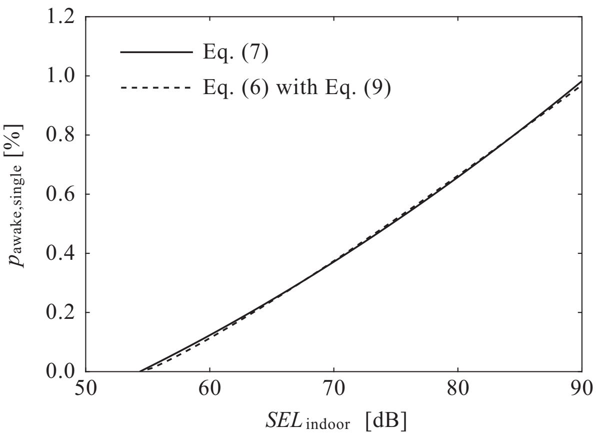

Figure 2: Dose-response relationship between SEL_{indoor} and percentage of awakening. The solid line is calculated from the existing dose-response relationship by Eq. (7), and the broken line is calculated from the integration of awakening potential by Eq. (6) with Eq. (9)

Figure 2 shows the dose-response relationship between SEL_{indoor} and percentage of awakening calculated from Eq. (7) and Eq. (6) with Eq. (9). The two dose-response curves agree very well, which means that Eq. (6) with (9) are able to use as a substitute for Eq. (7). Although Eq. (9) was preliminary obtained using Eq. (7), Eq. (6) would cover a wide-range of single noise events, since it is based on the neuro-physiological evidence. Moreover, the unit risk of Eq. (9) could be modified on the basis of the existing or new studies if the sound level fluctuation is available.

Noise index during nighttime

In the previous section, the expression to estimate the percentage of awakening due to a single noise event was developed on the basis of the neuro-physiological evidence. In this section, a new night noise index was developed for the evaluation of sleep disturbances during night. The index, L_{night}, is widely applied to evaluate long-term effects of noise during nighttime[7, 8]. However, L_{night} would show over/under estimates, since it is not based on the physiological facts but based on the integration of sound energy.

During nighttime, most of traffic noise is measured separately as a single event because of less traffic volume. Each awakening risk due to a single noise event can be summed up to estimate total awakening risk during night, since risk has additivity. Therefore, the total awakening risk is expressed as

$$N_{\text{awake,year}} = \sum_{\text{night,year}} P_{\text{single}} = \int_{\text{night,year}} R(L(t))\,dt. \qquad (10)$$

The index, $N_{\text{awake,year}}$ [/year], is caculated from the records of sound level fluctuation during nighttime and shows the expected number of awakening (or percentage of awakening) per year. In this study, long-term noise index which shows the number of awakening "per year" was proposed, since chronic adverse health effects may be caused by long-term effects of noise.

Simulated calculations based on the existing dose-response relationship between SEL and awakening percentage (Eq. (7)) was done to examine the validity of the developed noise index. In the calculations, linearly increasing and decreasing noise events (± 1 dB/sec) are assumed, and the number of noise events were 1–50 times per night. The level difference between outdoor and indoor was set at 15 dB[9].

Figure 3 shows the results of the simulated calculations. The curves in the figure indicate the relationship between the number of awakenings per year estimated from the simulated calculations and $L_{\text{night,outdoor}}$. There are remarkable differences between the curves in the figure, which suggests that using $L_{\text{night,outdoor}}$ as a single night noise index is not appropriate to evaluate sleep disturbance.

Figure 4 shows the relationship with $N_{\text{awake,year}}$. The developed index shows good agreement with the simulated calculations at any number of noise events. Although the condition of the single noise events in the simulated calculations was limited, the index $N_{\text{awake,year}}$ would be an more appropriate measure than $L_{\text{night,outdoor}}$.

If the index, $N_{\text{awake,year}}$, is applied to epidemiological studies on adverse health effects, the relationship between sleep disturbance and health effects will be evaluated more reasonably than L_{night}, and countermeasures to mitigate health effects could be taken effectively. Moreover, the index, $N_{\text{awake,year}}$, has an advantage that the index shows the awakening response of residents directly, though the index, L_{night}, shows just an average sound level in dB.

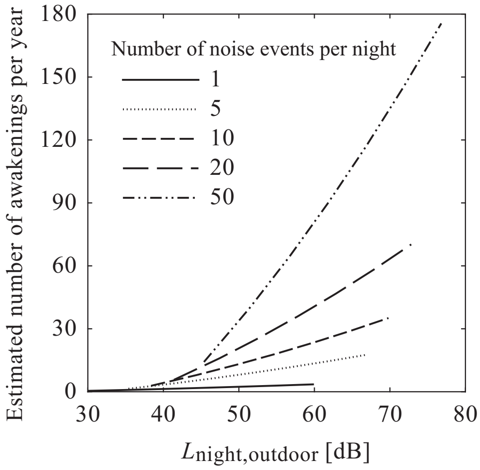

Figure 3: Number of awakenings from simulated calculations based on Eq. 7 *vs.* $L_{\text{night,outdoor}}$.

