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Relative and Combined Effects of Heat and Noise Exposure on Sleep in Humans

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Summary: In a counter-balanced design, the effects of daytime and/or nighttime exposure to heat and/or traffic noise on night sleep were studied in eight healthy young men. During the day, the subjects were exposed to baseline condition (ambient temperature = 20°C; no noise) or to both heat (35°C) and noise. The duration of the daytime exposure was 8 h ending 5 h before sleep onset. The following nights, the subjects slept either in undisturbed (20°C; no noise) or in noise, heat, or noise plus heat-disturbed environments. During the day, the various types of traffic noise were distributed at a rate of 48/h with peak intensities ranging between 79 and 86 dB(A). The background noise level was at 45 dB(A). At night, the peak intensities were reduced by 15 dB(A), the rate was diminished to 9/h, and the background noise was at 30 dB(A). Electrophysiological measures of sleep and esophageal and mean skin temperatures were continuously recorded. The results showed that both objective and subjective measures of sleep were more disturbed by heat than by noise. The thermal load had a larger impact on sleep quality than on sleep architecture. In the nocturnal hot condition, total sleep time decreased while duration of wakefulness, number of sleep stage changes, stage 1 episodes, number of awakenings, and transitions toward waking increased. An increase in the frequency of transient activation phases was also found in slow-wave sleep and in stage 2. In the nocturnal noise condition, only total number of sleep stage changes, changes to waking, and number of stage 1 episodes increased. Disturbed days followed by undisturbed nights only affected number of stage changes. The effect of heat and/or noise on sleep at night was not significantly enhanced by the presence of daytime disturbances. **Key Words:** Heat—Noise—Sleep—EEG—Humans.

Noise and heat can disturb sleep in two different ways: 1) in a direct manner when sleep occurs in a hot or in a noisy environment; 2) in a delayed manner when sleep follows exposure to these stressors during the day preceding nocturnal sleep. The direct effects of nocturnal exposure to noise on sleep have been extensively examined in a review by Griefahn (1). With regard to sleep architecture, no deleterious effect of noise was generally observed (2–4). However, for high noise levels, an increase in body movements as well as in cortical activity were found. An increase in wakefulness also was observed while the amount of slow-wave sleep (SWS) was found to decrease. The effects of noise on sleep also depend on both the characteristics of the noise and of the subject exposed. In contrast, nocturnal heat exposure causes very disturbed sleep. It has been found that humans sleeping in hot conditions exhibit a reduction in rapid eye movement sleep (REM), SWS, and marked increases in the number and duration of wakefulness episodes (5,6).

The effects of daytime exposure to heat and/or noise on the subsequent night of sleep have been investigated to a lesser extent. Blois et al. (7) reported that daytime noise reduced total sleep time and REM sleep duration. Fruhstorfer et al. (8) found an increase in SWS while stage 2 was decreased. The influence of daytime heat exposure on sleep has received more attention than that of noise (9–12). In these investigations, following daytime exposure to heat, SWS and particularly the duration of sleep stage 4 increased (13). For Bunnell et al. (12), this effect was only observed for daytime heat exposure ending within 5 h of sleep.

Little attention has been paid to the influence of the combination of heat and noise on sleep despite the fact that these ambient factors are often associated in many environments. The aim of the present study was to examine the individual effects of noise and heat and

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TABLE 1. *Experimental conditions*

	Subjects							
	1 and 2		3 and 4		5 and 6		7 and 8	
	Day	Night	Day	Night	Day	Night	Day	Night
Habituation	20°C	20°C	20°C	20°C	20°C	20°C	20°C	20°C
	35°C, N	35°C, N	35°C, N	35°C, N	35°C, N	35°C, N	35°C, N	35°C, N
Experimental conditions	20°C	35°C, N	35°C, N	35°C, N	35°C, N	20°C	20°C	20°C, N
	35°C, N	35°C, N	35°C, N	20°C, N	20°C	20°C, N	20°C	35°C, N
	35°C, N	20°C	20°C	20°C	20°C	35°C	35°C, N	35°C
	20°C	20°C, N	20°C	35°C, N	35°C, N	35°C	35°C, N	20°C
	20°C	35°C	35°C, N	35°C, N	35°C, N	20°C, N	20°C	20°C
	35°C, N	35°C	35°C, N	20°C	20°C	20°C	20°C	35°C
	35°C, N	20°C, N	20°C	20°C, N	20°C	35°C, N	35°C, N	35°C, N
	20°C	20°C	20°C	35°C	35°C, N	35°C, N	35°C, N	20°C, N

