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Traffic noise and its impact on sleep depth measured by the odds ratio product

Michael SMITH[1]; Magdy YOUNES[2]; Daniel AESCHBACH[3]; Uwe MÜLLER[3]; Mathias BASNER[1]

[1] Unit for Experimental Psychiatry, Division of Sleep and Chronobiology, Department of Psychiatry, Perelman School of Medicine, University of Pennsylvania, USA

[2] Sleep Disorders Center, University of Manitoba, Canada

[3] Dept. of Sleep and Human Factors Research, Institute of Aerospace Medicine, German Aerospace Center, Germany

Abstract

Traffic noise can lead to cortical and autonomic activation, disrupt sleep and impair physical and mental restoration. We used the odds ratio product (ORP), a validated continuous measure of sleep depth based on automatic analysis of physiologic sleep data in 3-second epochs, to investigate temporal changes of sleep in response to nocturnal noise events. Seventy-two healthy participants slept for 10 nights in a laboratory, during which we measured sleep with polysomnography. In 8 nights, participants were exposed to 40, 80 or 120 road, rail and/or aircraft noise events at 45-65 dB $L_{AS,max}$. Event-related change of ORP relative to pre-event baseline was analysed with linear mixed models. ORP increased during aircraft, road and rail noise, reflecting reduced sleep depth and quality, and there was a greater response to road and rail noise than to aircraft noise. The clinical relevance of event-related elevations of ORP is currently unknown, and warrants further investigation.

Keywords: Traffic noise, Sleep, Laboratory study, Odds ratio product, Road, Rail, Aircraft

1. Introduction

Sufficient sleep is a critical component of good physical and mental health. Nocturnal traffic noise can impair physiologic and subjective sleep, by causing cortical awakenings and self-reported sleep disturbance (1). In the short-term, noise-induced sleep disturbance can cause impaired mood and cognitive performance and increased daytime sleepiness (2, 3). In the longer term, nocturnal traffic noise has been positively associated with elevated blood pressure and incident cardiovascular disease (4-6). Consequently, sleep disturbance is believed to be the most harmful non-auditory effect of environmental noise (7), and recently the World Health Organization strongly recommended more strict nighttime regulations for road, rail and aircraft noise (8).

The "gold standard" for physiologic sleep measurement is polysomnography (PSG), which involves recording of electrical brain activity using scalp electroencephalography (EEG), eye movements via electrooculography (EOG) and muscle activity via submental electromyography (EMG). A major shortcoming of research into the effects of noise on sleep is that, according to current guidelines (9), PSG data are scored in 30-second epochs. This is a hangover from when EEG traces were plotted on 300 mm paper at a paper speed of 10 mm/s, thus a single page would reflect 30 s of EEG activity (10). The EEG activity occupying the majority of the 30-second epoch determines the discrete sleep stage that is assigned, either wake, rapid eye movement (REM) sleep or the non-REM sleep stages N1, N2 or N3, representing progressively deeper sleep (9). Any given 30 s epoch can therefore contain EEG activity indicative of a differentially scored sleep stage, providing these patterns are <15 s in duration. In this way, classical sleep scoring may not capture short duration yet

[1] michael.smith@pennmedicine.upenn.edu; basner@pennmedicine.upenn.edu

potentially biologically relevant changes in sleep activity induced by noise.

The odds ratio product (ORP) is a continuous measure of sleep depth based on alpha, beta, theta and delta activity in the EEG (11), where the minimum value of 0 means definitely asleep, and the maximum value of 2.5 means definitely awake. This ORP measure has a number of advantages over traditional sleep scoring for assessing the effects of noise. As a continuous metric, changes in ORP reflect alterations of sleep depth at a finer resolution than is possible using only the 5 discrete stages described in the current guidelines (9). Furthermore, the ORP is scored in 3-second epochs, which is shorter than the duration of many traffic noise events, so temporal changes of sleep within the period of a noise event can be tracked, for instance as a function of the sound pressure level of the event. Finally, ORP is scored using an automated algorithm. Although previous attempts to score sleep digitally have correlated poorly with manually scored sleep, such efforts have generally attempted to replicate the current scoring of the PSG data into the 5 discrete stages. Additionally, when sleep is scored manually there can be significant intra- and inter-scorer variation despite identical scoring rules (12), whereas automated ORP scoring precludes such subjectivity. Because of the advantages offered by ORP, we reanalysed data from a previously reported laboratory study into the effects of road, rail and aircraft noise sleep (13) using event-related ORP measures.

2. Methods

2.1 Participants and study procedure

The methods are described in detail elsewhere (13), and are only summarised here. Seventy-two participants (mean±SD 40.3±13.5 years, 40 women) were recruited for a laboratory study. They were habitually good sleepers with a habitual mean bedtime of 23:09 and rise time of 07:01 and did not suffer from self-reported sleep apnoea, loud snoring or symptoms associated with restless legs syndrome or periodic limb movement disorder. They all had normal age-related hearing determined with audiometry. Chronotype was measured using the German language version of the Morningness-Eveningness Questionnaire (14). The local ethics committee reviewed and approved the study. Participants provided informed consent prior to the start of the study and could discontinue at any time without explanation.