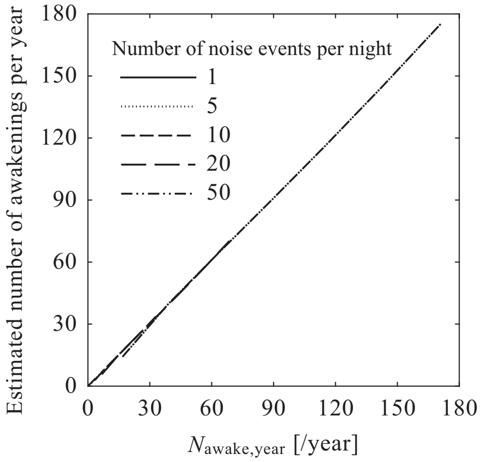

Figure 4: Number of awakenings from simulated calculations based on Eq. 7 *vs.* $N_{\text{awake,year}}$.

APPLICATION OF THE DEVELOPED INDEX

Measurements of community noise in a suburb

Community noise measurements were carried out in a suburb of Kyoto City for 24 hours, and some noise indices including the developed index, $N_{\text{awake,year}}$ were calculated. The four measurement points are shown in Figure 5.

The night noise indices (22:00–6:00) are listed in Table 1. In the calculation of $N_{\text{awake,year}}$, level difference between indoor and outdoor was set at 15 dB. The difference between the points B and C in $L_{\text{night,outdoor}}$ and $L_{\text{Amax,outdoor}}$ is only 4 dB. However, the awakening risk at the point B shows 7 times higher than that at the point C.

At all the measurement points, sound level in L_{night} and L_{Amax} are higher than the WHO guideline values on sleep disturbance[7] and EU night noise guideline (40 dB)[8]. The index, $N_{\text{awake,year}}$, at the points A and D, however, show low risk of sleep disturbance.

Effect of a noise barrier along a motorway

Another noise measurement was carried out along a motorway in Nara City (see Figure 6). A new noise barrier was set up

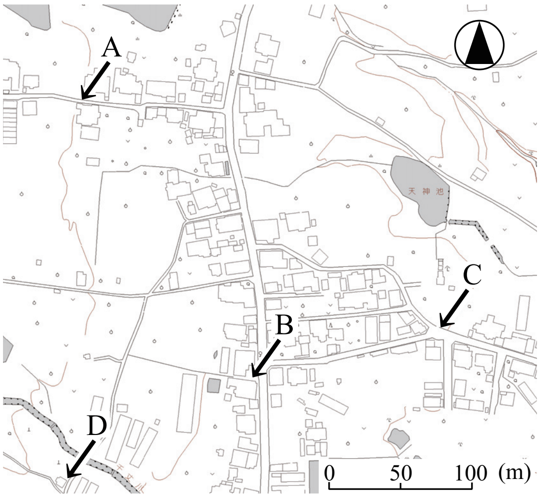

Figure 5: Measurement points at a suburb of Kyoto City.

Table 1: Measured L_{night}, L_{Amax} and calculated $N_{\mathrm{awake,year}}$

Measured point	$L_{\mathrm{night,outdoor}}$ [dB]	$L_{\mathrm{Amax,outdoor}}$ [dB]	$N_{\mathrm{awake,year}}$ [/year]
A	49.8	86.6	4.4
B	55.7	84.1	51.0
C	51.7	80.0	7.1
D	46.0	70.7	0.35

to reduce the traffic noise, and the measurements were done before and after the setting up of the barrier for 24 hours at six points along the motorway.

Figure 7 shows the reduction of traffic noise in L_{night} [dB] (22:00–6:00). Although L_{night} decreased by 5–10 dB after the setting up of the noise barrier, the mitigation of sleep disturbance was not able to be evaluated only from these measurements.

The developed index, $N_{\mathrm{awake,year}}$, was also calculated from the measurements. In the calculation, the level difference between indoor and outdoor was set at 15 dB. As shows in Figure 8, the awakening risks in $N_{\mathrm{awake,year}}$ are remarkably decreased and the risks are almost zero [/year] at all the measurement points after setting up the barrier.

CONCLUSION

Noise indices, i.e. L_{AE}, L_{Amax} and L_{night}, have been applied to evaluate sleep disturbance due to noise. These indices are, however, developed in the engineering science, and are mainly applied for practical reason.

This paper proposes a noise index based on the neurophysiological evidences of awakening process in the brainstem. Simulated calculations[3] based on the mathematical model of the brainstem[1, 2] revealed that the brainstem does not integrate sound energy of external stimuli but integrates awakening potential of external stimuli and that time constant for integrating the potential was about 10–100 when the lag system of first-order was assumed.

From these evidences, a night noise index, $N_{\mathrm{awake,year}}$, was developed on the basis of the integration of awakening potential (Eq.(10)). The unit risk of awakening per second as a function of sound level (Eq.(9)) was preliminary derived using the existing dose-response relationship between SEL and the percentage of awakening due to a single noise event.