N, noise.

their combined effects on sleep when presented at night. Further we evaluated whether daytime heat and noise exposure affected subsequent undisturbed sleep and whether the disturbed days enhanced the effects of heat and/or noise during the night.

METHODS

Subjects

Eight male subjects (21 ± 1 years old; 68 ± 3 kg; 1.77 ± 0.04 m) volunteered for the study. After a clinical examination, the subjects completed two questionnaires. The Horne and Ostberg's morningness–eveningness questionnaire (14) and the Eysenck Personality Inventory (15). All subjects were within a normal range according to these two tests. Care was taken that: 1) the values of body weight to body area ratio did not differ greatly from one subject to another (37.12 ± 1.18 kg/m^2); 2) the subjects had not lived in a hot climate during the last 6 months; 3) their hearing level tested by an automatic audiometer was normal.

Procedure

The experiments were carried out in two soundproofed, air-conditioned rooms, each with 10 m^2 surface area. Recordings were performed simultaneously on two subjects. After two habituation day–nights, one in neutral (20°C of air temperature, T_a) and the other in heat (35°C) plus noise conditions, each pair of subjects was exposed in a counterbalanced order to eight experimental conditions (see Table 1): 1) daytime (20°C, no noise) and nighttime (20°C, no noise) represented the undisturbed reference; 2) daytime (20°C, no noise), nighttime (20°C, noise); 3) daytime (20°C, no noise), nighttime (35°C, no noise); 4) daytime (20°C, no noise), nighttime (35°C, noise); 5) daytime (35°C, noise), nighttime (20°C, no noise); 6) daytime (35°C, noise), nighttime (20°C, noise); 7) daytime (35°C, noise), nighttime (35°C, no noise); 8) daytime (35°C, noise), nighttime (35°C, noise). Daytime when subjects lived under 20°C T_a and no noise was defined as an undisturbed day, in contrast to a disturbed day when subjects lived under 35°C and noise.

Various recorded traffic noises (truck, car, motorbike) were presented through loudspeakers. In order to reflect real-life environment, the traffic noise was designed to be more frequent and louder during daytime than at night. The noise intensities were usual sound levels of traffic noises recorded in a city. The noises were semirandomly distributed at a rate of 48/h during the day and at a rate of 9/h during the night. During the day, the peak intensities were 79 dB(A) for the car, 82 dB(A) for the motorbike, and 86 dB(A) for the truck. The background noise level (pink noise) was set at 45 dB(A). The peak intensities were similar to those recorded in a bedroom with open windows and vehicles passing at a speed of 60 km/h within 15 m in front of the facade of the dwelling.

During the night, the peak levels of noises were all reduced by 15 dB(A). This corresponded to the noise obtained when the windows were closed.

In the thermoneutral environment, air and wall temperatures (20°C), air humidity (dew-point temperature = 10°C), and air velocity (0.2 m/s) were kept constant. During the day, the subjects wore cotton tracksuits and sneakers. At night, they slept in pajamas in a bed and were covered by one cotton sheet and one wool blanket.

In the hot condition, air and wall temperatures were increased to 35°C. Air humidity and velocity were unchanged. Daytime clothing consisted of a tee-shirt, shorts, and sneakers. During the night, the subjects slept wearing only underpants covered by one cotton sheet. For this clothing condition, the air temperature imposed during the night was slightly above the thermoneutrality zone at a level able to induce sleep disturbances (16) (30–32°C).