Participants slept for 10 consecutive nights in the laboratory. The first night served as an adaptation period only, and was not included in any analyses. Nights 2-10, summarised in Table 1, consisted of 8 nights with 40, 80 or 120 noise events and a quiet control night, in a randomised order. Within noise exposure nights, we varied the maximum sound pressure level of events between 45-65 dB $L_{AS,max}$. Noise events also had variations in noise onset rate and duration, as summarised in Table 2.

Table 1 Summary of the noise scenarios in different study nights.

L_{AEq}: Equivalent A-weighted sound pressure level over the 8-hour nighttime period

Night	Noise types	Number of noise events (n)	L_{AEq} (dB)
Control	-	0	30.0
AI	Aircraft	40	39.7
RO	Road	40	36.9
RA	Rail	40	39.7
AIRO	Aircraft, Road	80	41.2
AIRA	Aircraft, Rail	80	42.5
RORA	Road, Rail	80	41.2
RORO	Road	80	39.7
AIRORA	Aircraft, Road, Rail	120	43.3

Table 2 – Temporal acoustic properties of noise events for different traffic modes.

SPL: Sound Pressure Level. SD: Standard Deviation.

Variable	Aircraft. Mean (SD; range)	Road. Mean (SD; range)	Rail. Mean (SD; range)
SPL rise time (dB/s)	3.6 (1.1; 1.2-5.8)	6.3 (1.9; 3.1-13.6)	7.1 (2.6; 2.3-12.7)
Duration (s)	66.0 (16.6; 36.8-109.5)	20.5 (7.2; 9.0-38.1)	25.9 (7.9; 14.0-46.4)

We measured sleep with PSG, employing central EEG derivations (C_3-M_2, C_4-M_1), EOG and EMG electrodes. EEG records electrophysiological activity in the cerebral cortex, EOG records eye movement, and EMG records muscle movement. These data were used to calculate the ORP in 3-second epochs, via an automated algorithm (11). A single researcher, who was blind to the study design, manually inspected ORP data to identify artefacts and/or periods of poor data quality.

2.2 Data analysis

For every noise event in every person-night, we identified the maximum ORP that occurred during the duration of that specific noise event. From this value, we subtracted the pre-event baseline ORP, defined as the mean ORP in the 30 seconds before the onset of that particular noise event, thus giving a value expressing the maximum event-related change of ORP relative to baseline (ΔORP_{max}). We also calculated the area under the ORP curve (ORP_{AUC}) in a 111-second window, corresponding to the shortest window length that would fully enclose the longest noise event. We calculated the expected natural baseline variation in ΔORP_{max} and ORP_{AUC} by analysing forty 30-second sham events in the quiet control night at times corresponding to noise events in the 40-event noise nights.

We performed statistical analysis using IBM SPSS version 25. We analysed the effect of the independent variable traffic mode on ORP outcomes in a repeated measures random intercept linear mixed model, using a first-order autoregressive covariance structure with homogeneous variances. We calculated post-hoc comparisons between traffic modes using Bonferroni adjustments for multiple testing. A p-value <0.05 was considered statistically significant.

3. Results

There was a significant main effect of traffic type on noise-induced ΔORP_{max} ($F(3,21391)=2054.7$, $p<0.0001$). As shown in Figure 1, ΔORP_{max} was significantly greater during noise from aircraft ($p=0.013$), road ($p<0.0001$) and rail ($p<0.0001$) than in noise-free sham periods. There was a significantly higher ΔORP_{max} during road ($p<0.0001$) and rail ($p<0.0001$) than aircraft noise. Event-related ΔORP_{max} did not significantly differ between road and rail noise ($p=1.0$).

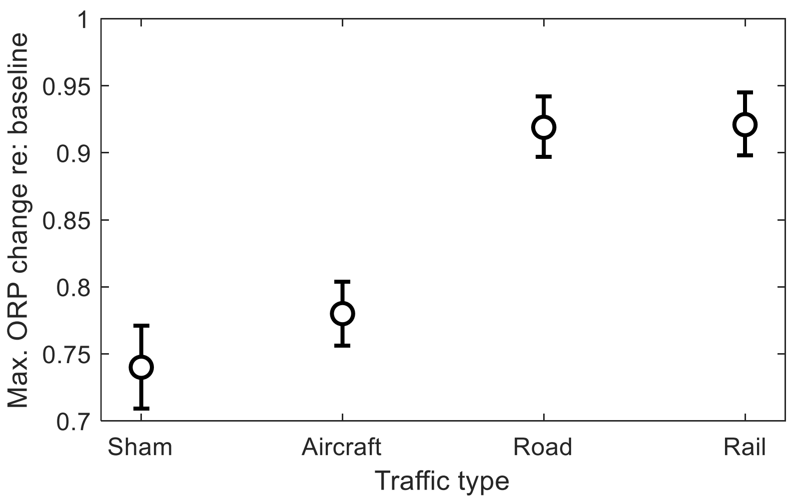

Figure 1 Event-related maximum change in ORP relative to pre-event baseline (estimated marginal means).

