

Sleep disturbances caused by vibrations from heavy road traffic

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The influence of whole-body vibrations, noise, and a combination of the two, caused by heavy road traffic (150 events/night) on sleep, subjectively experienced sleep quality, and performance was investigated under controlled laboratory conditions for male and female subjects 20–35 years of age. A room was built above a vibrator table, with the legs of the bed mounted directly on the table through holes in the floor. Vertical vibrations were found to be attenuated by the mattress with 20–40 dB for frequencies > 10 Hz, whereas horizontal vibrations were slightly amplified. It could be concluded that when traffic noise [50-dB(A) peak level] is accompanied by vibrations with peak levels of 0.24 m/s² vertically and 0.17 m/s² horizontally as measured on the frame of the bed (stimulus duration approximately 2 s, dominant frequency approximately 12 Hz), sleep is more disturbed than is the case when noise alone occurs. The amount of REM sleep, which was significantly reduced for the vibration level mentioned above, was even more disturbed when a higher exposure level, 0.34 m/s² vertically and 0.24 m/s² horizontally, was applied. The subjectively rated sleep quality was lower for the higher than for the lower vibration level. Performance in the morning was only influenced for the higher vibration level. It could be concluded that vibration exposure levels near the recommendation made in ISO-standard 2631 for the awake state disturb sleep in man.

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INTRODUCTION

Man is continuously exposed to different types of vibrations, for example, in buildings and transportation vehicles. This can lead to experiences of discomfort and fatigue as well as having a detrimental influence on work performance. Norms exist for acceptable whole-body vibrations,¹ based on perception, comfort, performance decrement, and health risk judgments. However, nothing is known about the influence of whole-body vibrations on sleep.

On the other hand, a number of studies performed in recent years in the homes of the subjects have dealt with the effects of traffic noise on sleep.^{2–9} However, in none of these studies has the role of possible whole-body vibrations and infrasound, caused by road traffic, been taken into account. It is not at all impossible that some of the discrepancies in sleep research findings concerning the effects of noise might be due to contributions from vibrations and infrasound. This is supported, e.g., by Sando and Batty,¹⁰ who, in a large social survey in England, found that 8% of the population is greatly disturbed by road traffic vibrations.

The present study investigates some of the research questions mentioned above. In this investigation, the influence of vibrations, noise, and a combination of the two as

caused by heavy road traffic (trucks and buses) on sleep subjectively rated sleep quality, and performance in the morning was investigated under controlled laboratory conditions.

I. MATERIALS AND METHODS

A. The vibration simulator

A room (2.25 × 2.75 m) was built above a 1.25 × 1.25-m large vibration simulator table (Schenck). The legs of the bed were mounted directly on the table through holes in the floor. The simulator could be driven hydraulically, both horizontally and vertically, by analogous signals from recorded "realistic" traffic vibrations. The subjects could be exposed to noise and infrasound simultaneously. In the present study, the effects of infrasound were not investigated, however. Both traffic noise and vibrations were recorded indoors in buildings built on clay where vibrations from passing trucks and buses were reported to be a problem. The horizontal and vertical components of the vibrations were of approximately the same amplitude.

Prior to the sleep studies, the vibration signal transfer functions of the simulator were studied, together with the vibration attenuation properties of three different mattresses and four different pillows. Accelerometers were located on the vibrator table, between the shoulder blades of the subject lying on his back (using a standard seat accelerator, Brüel & Kjaer type 4322) and on the forehead. Three subjects of

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varying weight and length (53 kg/161 cm, 69 kg/175 cm, and 91 kg/181 cm) participated. The vibration signals were analyzed with a digital signal analyzer (HP 5420A). In the subsequent sleep studies, only bed #1 and pillow #1 were used.

B. Subjects and exposure

After a short pilot study, in which one subject was exposed to vibrations of different amplitude in order to get some conception about awakening thresholds, three studies were performed using vibration levels that were not expected to cause awakenings, but could be perceived by the subjects when awake. In two studies the subjects, aged 20–35 years, were exposed to prerecorded vibrations from heavy road traffic and in one study the exposure consisted of road traffic noise and a combination of this noise and the same vibration exposure as above.

The exposure tape, recorded on an FM recorder, consisted of a sequence of ten bus passages that was repeated at approximately 30-min intervals, i.e., about 14 times during a 7-h night. Within the sequence, the time interval between the ten different stimuli was 90–130 s. Between the sequences there was a longer pause of about 10 min. Examples of typical stimuli are shown in Figs. 1 and 2. Each stimulus lasted approximately 2 s and had a dominant frequency of about 12 Hz. The ten bus passages were all recorded at the same location. Since the properties of the vibrations caused by heavy traffic are mainly determined by the unevenness of the road surface, the recorded stimuli were very much alike.

The purpose of the first two studies was to investigate arousal reactions, directly following the stimuli. In the third experiment, effects on the whole-night-sleep stage pattern were studied.