The daytime exposure lasted for 8 h (from 9 a.m. to 1 p.m., and from 2 p.m. to 6 p.m.) interrupted by a 1-h lunch break. The subjects went to bed at 10:50 p.m., lights off at 11 p.m., and they were awakened at 7 a.m. During the day subjects carried out their usual activities (reading, writing) and performed various short paper-and-pencil tests. They were continuously monitored via closed-circuit television.

All subjects were under the same regimen. They ate standard meals at 1 p.m., at 7 p.m., at 8 a.m., and drank bottled spring water ad libitum.

Measurements of physiological variables

Esophageal temperature (T_{es}) was continuously measured 36–40 cm beyond the external nasal opening by a thermistor introduced into the esophagus through the nose.

Four local skin temperatures (right pectoral region, right upper arm, right upper and lower leg) were measured by thermistors sandwiched between two thin layers of self-adhesive copper ribbons. Mean skin temperature ($\bar{T}_{sk}$) was calculated by using the weighting area factors of Ramanathan (17). All temperatures were recorded at 1-h intervals during the day and at 1-min intervals throughout the night.

The electrophysiological recordings during sleep included C3 and F3 referenced to the opposite mastoid (A2); right and left electrooculograms from the outer canthus referenced to the left mastoid (A1); electromyogram of the chin and electrocardiogram. Sleep stages were scored every 30-s period of the night following the recommendations of the Rechtschaffen and Kales' Manual (18).

After awakening, subjects completed a 7-point scale questionnaire of sleep quality (depth, stability, and efficiency of sleep).

Statistical analysis

In the experimental design, four nocturnal environmental conditions (20°C, no noise; 20°C, noise; 35°C, no noise; 35°C, noise) were combined with two daytime conditions (20°C, no noise and 35°C, noise). The primary statistical procedure was an analysis of variance (ANOVA) for repeated measures. The three factors were day (two levels: disturbed, undisturbed), nocturnal air temperature (two levels: 20°C, 35°C), and noise (two levels: no noise, noise). When overall F values were significant ($p < 0.05$), pairwise t tests were computed.

Because previous studies had reported deleterious effects of both noise and heat on sleep, one-tailed t tests were used for all pairwise comparisons of the experimental conditions with the reference night. Two-tailed t tests were used for pairwise comparisons between the seven treatment conditions, i.e., between heat and noise exposure.

When sleep stages were expressed as percentages of total sleep time, they were tested after an arc-sin transformation ($0 = 2 \text{ arc-sin}\sqrt{x}$) in order to stabilize the variances as recommended by Winer (19).

RESULTS

Daytime and nocturnal mean skin and esophageal temperatures plotted against time are presented in Figure 1. Body temperatures were analyzed for rate of change over day and night and for overall mean levels at night. During 35°C T_a days both T_{es} and $\bar{T}_{sk}$ showed a significant increase ($p < 0.001$) in mean levels from 36.50 ± 0.06°C to 36.81 ± 0.09°C for T_{es} and from 34.80 ± 0.20°C to 35.15 ± 0.25°C for $\bar{T}_{sk}$ over the day (morning–afternoon values).

The circadian rhythm of body temperatures observed during nights at thermoneutrality was still present following an undisturbed day when T_a was 35°C at night, although the mean temperatures were higher, i.e., the change was not as great. When T_a was 35°C at night following a disturbed day, the circadian rhythm was absent for both T_{es} and $\bar{T}_{sk}$. Relative to undisturbed days, T_{es} and $\bar{T}_{sk}$ decreased abruptly during the first part of the night when 20°C nights were preceded by a disturbed day (see Fig. 1). Analysis of difference scores between early night $\bar{T}_{sk}$ (11 p.m.) and their nocturnal minimum values indicated that $\bar{T}_{sk}$ changes were significantly larger ($p = 0.014$ at 20°C T_a and $p = 0.015$ at 20°C plus noise). Although the pattern of change was similar to $\bar{T}_{sk}$, the amount of change of T_{es} was not significant. At night, for $\bar{T}_{sk}$ the respective means and standard deviations (SD) thermoneutral and 35°C temperature levels were 33.82 ± 0.36°C and 35.17 ± 0.32°C. For T_{es}, the respective means, SDs, night thermoneutral, and 35°C levels were 36.10 ± 0.25°C and 36.51 ± 0.16°C. The mean night body temperatures were not significantly different when means following disturbed and nondisturbed days were compared for each of the experimental conditions. Daytime exposure only affected the time patterns of nocturnal peripheral and internal temperatures.