Error bars: 95% confidence intervals.

There was a significant main effect of traffic type on noise-induced ORP_{AUC} ($F(3,23650)=69.54$, $p<0.0001$). As shown in Figure 2, ORP_{AUC} was significantly greater following noise from aircraft ($p<0.0001$), road ($p<0.0001$) and rail ($p<0.0001$) than in noise-free sham periods. There was a significantly higher ORP_{AUC} following road ($p<0.0001$) and rail ($p<0.0001$) than aircraft noise. Event-related ORP_{AUC} did not significantly differ between road and rail noise ($p=1.0$).

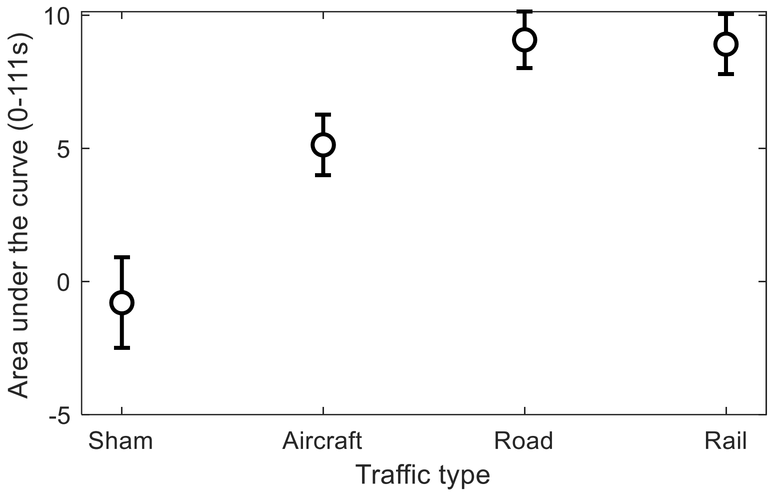

Figure 2 Event-related area under the ORP curve in a 111s window (estimated marginal means).

Error bars: 95% confidence intervals.

4. Discussion

Noise from aircraft, road and rail led to elevations of ORP, reflecting reduced sleep quality and changes to less deep, more unstable sleep depth (11). A greater physiologic response following road and rail noise than aircraft noise is in good agreement with analysis of the current data using more traditional methods of sleep and arousal scoring (13). While these results are not especially novel in terms of demonstrating a sleep-disrupting effect of noise (1), they do demonstrate that ORP is a suitable method for assessing event-related effects of traffic noise on sleep, which can offer certain advantages in future research in the field. Among these advantages are that a more graduated measure of sleep depth allows for identification of subtle (yet potentially relevant from a health perspective) alterations of sleep, and a 10-fold increase in temporal precision compared to traditional 30-second epochs which will aid in uncovering the dynamics of noise-induced sleep disruption. A further advantage is the high degree of automation in the ORP scoring process, rather than the manual sleep scoring currently recommended (9), which decreases analysis time and mitigates individual error.

In further work, we will examine the effects of noise level, number of noise events, sleep stage, sex, age and sleep spindle rate on noise-induced changes in ORP. We will also investigate the suitability of ORP as an indicator of individual trait-like characteristics including chronotype and noise sensitivity, and examine the ability of ORP indices to predict the impact of sleep disruption on subjective self-assessment of sleep and waking psychomotor and cognitive performance.

4.1 Limitations

There were 120 different noise events in total, 40 for each traffic mode (8 different recordings, each at 5 different sound pressure levels). However, the distribution of these noise events in this laboratory study may not be truly representative of traffic patterns in the real world. Furthermore, the noise recordings were made in 2004, and vehicles that are more modern may have different acoustical characteristics.

As a laboratory study, the results may not translate directly to response in more naturalistic settings. The participants were generally healthy, whereas in the field the disrupting effects of noise may be higher among vulnerable populations and residents with pre-existing sleep disorders. Furthermore, there may be at least some degree of habituation among chronically noise-exposed individuals, which would not be reflected in the data presented here.

5. Conclusions

Traffic noise, already established as having adverse effects on sleep, accordingly induced elevations of the odds ratio product of sleep, reflecting less deep, more unstable sleep. This response was higher for road and rail than aircraft noise. The clinical relevance of event-related elevations of ORP is currently unknown, and warrants further investigation.

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