Impact of Reduced Reverberation Time on Sound-Induced Arousals During Sleep

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Abstract: The effect of reducing reverberation time was studied in 12 subjects during sleep. EEG-arousals following specific sound stimuli were significantly reduced ($p<0.007$) when reverberation time was reduced with sound-absorbing ceiling-tiles. On average reverberation was reduced 0.124 seconds at similar sound levels. It is proposed that increased sound absorption, i.e. reduced reverberation time, by contributing to a better acoustic environment may reduce sound-induced sleep fragmentation.

Key words: Sound stimuli; sleep; arousal; reverberation time.

INTRODUCTION

THE ACOUSTIC ENVIRONMENT IS IMPORTANT TO PHYSICAL AND MENTAL WELL-BEING. Many office-buildings, schools, kindergartens, gymnasiums, and other public places are therefore equipped with sound-absorbing ceiling tiles.

Several studies of the negative impact of environmental noise on sleep have confirmed that specific sources of noise may disturb sleep.[2-5]

Correlation between environmental noise and disturbed sleep has been found for normal sleep in an everyday environment (i.e., your own bedroom[6,7]) and when the sleeping subject is under physical or mental stress (e.g., as while in hospital[8-10] or a nursing home[11]).

Consequently, it is important to alter the acoustic environment in order to eliminate, reduce, or modify inappropriate noise.

One way of modifying environmental noise is to reduce acoustic reverberation time by increasing sound absorption.

The present study is an attempt to evaluate the effect of reduced reverberation time on sleep by exposing healthy subjects to specific sound stimuli, with and without sound-absorbing ceiling tiles.

MATERIALS AND METHODS

Subjects

Twelve healthy students, six women and six men, aged 20—25 years, were included in the study after written consent. None were under medication or reported disturbed sleep and all had normal hearing as determined by audiometry.

No intake of alcohol or coffee/tea was allowed eight hours before start of the sleep studies and all subjects were instructed not to sleep or nap during the daytime prior to the study.

All subjects were ignorant of the purpose of the investigation.

Acoustic Environment

A three-bed room in a (former) surgical ward was refurbished with a suspended false ceiling 250 mm below the soffit.

During the first two nights the ceiling was mounted with sound-reflecting plaster tiles. On the third night visually identical sound-absorbing tiles (Ecophon®) replaced the plaster tiles.

The sound absorbing Ecophon© ceiling tile is made from a 15-mm thick high-density resin bonded glass wool. The white painted surface visually looks sealed, but lets close to 100% of the sound energy penetrate the surface into the glass wool. The sound absorbing property of the material has been measured according to EN ISO 354 over a wide frequency range and found to conform to absorption class A (according to EN ISO 11654) when mounted 200 mm beneath the structural soffit.

In co-operation with Department of Engineering Acoustics, University of Lund, a specific sound-stimulus scheme was designed.

The sound scheme consisted of 12 different sounds at varying frequencies played during the sleep studies with 30-minute intervals at predetermined times synchronized with the sleep recording. The type of sounds and their character is listed in Table 1.

Sound level (A-weighted sound pressure level) varied from 27 dB to 58 dB between different types of sounds. The loudspeaker was constructed and placed so that all subjects received the same sound stimulus.

Sleep Recordings

Somnography included monitoring of EEG, EOG, and submental electromyogram.

Recordings were done with EMBLA-devices (FLAGA®), stored on PCMCIA-harddiscs and displayed with SOMNOLOGICA- software (FLAGA®).

Sleep stages were scored blindly according to Rechtscaffen and Kales[1] by an independent licensed sleep-technician from Institute of Psychology, University of Iceland.

Arousal response to sound stimuli was scored if sleep was interrupted by continuous alpha-activity lasting more than three seconds during or up to 15 seconds after the sound stimulus. Sleep-stage changes were considered valid if they persisted for more than two minutes after sound stimulus.

Data Analysis

To avoid a "first-night effect" the first night of three with sound stimulation and sleep registration was discarded and only data from the second and third night were considered. To avoid habituation, the individual registrations were done within a three to five-day interval.

