A Markov State Transition Model for the Prediction of Changes in Sleep Structure Induced by Aircraft Noise

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INTRODUCTION

- The demand for mobility has been strongly increasing over the past few years. As minimum intervals between two starting or landing planes are necessary for security reasons, evasion of air traffic to shoulder hours and even the nighttime has been observed in the past and will even increase in the future. Simultaneously, the strain of residents living in the vicinity of airports is likely to increase due to noise emitted from nocturnal air traffic.
- Environmental noise is a potential disruptor of the sleep process and may cause changes in the structure of sleep. These changes may diminish the restorative power of sleep.
- By dividing polysomnographic recordings into intervals of 30 seconds, human sleep can be classified in six distinct states: Awake, sleep stages 1-4, and REM [1].
- The sleep states differ in their contribution to the restorative power of sleep. Stages 3 and 4 (SWS) and REM sleep play an important role for the recuperative value of sleep. Research effort in the past was restricted to the prediction of noise induced awakenings.

OBJECTIVES

1. To build a Markov state transition model for the simulation of noise-free baseline nights (baseline model)
2. To extend the baseline model for the consideration of the influence of aircraft noise on transition probabilities depending on maximum sound pressure level $L_{AS,max}$ and the time pattern of aircraft noise events (ANEs)
3. To compare three nocturnal air traffic scenarios with $L_{AS,max}$ 65 dB:
   (1) unrestricted nocturnal air traffic
   (2) as (1), but no air traffic from 11 pm to 5 am (silent period)
   (3) as (2), but traffic from 11 pm to 5 am from (1) rescheduled during the 2 hours preceding and following the silent period

METHODS

- **Data Sources:** In four laboratory studies with 112 subjects (74 female, aged 18-65) lasting from 1999 to 2003, the Institute of Aerospace Medicine of the German Aerospace Center (DLR) investigated the influence of aircraft noise on human sleep [2]. Data of more than 33,000 ANEs and related events were used to estimate transition probabilities between different sleep states as a function of the maximum sound pressure level of the ANE.
- **Statistical analysis:** Transitional models based on multinomial autoregressive logistic regression [3] were build in a stepwise manner to simulate noise-free baseline nights. A linear term representing $L_{AS,max}$ of the ANE was then added to the model that produced the most valid results. It was assumed that ANEs influenced transition probabilities for no longer than 60 seconds.
- **Simulation:** Baseline sleep and the 3 different nocturnal air traffic scenarios were simulated using a Markov state transition model with Monte Carlo (MC) simulation.
- **Model Validation:** The following variables were used for extensive validation of the baseline model: duration of ultradian sleep cycles, fractions of SWS, REM and awake in sleep cycle length, fractions of different sleep stages in total sleep time, number of sleep stage changes, time spent in each sleep stage without transition to different stages. Additionally, Markov traces produced by first-order MC simulations should resemble realistic human hypnograms.

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RESULTS

- **Model:** A second order Markov state transition model turned out to satisfy the internal validation criteria best. The following variables were included in the final model: intercept, variables representing sleep stage 30 seconds (T_{-1}) and 60 seconds (T_{-2}) prior to transition (first and second order terms with 5 indicator variables each), 5 indicator variables C1-C5 representing the time spent in the same sleep stage (30, 60, 90, 120 and 150 seconds), interactions REM_ T_{-1}* C1 and REM_ T_{-1}* C2, cycle number after sleep onset (linear term).
- **Model validation:** Sleep stage fractions in total sleep time: Comparison of mean values from baseline nights and 10,000 first-order MC trials showed good agreement (model vs. raw data: Awake –0.7%, S1 +27.5%, S2 +0.5%, S3 +2.5%, S4 –8.8%, REM –1.5%).
- **Effect of nocturnal air traffic on sleep:** Changes of the sleep stage fractions in total sleep time depending on the three different noise patterns (see OBJECTIVES) are shown in figure 1. Noise restriction between 11 pm and 5 am (scenario 2) reveals clear benefits compared to unrestricted traffic in terms of less time spent awake and more time spent in sleep stages 3 and 4 and REM sleep. Although these benefits were reduced if the traffic that formerly took place between 11 pm and 5 am was rescheduled to the time before and after the silent period (scenario 3), the sleep pattern of scenario 3 was still superior to unrestricted nocturnal air traffic (scenario 1).

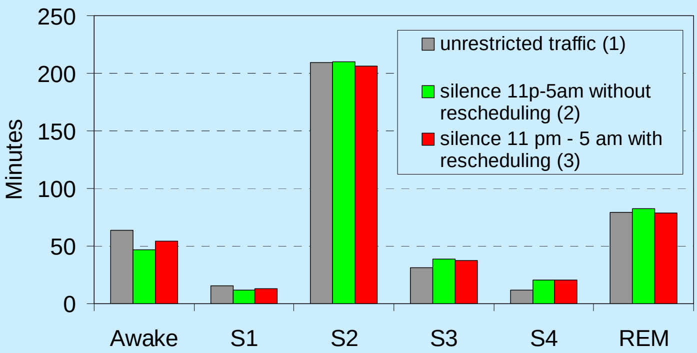

Figure 1: Comparison of model results for air traffic scenarios 1-3

LIMITATIONS

- The interaction of several successive ANEs as well as more complex countermeasures of the body in form of adaptation processes has not been taken into account. Data based on laboratory studies were used.

CONCLUSIONS & RECOMMENDATIONS

- It was possible to validly reproduce key features of noise-free baseline nights with a Markov state transition model based on multinomial autoregressive logistic regression.
- The extension of the model based on extensive data on the reactions to ANEs allows for the comparison of the sleep structures induced by different noise patterns and may serve as a valuable tool for structuring nocturnal air traffic and for political decision making.

REFERENCES

(1) Rechtschaffen, A. et al.: A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects (1968) Washington, D.C., Public Health Service, U.S. Government, Printing Office
(2) Basner M. Samel A.: Nocturnal Aircraft Noise Effects (2004) Noise Health (6) 22: 83-93
(3) de Vries S.O. et al.: Fitting Muultistate transition Models with Autoregressive Logistic Regression (1998) Med Decis Making (18): 52-60