In the first study, four subjects (one male and three females) were, after three habituation nights (no recordings made), exposed to approximately 140 vibration stimuli per night for three consecutive nights. The peak level for the stimuli, measured on the frame of the bed, was 0.24 m/s^2 vertically and 0.17 m/s^2 horizontally.

In the second study, the same four subjects participated. The experimental design was similar to that of the first study. During the second exposure night, the same tape with vibrations as during the first study was played back, but the

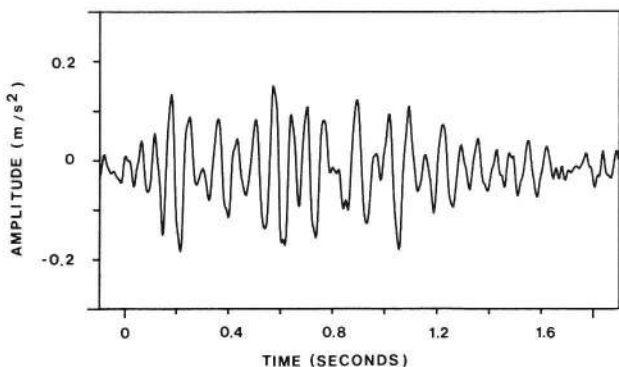


FIG. 1. Horizontal road traffic noise vibrations measured on the frame of the bed.

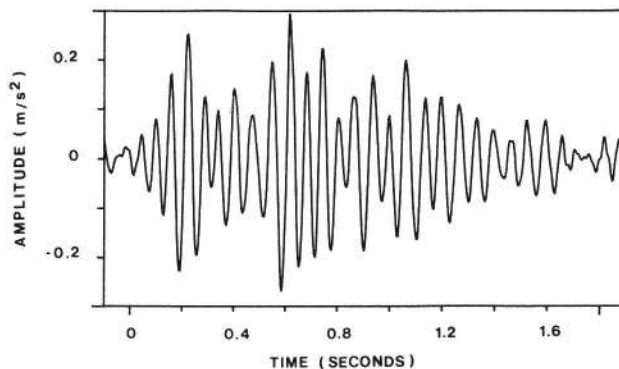


FIG. 2. Same as Fig. 1, but measured on the mattress.

vibrations were accompanied by the noise of the vehicles [with a maximum noise level of $L_{p \text{ max}} = 50 \text{ dB(A)}$]. During the first and third nights, the subjects were exposed to the noise only.

In the third study, five subjects (three males and two females), who had not participated earlier, were, after two habituation nights, exposed for five consecutive nights (first night not included in the analysis). After a 1-week break, they spent another four consecutive nights in the laboratory, without any exposure, and after an additional week off, the study ended with four exposure nights. During the first week, the exposure level was the same as in the first study (V_{low}). The vibration pattern consisted of a bus passage (one of the ten mentioned above) recorded digitally on the floppy disk of a small microcomputer and replayed semirandomly about 155 times per night (time interval between two stimuli at least 90 s). This procedure gives a greater flexibility, and since the ten recorded vibrations were very similar, the limitations of the use of one single bus passage repeated all through the nights was not felt to be severe. The second week was without exposure and served as a control. During the third week, the peak vibration level was raised to 0.34 m/s^2 vertically and 0.24 m/s^2 horizontally (V_{high}). A design with two 1-week breaks was chosen in order to prevent too much habituation to the stimuli. It was shown by Lukas *et al.*^{11,12} and Muzet *et al.*¹³ that a discontinuation of the experimental series largely prevents habituation.

C. Registrations and analysis

Eight channels of electrophysiological and exposure data [vertical and horizontal acceleration measured on the frame of the bed; noise level (infrasound if needed); EEG (C3-A2 and C4-A1); EOG; and submental EMG] were recorded digitally on one track of a tape recorder using the PCM technique (pulse code modulation) (John + Reilhofer). Each 1/4-in. tape holds four tracks. At the low tape speed used, the bandwidth of the system is 0–50 Hz. The EMG signals were rectified and smoothed before recording. For analysis, the signals were replayed at 16 times the recording speed.

The three experimental series were analyzed on arousal reactions indicating disturbed sleep, such as shifts in sleep stage toward lighter sleep, disturbances in the EEG too short

to be scored as a change of sleep stage, and motor activity. Short EEG reactions that were considered were bursts of alpha activity in stages 2-4, a sudden decrease in delta activity, or K-complexes occurring in stage 1 or REM. In the analysis of arousal frequencies, spontaneous reactions have to be taken into account. This is done by comparing the probability of a reaction during a 30-s period following the stimulus with a matched control period 30 s prior to the stimulus.^{7,14} In this way, matching is obtained with respect to time of night and sleep stage, two factors known to be of importance for the arousal frequency (see, for example, a review by Griefahn¹⁵).