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Table 1—Sound levels, with and without sound-absorbing tiles

Nr	Type	Type	Absorbing tiles		Non-absorbing tiles	
			L_{pA} (dB)	L_{pAFmax} (dB)	L_{pA} (dB)	L_{pAFmax} (dB)
1	China-plate dropped	Impulse	-	57	-	58
2	Traffic noise	Continuous	34	35	35	37
3	Fan noise	"	35	36	35	36
4	Traffic noise	"	35	44	36	45
5	Traffic noise	"	34	43	35	45
6	Machine noise	"	36	41	36	42
7	Muffled gun shot	Impulse	-	54	-	54
8	Gun shot	"	-	57	-	57
9	Fan noise	Continuous	27	28	27	29
10	Closing door	Impulse	-	51	-	52
11	Radio music	Continuous	33	38	34	39
12	Radio news	"	27	29	28	31

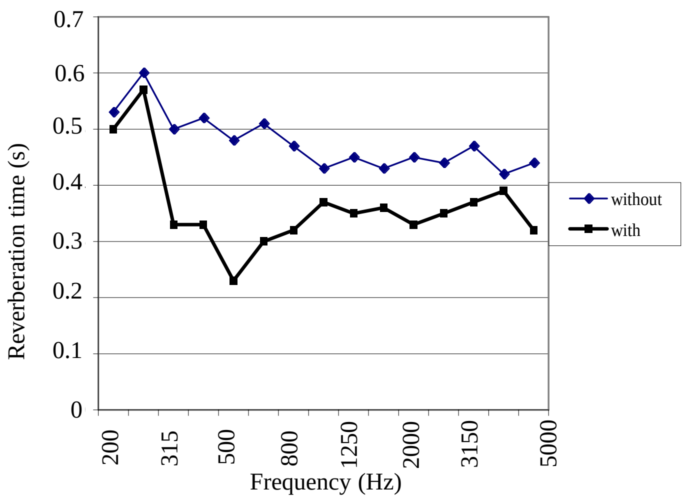

Figure 1—Reverberation time without and with sound absorbing ceiling

Statistical Methods

Arousals and sleep-stage changes were compared between patients sleeping without and with sound absorbing ceiling tiles using Wilcoxon Signed Ranks Test. The same test was used for comparison of arousals in different sleep stages. Student's two-tailed t-tests were used to compare total sleep time and sleep-stages. All statistical analysis was performed using SPSS for Windows®, version 9.0.

RESULTS

Sound Analysis

Department of Engineering Acoustics, University of Lund did analysis of sound levels. Baseline sound pressure level of the recording room was 28dB. Only minor differences in sound levels between specific sound stimuli was found between tiles with and without sound absorption (Table 1).

With sound-absorbing tiles reverberation time was reduced on average 0.12 seconds in a frequency range of 200—5000 Hz. Figure 1.

Sleep Architecture

No significant difference in mean total sleep time or in distribution of sleep stages was found between overnight studies without and with sound absorbing ceiling tiles (Table 2).

Sleep-stage distribution was found to be within normal limits.

Arousal Response to Sound Stimuli

Out of a total of 288 possible episodes (12 subjects x 12 stimuli x 2 nights) with sound stimuli, 271 could be evaluated (episodes commencing while subjects were awake were not analyzed; there were seven such episodes during night one and ten on night two).

With non-absorbing tiles mean value of arousal response to stimuli was 5.1±1.3 responses/sleep investigation. Significantly lower values were found with sound-absorbing tiles, 3±1.5 responses/sleep investigation ($p< 0.007$) (Figure 2).

Significantly more arousals were found during sleep stages 1 and 2 than during sleep stages 3 and 4 and REM ($p<0.007$).

Sleep-Stage Changes Following Sound Stimuli

No significant differences were found between sleep-stage changes without and with sound absorbing ceiling tiles (2.7±1.4 without vs. 1.4±1.2 with tiles).

DISCUSSION

Whereas several studies have investigated the effect on sleep of reducing the sound level, few studies have dealt with the effect of altered sound quality. We therefore decided to investigate whether reducing reverberation time had an impact on sleep disturbance caused by specific sound stimuli, and to create the "worst possible scenario" for our hypothesis, we chose to investigate 12 healthy young students with no history of sleep-problems or hearing impairment.

Since our results were obtained from young subjects, one could argue that it would be more appropriate to investigate older subjects more susceptible to environmental noise.[16] But there are other factors that influence sleep, such as sleep-related upper airway obstruction, possible diseases, and medication more commonly found in older subjects, that might have complicated data-

Table 2—Sleep-stage distribution, with and without sound-absorbing tiles

	Absorbing tiles	Non-absorbing tiles
Total Sleep Time (min)	371±27	370±26
SS 1 (min)	23±10	22±9
SS 2 (min)	182±37	169±51
SS 3 (min)	41±15	39±13
SS 4 (min)	54±26	44±14
REM (min)	70±15	78±20

interpretation.

Possible confounding factors, such as the negative impact on sleep of an unfamiliar experimental setting, was also the reason for studying the immediate effect of specific sound stimuli rather than the effect on overnight sleep architecture. We tried to eliminate "first-night effects," by discarding data from the first study night. We would have preferred to install sound-absorbing tiles and reflecting tiles randomly, but for practical reasons we were forced to accept the installation of sound-absorbing tiles after installing sound-reflective tiles. However, by discarding the first night and investigating non-consecutive nights we think we have reduced possible order and habituation effects.