Sleep

The means and SDs for each of the sleep variables for the reference (undisturbed) night, column 1, and for each of the seven treatment conditions are presented in Tables 2 and 3. In addition to the changes in mean values, there was also an increase in variability under the treatment conditions reflecting the marked

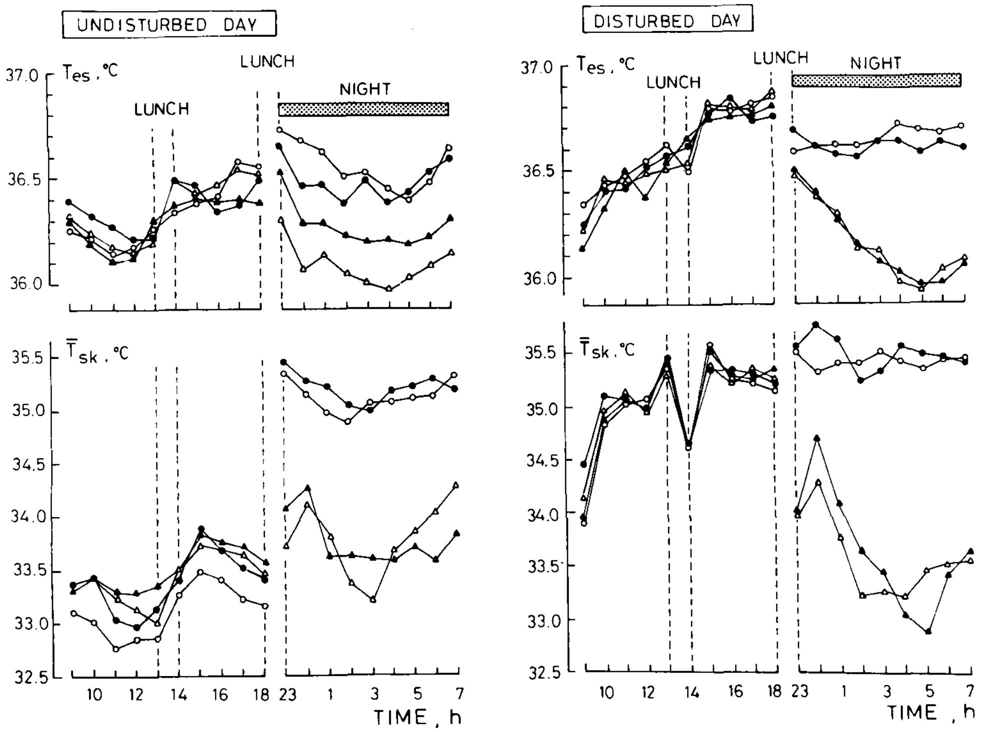

FIG. 1. Mean skin ($\bar{T}_{sk}$) and esophageal (T_{es}) temperatures recorded during daytime and night plotted against time of exposure for the different nocturnal experimental conditions: △ (20°C T_a); ▲ (20°C T_a + noise); ○ (35°C T_a); ● (35°C T_a + noise).

individual differences in how subjects adjusted to the disturbances.

The variables with significant *F* values are presented in Table 4 for each factor (noise, temperature, day) along with the significant interactions. The mean values for variables under each factor are also listed. The significant effects of noise at night were increases in number of stage changes from 90 to 108, changes toward wakening (28–35) and number of stage 1 episodes (25–32). At 35°C T_a, sleep was less efficient: TST decreased from 448 to 420 min whereas the duration of wakefulness and stage 1 increased (from 28 to 58 min and from 21 to 29 min, respectively). Sleep was also more restless, as indicated by significant increases in the total number of sleep stage changes (93–105), the number of transitions toward a wakening (27–37), the number of episodes of wakefulness (10–20), stage 1 (26–31), and of the frequency of transient activation phase (TAP) in stage 2 (0.28–0.35) and SWS (0.09–0.14).