Besides arousals, the influence of the two vibration levels on the sleep stage distribution, analyzed according to Rechtschaffen and Kales,¹⁶ was studied in the third experiment. The subjects had to answer a questionnaire and carry out a performance test both before bedtime and in the morning directly after awakening. The morning questionnaire contained questions about the subjectively experienced sleep quality, as described in Ref. 7, but two questions, administered on the subsequent afternoon, "How disturbed were you in your daily work?," and "How did you function in your daily work as compared to normally?," each with five answer alternatives, were added.

In the performance test, the subjects had to watch a computer monitor where, at irregular time intervals, one out of three possible dot patterns occurred in a random position on the screen. When a pattern was observed, a corresponding button had to be depressed as promptly as possible. The reaction times, number of errors and number of unobserved patterns were recorded. Each performance test lasted for about half an hour and consisted of approximately 50 trials. The test was practiced about six times before the start of the experiment in order to reduce learning effects during the experimental series.

The statistical analysis of the arousal frequencies was carried out with a chi-squares test. The whole-night sleep parameters and the performance parameters were analyzed using two-way analysis of variance, studying the effects of the three experimental conditions and interindividual differences. For the results of the questionnaire, which were measured in an ordinal scale, the experimental conditions were compared for each subject separately with Mann-Whitney's U-test. The same test was used for the pooled scores of the different subjects. Since the direction of the change that occurs under exposure conditions is predicted, one-tailed tests were performed.

II. RESULTS

A. The vibration simulator

Figure 3 shows the background vibrations of the simulator table that occur in the absence of any input signal. These vibrations have a peak level around 80 Hz and occur mainly in the vertical direction. Since the beds show a considerable attenuation for vertical vibrations > 10 Hz (see Fig. 7 and text below) the background vibrations were reported by the subjects to be not perceivable in bed. The higher low-frequency vibration levels in the bed, compared to the table, were probably caused by movements of the subjects.

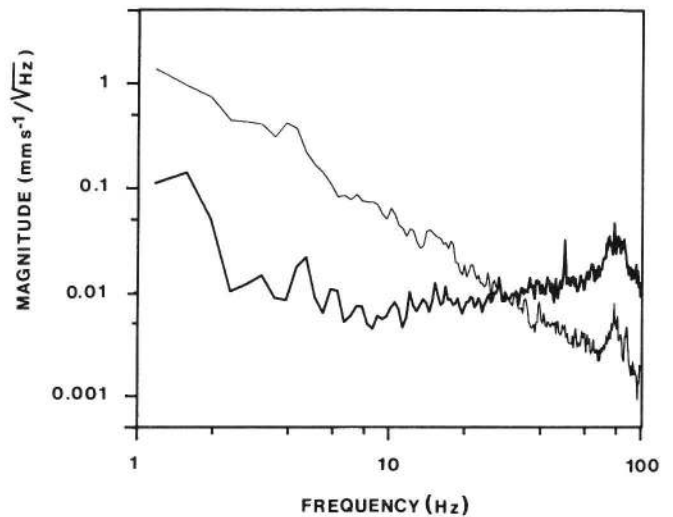


FIG. 3. Vibration velocity spectrum: background noise — on the vibration table and — in bed No. 1.

The ability of the table to reproduce the input signals is limited by background noise, modulation noise, and nonlinearity of the system. Figure 4 shows the response of the table as the result of a sine-wave excitation with 16 Hz. The velocity spectrum on the table compared to an input pink noise signal with frequencies below 30 Hz is shown in Fig. 5. Figure 6 shows the transfer functions of the vibration system for vertical and horizontal directions. It can be concluded from the figures that the response of the system is quite acceptable for frequencies ranging from 1–30 Hz.

A typical attenuation curve for vertical vibration for the bed and mattress used in the sleep experiments (bed No. 1) is shown in Fig. 7. The different beds show no attenuation for very low frequencies, an amplification of about 15 dB at a resonance frequency of 2–5 Hz (the low frequency for a soft, foam plastic mattress) and a maximum attenuation of 15–20

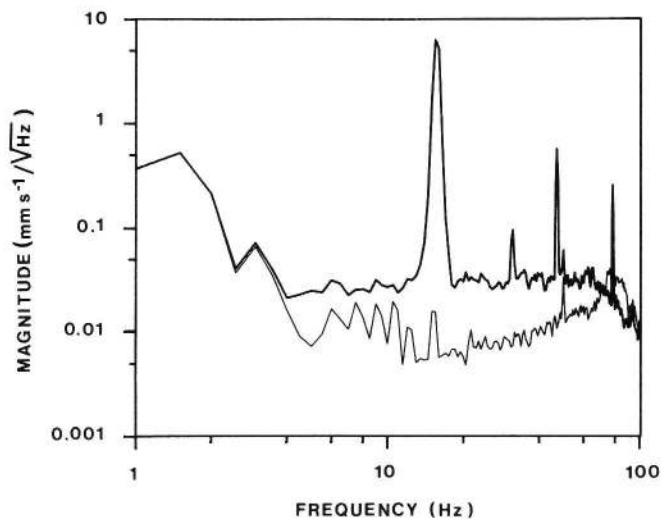


FIG. 4. Vibration velocity spectrum: The effect of a 16 Hz sine wave excitation — as compared to the background noise — (both measured on the vibrator table).