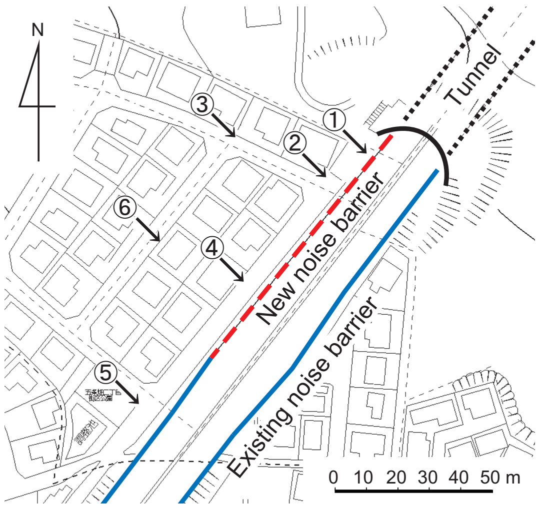

Figure 6: Measurement points along a trunk road. Sound levels were measured before and after setting up a noise barrier (broken line).

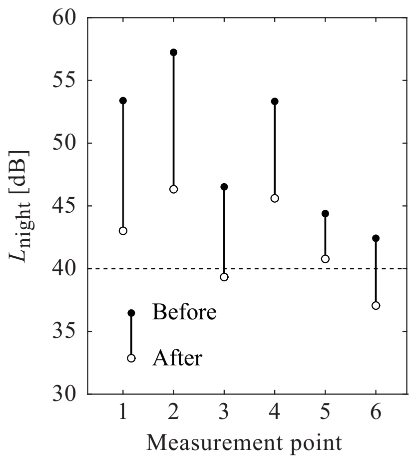

Figure 7: Decrease in L_{night} by the noise barrier.

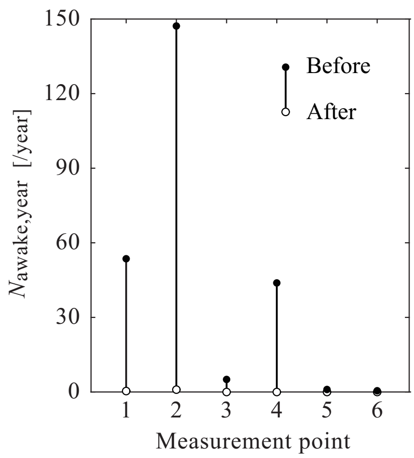

Figure 8: Decrease in $N_{\mathrm{awake,year}}$ by the noise barrier.

The developed index, $N_{\text{awake,year}}$, gives the expected total number of awakenings per year. Simulated calculations were carried out to compare the validity of $N_{\text{awake,year}}$ and L_{night}, where a wide variety of the number of noise events during a night was assumed. The index, $N_{\text{awake,year}}$, showed good agreement with the number of awakenings estimated from the simulated calculations, while L_{night} brought about remarkable variation in the relationship.

Some examples of the application of $N_{\text{awake,year}}$ were presented using the measurements of community noise. The index, $N_{\text{awake,year}}$, seemed to have distinct advantages to evaluate nighttime noise as well as sleep disturbance.

Epidemiological studies using $N_{\text{awake,year}}$ may show more reasonable dose-response relationships between sleep disturbance and adverse health effects than using L_{night}. Further studies should be required to modify the function of unit risk on awakening.

ACKNOWLEDGEMENTS

This research was supported in part by Environmental research and technology development fund from the Ministry of the Environment of Japan.

REFERENCES

1 Phillips, A. and Robinson, P. (2007): A quantitative model of sleep-wake dynamics based on the physiology of the brainstem ascending arousal System, Journal of Biological Rhythms, 22(2), 167–179.
2 Phillips, A. and Robinson, P. (2008): Sleep deprivation in a quantitative physiologically based model of the ascending arousal system, Journal of Theoretical Biology, 255(4), 413–423.
3 J. Tagusari, J., Matsui, T., Hiramatsu, K. (2009): Neurophysiological approach for evaluating noise-induced sleep disturbance: time constant of the dynamic characteristic in the brainstem, Acta Acustica united with Acustica 95(Suppl. 1), p. S52.
4 Fulcher, B. D., Phillips, A. J. K. and Robinson, P. A. (2008): Modeling the impact of impulsive stimuli on sleep-wake dynamics, Physical Review E, 78(5), 051920.
5 Bonnet, M., Webb, W., Barnard, G. (1979): Effect of flurazepam, pentobarbital, and caffeine on arousal threshold, Sleep, 1(3), 271–279.
6 Passchier-Vermeer，W. (2003)：Night-time noise events and awakening，TNO Inro report 2003-32.
7 WHO (1999)：Guidelines for community noise.
8 WHO Regional Office for Europe (2009)：Night Noise Guidelines for Europe.
9 Miyakawa, M., Matsui, T., Uenoyama, S., Murayama, R., Uchiyama I. (2004): Residents' opinions on th environmental quality standars for indoor noise—case study by an interview method—, Journal of INCE of Japan，28(6), 435–441 (in Japanese).