By performing the studies in a quiet milieu, an empty former surgical ward in a small hospital, we purified sound stimuli. It therefore seems reasonable that EEG-responses measured after stimuli are not random or the effect of "natural" ambient background noise, even though the stimuli used were considerably lower intensity (27-58dB) than those of other studies (55-83dB).[4,5]

Due to the relatively small size of the room (three-bed room) and the placement and type of loudspeaker, direct sound was dominating. Under these circumstances sound level is only slightly reduced with sound-absorbing ceiling tiles. This implies that the major change of the acoustic environment may result from reduction of reverberation time, "smoothening" the sharpness of sound stimuli.

Accordingly, we speculate that smoothening of sound sharpness may play an important role in reducing impact of environmental noise on sleep and in part explain the reduced number of EEG-arousals found in our study.

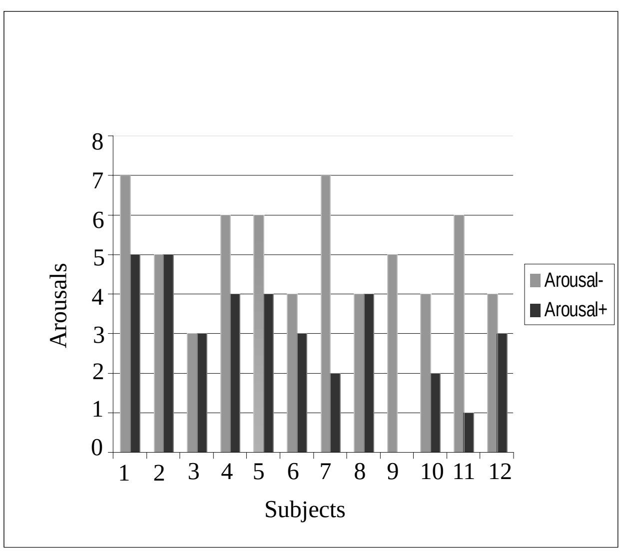

Figure 2—Arousal response/sleep registration to sound stimuli without (-) and with (+) sound absorbing tiles.

Since there is a lack of published studies on this specific subject it is difficult to compare our results with those of others. Thiessen et al.[6] found that sleep-stage changes were least adaptable with repeated sound stimuli over successive nights, whereas a certain adaptation could be found for waking. According to these results it seems as if sleep-stage changing could be an indicator for sleep disturbance. This is also indicated by Kawada et al.[15] who studied changes in REM-stage and found that maintenance of REM sleep requires a quiet environment.

These results do not correlate with our observations on sleep-stage changes, as we did not find any significant difference in number of sound induced sleep stage changes without and with absorbing tiles. However, the level of sound stimuli in our study (27-58 dB) was considerably lower than in others (55-83dB) which might explain the lack of sleep stage changes we found.

On the other hand, the very fact that we could demonstrate EEG-arousals and not sleep-stage changes in response to low level decibel stimuli suggests that EEG-arousals may be a more sensitive indicator of sleep disturbance than sleep stage changes.

This corroborates with previous findings by Terzano et al.,[19] who reported that the perturbing effects of noise on non-REM sleep were revealed by a significant increase in the CAP (cyclic alternating pattern) rate. This study differed from ours in using a continuos "white noise" of 55dB(A) during the night, but it is quite possible that measuring microstructural EEG-events (CAP) may be an even more sensitive indicator of reduced sleep disruption with reduced reverberation time.

We find it interesting that most arousals were found in sleep stages 1 and 2. These findings support the general conception that slow-wave sleep needs more intense stimuli to produce an arousal. They also indicate that sleep may indeed be disturbed even at low decibel levels (like those recommended in bedrooms) leading to increased arousals and consequent increased daytime sleepiness.

The observed reduction of arousals with reduced reverberation time indicates that sound quality is important to consider in noise reduction. An important question posed by our data is then whether sound stimuli response also is correlated to frequency content and duration? Thiessen found that response correlated positively to length of stimulus,[6] but no information is found in the literature regarding frequency content. The present study was not designed to investigate this particular question, but further investigation of arousal probability by frequency of stimulus may give important guidelines as to when and where reduction of reverberation time is optimal.

Generally, investigation into environmental noise needs to be more thoroughly pursued. This should be done not only in settings where noise-induced sleep disruption may be thought to delay the healing process, as in hospital units. Also in daily life environmental noise can cause discomfort and sleep problems and represent a health hazard (e.g., in hypertension.[1,7,18]) Further research in identification and modification of environmental noise is therefore needed, addressing as well problems of loudness as sound frequency and quality.

In conclusion, this study indicates that sound-absorbing ceiling tiles may reduce the sleep-fragmenting effect of sound stimuli. This may be of importance for the quality of sleep both during normal and vulnerable sleep.

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