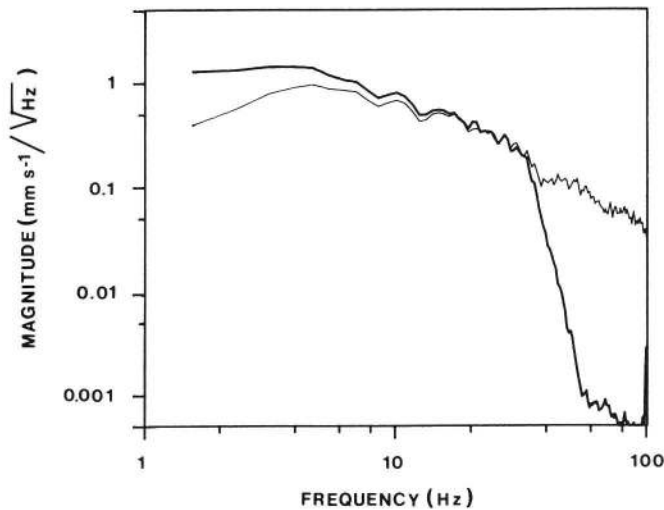


FIG. 5. Vibration velocity spectrum: — pink noise excitation signal ($f < 30$ Hz) and — the resulting vibration as measured on the vibrator table.

dB for high frequencies. The influence of the subjects' body weight on the attenuation properties of the beds was found to be negligible. Horizontal vibrations were amplified rather than attenuated by the different beds (see Fig. 7). The four pillows had very similar attenuation properties, except for pillow No. 1 (feather-filled) that showed 10 dB less attenuation in the frequency range 10–20 Hz (see Fig. 8 for pillows Nos. 1 and 2). It should be pointed out that the subjects were lying on their backs during the vibration measurements, and thus it cannot be excluded that different body positions can influence the transmission of the vibrations to the body.

B. Experiments 1 and 2

The probabilities of immediate reactions, together with reaction times and subjective estimates of sleep disturbance,

are shown in Table I for the first experiment. All probabilities are corrected for spontaneously occurring reactions. It is obvious from the data that two subjects were greatly disturbed by the vibrations, both objectively and subjectively. They also performed more poorly in the reaction time test. One subject (CJ) showed only an increased number of changes toward lighter sleep. This subject only complained of irritability during the next day. For the group as a whole, it can be concluded that immediate reactions were induced by the vibrations.

In the second experiment, no effects on sleep-stage changes were found. Short EEG reactions were rare and therefore not analyzed separately. The results of experiments 1 and 2 are compared in Table II.

C. Experiment 3

1. Arousal reactions

In order to study body movements in more detail than in the former two experiments, a case-control study with two matched controls was performed as described earlier by Eberhardt.⁷ The occurrence of the peak of a vibration stimulus during different 15-s test intervals before (45–30 s, 30–15 s, 15–0 s, or 0–15 s) the start of the body movement was compared to the occurrence during one or two control intervals, 15–30 s and 30–45 s, after the start of the movement. An increased probability of occurrence is expressed in the relative risk of an occurrence, as compared to a random distribution of vibrations around the body movement. Table III shows the results for the test periods 15–0 s before the start of the movement and 0–15 s after. (A vibration with its peak during this period could already start before the start of the body movement.) Vibrations during the other test intervals could not be statistically connected to the following body movement. From the table, it is clear that it was mainly during sleep stage 2 that body movements were elicited by the vibrations. The probability that a vibration induces a body movement was 8.5% and 15.7% for V_{low} and V_{high} , respectively.

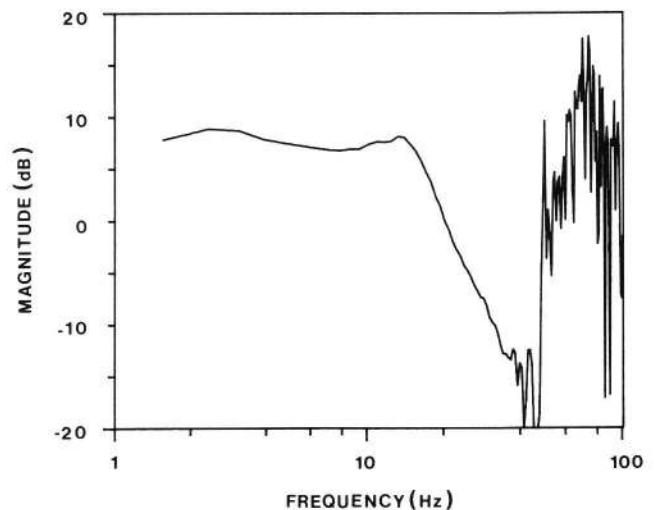
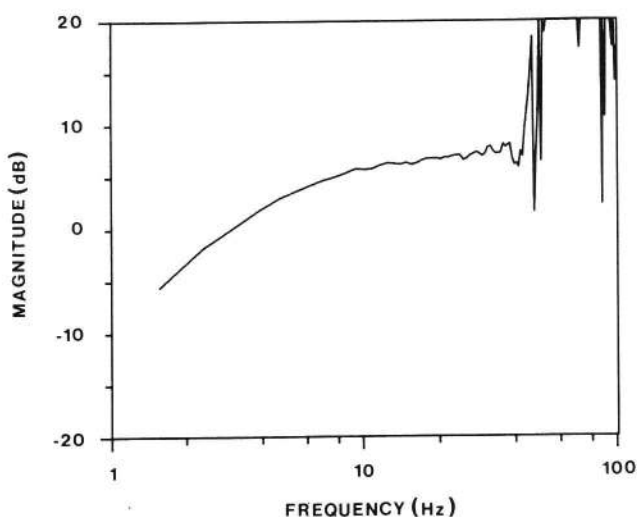


FIG. 6. Transfer function between excitation signal in a vertical (left) and horizontal (right) direction and the resulting acceleration of the vibrator table.

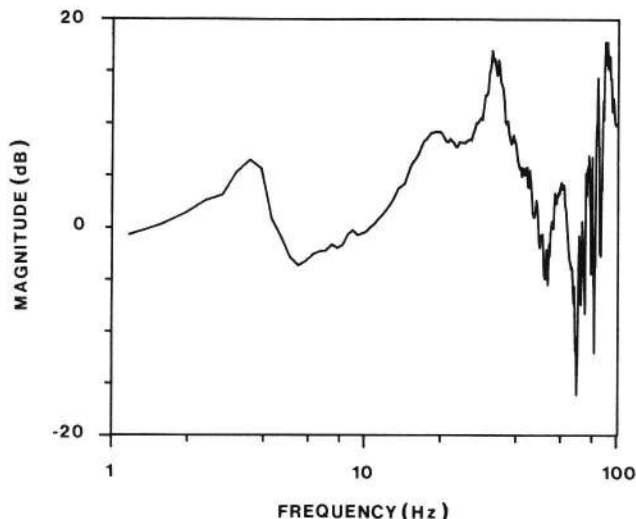
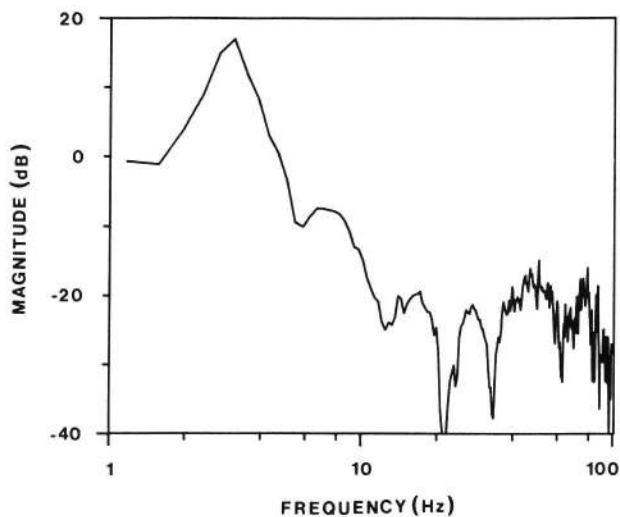


FIG. 7. Typical transfer function between vertical (left) and horizontal (right) vibrations measured on the table and in the bed between the shoulder blades (see text) for bed No. 1, pillow No. 1, and subject No. 2 (69 kg).

The occurrence of changes toward lighter sleep, induced by vibrations, was studied with the same method of analysis as that used for the body movements. The occurrence of a vibration during a 30-s-long test period preceding the sleep stage changes was compared to an equally long period following the change (see Table IV). The low vibration level did not induce changes toward lighter sleep. The high vibration level induced changes toward lighter sleep from stage 2 only ($RR = 3.4$, $\chi^2 = 6.6$, $p = 0.01$). The low value for RR (relative risk) for stage 3 seems to indicate that the probability of stage 3 after a vibration is increased rather than reduced. Since the data for each sleep stage are rather poor, the

combination of V_{low} and V_{high} was also investigated. The data suggest that the stimuli can induce sleep stage changes toward REM sleep ($RR > 1$, $p < 0.05$), whereas sleep stage changes from REM sleep occurred with a lower frequency than expected from the frequency of spontaneous reactions ($RR < 1$, $p < 0.05$).

The total number of sleep stage changes (spontaneous plus stimulus-induced) per night increased for four of the five subjects when exposed to the stimuli. For the group as a whole, this increase (from 55 to 67) was significant for exposure V_{low} (Mann-Whitney, $p = 0.02$) (see Fig. 9).

2. Sleep stages

Of all duration and barycenter parameters⁷ studied, the amount of REM sleep only, both absolute and in terms of percentage of total sleep time, was influenced by the vibration conditions ($F = 5.6$, $p = 0.01$) (see Table V). Large

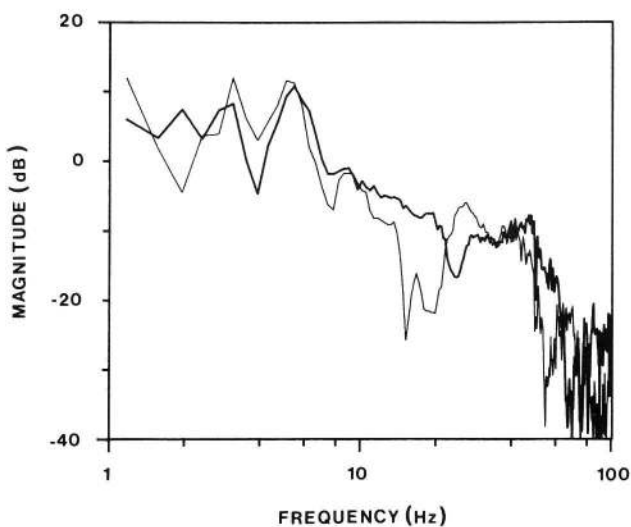


FIG. 8. Transfer function between vertical vibrations of the table and the head of subject No. 2 for —, pillow No. 1 and - - -, pillow No. 2 (bed No. 1).

TABLE I. Results for experiment 1. Probabilities of different types of reactions for the four subjects. --, much disturbed; -, disturbed; and 0, not disturbed. Reaction time after control nights in parentheses.

| Subject | Body movement (%) | Short EEG reaction (%) | Sleep stage change (%) | Subj. sleep quality | Reaction time (s) | Daily work |
|---------|-------------------|------------------------|------------------------|---------------------|-------------------|------------|
| GH | 6.0 ^c | 2.5 | 4.0 ^c | -- | 1.2(1.0) | -- |
| MS | 11.8 ^b | 7.4 ^b | 18.4 ^c | -- | 1.3(1.1) | -- |
| ME | 1.7 | 1.7 | 2.8 | 0 | 1.3(1.3) | 0/- |
| CJ | 3.4 | 0.7 | 7.0 | 0 | 1.2(1.2) | - |
| Total | 5.1 ^c | 2.3 ^b | 6.7 ^c | | | |

^a $p < 0.05$.

^b $p < 0.01$.

^c $p < 0.005$.

TABLE II. Comparison between experiments 1 and 2.

| Type of reaction | Probability in % of a reaction for | | |
|--------------------------------------|------------------------------------|------------------|--------------------|
| | Vibrations | Noise | Noise + vibrations |
| Body movements + short EEG reactions | 7.4 ^a | 3.5 ^b | 8.5 ^c |
| Sleep stage changes | 6.7 ^a | 0.1 | 3.5 |

^a $p < 0.001$.
^b $p = 0.03$.
^c $p < 0.002$.

interindividual differences in the amount of REM sleep were found ($F = 12.1, p < 0.0001$). For V_{low} , the amount of REM sleep decreased with 22 min and 5% units and for condition V_{high} , the decrease was 24 min and 7% units (see Fig. 9). Linear regression analysis was applied for the different nights for each experimental condition. Because of the limited material and the large interindividual differences, no trends with time could be discerned.

3. Morning questionnaire and performance test

The statistical test for each subject taken separately revealed ($p < 0.05$) that after nights under condition V_{low} , one subject (HL) felt tired and one subject (PW) felt that he had slept worse than normally. For the group as a whole, these two parameters showed significant effects ($p < 0.05$). During condition V_{high} , the subjects stated (subjects pooled) that they had experienced difficulty in falling asleep ($p = 0.006$), had slept poorly, and worse than at home, were tired, had difficulty returning to sleep after awakening, and had difficulties at work the next day ($0.01 < p < 0.05$). Three subjects (KH, PW, and EA) showed significant effects for at least one question. One of these (PW) showed significant effects for five of the questions. A combination of the different questions into a total subjective sleep quality score for the three conditions is shown in Fig. 9.

TABLE III. The relative risk (RR) and associated χ^2 -value for the peak of a vibration to fall within the test intervals 15-0 s or 0-15 s as compared to two control intervals 15-30 s and 30-45 s after the start of a body movement.

| Sleep stage | V_{low} | | | | V_{high} | | | |
|-------------|-----------|-------------------|------|-------------------|------------|-------------------|------|-------------------|
| | - 15-0 | | 0-15 | | - 15-0 | | 0-15 | |
| | RR | χ^2 | RR | χ^2 | RR | χ^2 | RR | χ^2 |
| 1 | 3.5 | 4.6 ^a | 2.5 | 2.0 | 3.0 | 3.2 | 0.5 | 0.4 |
| 2 | 3.5 | 33.4 ^c | 2.7 | 19.0 ^c | 5.4 | 90.7 ^c | 3.9 | 49.5 ^c |
| 3 + 4 | 2.0 | 0.8 | 0.7 | 0.1 | 2.0 | 1.3 | 1.2 | 0.1 |
| REM | 1.0 | 0.0 | 1.7 | 3.4 | 1.7 | 3.9 | 1.5 | 2.0 |
| All | 2.5 | 28.9 ^c | 2.2 | 21.6 ^c | 3.6 | 86.1 ^c | 2.6 | 39.4 ^c |

^a $p < 0.05$.
^b $p < 0.01$.
^c $p < 0.001$.

TABLE IV. The relative risk (RR) for the peak of a vibration to occur within a test interval 30-0 s prior to a change toward lighter sleep as compared to a control interval 0-30 s after the change.

| Sleep stage | V_{low} | | V_{high} | | $V_{low} + V_{high}$ | |
|----------------|-----------|------------------|------------|------------------|----------------------|------------------|
| | RR | χ^2 | RR | χ^2 | RR | χ^2 |
| 1 → 0 | ∞ | 3.0 | ∞ | ∞ | ∞ | 3.0 |
| 2 → 1,0 | 0.7 | 0.6 | 3.4 | 6.6 ^b | 1.4 | 1.3 |
| 3 → 2,1,0 | 1.1 | 0.2 | 0.6 | 7.5 ^b | 0.7 | 3.7 |
| 4 → 3,2,1,0 | 1.2 | 0.2 | 0.6 | 1.0 | 0.9 | 0.1 |
| REM → All | 0.2 | 7.1 ^b | 0.7 | 1.0 | 0.7 | 5.8 ^a |
| All → REM | 1.6 | 1.7 | 2.2 | 2.6 | 1.8 | 4.1 ^a |
| NREM → lighter | 1.1 | 0.2 | 0.8 | 2.4 | 0.9 | 0.8 |

^a $p < 0.05$.
^b $p < 0.01$.

Analysis of variance revealed a large between-subject variability for the different performance parameters ($p < 0.0001$). The only parameter influenced by the exposure condition was the number of unobserved patterns ($F = 15.2, p < 0.001$). In addition, the different subjects do not react in the same way to a change in noise condition ($F = 28, p < 0.0001$). As shown in Table VI, only two subjects were found to be less alert.

III. DISCUSSION AND CONCLUSIONS

From the first two experiments (see Table II), it can be concluded that when road traffic noise is accompanied by

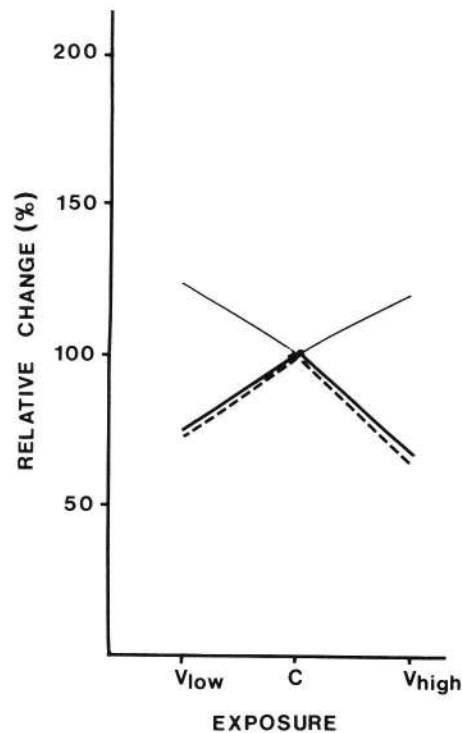


FIG. 9. The relative change for the two vibration exposure conditions as compared to the control condition for: —, the amount of REM sleep; ---, an index for the subjective sleep quality; and ···, the total number of sleep stage changes per night.

TABLE V. The duration of REM sleep in percent of total sleeping time (s.d. in parentheses) for each individual for experiment 3.

| Subject | Experimental condition | | |
|---------|------------------------|-----------|------------|
| | Control | V_{low} | V_{high} |
| KH | 19(6) | 15(6) | 9(2) |
| PW | 33(5) | 22(2) | 13(4) |
| EA | 13(4) | 11(5) | 15(4) |
| SJ | 31(6) | 24(8) | 29(6) |
| HL | 22(2) | 20(4) | 19(4) |
| Mean | 23.4 | 18.4 | 16.6 |

vibrations, arousal reactions occur more often than is the case when noise alone occurs. Table II also indicates that vibrations without noise cause sleep stage changes more often than when the vibrations are accompanied by the noise of the trucks. The question of whether this is an effect of an increased habituation to the experimental situation or an effect of the vibrations being perceived as more threatening (and thereby more disturbing) when they are not accompanied by a noise that makes identification possible cannot be answered within the present design. From studies on the influence of noise on sleep, it is known that the information content of the noise stimuli is of importance for the awakening frequency.¹⁷⁻¹⁹ The frequency of noise-induced changes toward lighter sleep, as found in experiment 1, is comparable to the frequency reported by Eberhardt *et al.* in a recent study²⁰ using road traffic noise with $L_{p,max} = 45$ dB(A), whereas the frequencies found in experiments 2 and 3 are much lower. Part of the difference might be explained by the difference in the number of stimuli per night (150 vs 50), since it has been found¹⁵ that the probability of a noise event inducing a reaction decreases with an increased number of stimuli per night.

The probability of vibrations inducing a body movement during condition V_{low} in experiment 3 is comparable to that of experiments 1 and 2. In contrast to experiment 1, however, no changes toward lighter sleep were induced by the vibrations. As shown in Table IV for the combination of $V_{low} + V_{high}$, transitions to REM sleep are induced by the vibration stimuli ($RR = 1.8$), and at the same time, transition from REM sleep seems to be hindered by the stimuli

TABLE VI. Number of unobserved dot patterns [mean (s.d.)] for each subject in experiment 3.

| Subject | Exposure condition | | |
|---------|--------------------|-----------|------------|
| | Control | V_{low} | V_{high} |
| KH | 6.7(3.2) | 4.3(3.0) | 28.3(3.1) |
| PW | 0.2(0.4) | 0.3(0.6) | 0.5(0.7) |
| EA | 0 | 0 | 0 |
| SJ | 0.3(0.6) | 2.0(0) | 0 |
| HL | 0 | 0 | 0 |

($RR < 1$). Similar effects have been observed in other investigations.^{7,21,22} However, the effect observed for the *whole-night* sleeping pattern is a reduction of the total amount of REM sleep, followed by tiredness in the morning. Despite possible habituation effects during the experimental series, an increase of the vibration level during the third experiment week caused a larger reduction of the amount of REM sleep, an estimated lower sleep quality and negative effects on test performance and daily work.

The results of the present experiments imply that vibrations caused by road traffic have synergetic effects on the traffic noise-induced sleep disturbances. It is thus advisable to take this source of exposure into account in future field studies.

In order to be able to compare the vibration levels used in the present experiments with recommendations for whole-body vibrations as published in ISO-standard 2631,¹ the peak vibration levels have to be converted to frequency-weighted whole-night rms values. The ISO recommendations are based on the negative effects of continuous whole-body vibrations on comfort, performance, and health. When the comfort criterium is used for an 8-h exposure time for vibrations of 12 Hz (the dominant frequency of the traffic vibrations), rms vibration levels below 0.45 m/s² and 0.16 m/s² are recommended for the vertical and horizontal components, respectively. The corresponding frequency-weighted values are 0.07 and 0.1 m/s, respectively (see Table VII). In Table VII, the stimulus peak values, frequency weighted according to ISO 2631, are also given, both measured on the frame of the bed (corresponds to measurements of floor vibrations) and measured on the mattress. The whole-night rms value of the 150 vibration stimuli can be calculated by dividing the peak values by 170. The actual whole-night vibration rms values, as measured on the bedframe and on the mattress (see Table VII), were found to be considerably higher (in the order of perception threshold) and were completely determined by the residual vibrations of the vibrator table. The discussion above illustrates one of the main problems concerning assessment of transient vibrations with low

TABLE VII. Comparison between exposure levels and ISO 2631.

| Exposure | | Vibration level (weighted according to ISO 2631) | | | |
|--------------|------------|---|-------------------------|---|-------------------------|
| | | Peak value (m/s ²) | | rms ^c (m/s ²) | |
| | | vertical ^a | horizontal ^b | vertical ^a | horizontal ^b |
| Frame of bed | V_{low} | 0.03 | 0.09 | 0.004 | 0.02 |
| | V_{high} | 0.04 | 0.13 | 0.004 | 0.02 |
| On mattress | V_{low} | 0.008 | 0.14 | 0.001 | 0.03 |
| | V_{high} | 0.011 | 0.20 | 0.001 | 0.03 |
| ISO 2631 | | ... | ... | 0.07 | 0.1 |

^a Direction X according to ISO 2631.

^b Direction Z according to ISO 2631.

^c Residual vibrations of the vibrator table (see text).

repetition rates. It is obvious that some assessment method other than rms values has to be developed. In the present study, vibration stimuli with *peak* levels near the ISO recommendation for *continuous* vibrations clearly caused sleep disturbances, despite the low average rms value. Similar results have been obtained in studies with low density nocturnal traffic noise:²⁰ The equivalent sound-pressure level was found to be an inadequate descriptor of the noise dose. Better results were obtained when the intermittent character of the noise was taken into account, as expressed in $L_{1, NPL}$ or TNI ⁵, emergence from the background^{23,24} or the number of events per night exceeding a certain noise level.⁷

The present investigation, performed on small groups of subjects, was a first pilot study, designed to establish under which conditions sleep might be affected by traffic vibrations. Much larger studies, with varying vibration amplitudes and repetition rates, will be needed in order to establish dose-response relationships with respect to sleep disturbances.

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