The day disturbances only increase the number of sleep stage changes from 93 to 105. Noise interacted with day and with T_a. The daytime exposure to heat and noise caused significant ($p < 0.01$) increase in stage changes (+31%), in number of stage shifts toward wakening (+34%), and in the duration of stage 1 (+16%) when noise was not present at night. However, these sleep variables were not affected when subjects slept in noise conditions, whether the preceding day was disturbed or not. Noise did not alter the SWS barycentric point when the preceding day was undisturbed, but the barycentric point was postposed (+21.4 min; $p < 0.01$) when the day was disturbed. Noise interacted with T_a on two of the REM sleep variables (REM cycle length, REM episode length) and with frequency of TAPs during REM. The TAP frequency decreased in noise condition only at 35°C T_a (−18%; $p < 0.01$). REM cycle lengths were similar in heat and no heat conditions without noise, but in noise heat increased cycle length relative to quiet environment (+15%; $p < 0.05$). The REM episodes were shortened in heat without noise (−29%; $p < 0.01$). When noise was added, REM episodes were similar for the heat and no heat condition.

Ambient temperature interacted with daytime exposure only for the number of stage 1 episodes. The increase in this sleep stage induced by elevated T_a (+28%; $p < 0.01$) was enhanced when the night was preceded by a disturbed day (+52%; $p < 0.01$).

Analysis by thirds of night

As the above analysis clearly indicated that exposure to heat, and to a lesser extent noise, altered the quality of sleep, it was of interest to see if a within-night adaptive mechanism might exist. To examine this question variables related to sleep quality (number of awaken-

TABLE 2. *Means and standard deviations of measures of sleep quality for reference night and for the different experimental conditions*

	Night after undisturbed day				Night after disturbed day			
	20°C	20°C + noise	35°C	35°C + noise	20°C	20°C + noise	35°C	35°C + noise
TST (min)	457.6	449.9	425.4*	415.5*	435.1*	451.7	422.0*	418.0*
	19.3	18.9	25.0	53.4	19.7	17.4	39.4	53.7
Duration (min) of								
L	5.9	14.0	16.2	20.5	16.2	13.7	18.9	24.0
	3.7	12.0	17.0	20.3	17.7	10.5	22.2	20.9
Stage 1	14.8	23.2***	22.7***	30.5**	22.7*	21.7	30.7**	32.2**
	5.7	7.4	4.5	12.0	7.4	12.9	11.6	13.0
WASO	20.9	25.1	49.6*	64.7*	42.4	25.6	57.5*	58.7*
	19.5	12.4	24.6	53.1	21.0	15.7	34.8	54.6
Number of								
Stage change toward wakening	18.6	31.5**	29.1**	39.2**	25.0**	31.1**	39.0**	40.1**
	9.1	11.8	10.3	12.2	7.7	10.9	10.7	19.5
WASO	8.4	12.5*	15.6*	18.5**	9.5	11.6*	25.9*	20.0*
	4.7	7.7	8.1	11.3	5.0	7.1	24.1	15.0
Stage 1	16.5	29.9**	26.0**	33.5**	22.2*	26.5**	36.1**	38.0**
	6.8	9.1	9.3	10.5	7.4	12.2	11.1	19.2
Stage change	66.1	100.6**	89.5**	114.7**	82.6*	97.9**	120.9**	118.7**
	15.1	20.0	24.2	25.4	18.2	23.0	25.3	38.7
Frequency TAP (number per min) in								
Total sleep	0.225	0.277*	0.296	0.287**	0.236	0.265*	0.327*	0.300*
	0.069	0.105	0.145	0.081	0.075	0.089	0.122	0.131
Stage 2	0.240	0.327*	0.352*	0.317*	0.264	0.275	0.380**	0.351*
	0.096	0.149	0.164	0.105	0.138	0.129	0.131	0.188
SWS	0.061	0.097*	0.110*	0.150**	0.086*	0.115	0.170**	0.145**
	0.028	0.047	0.072	0.077	0.041	0.101	0.093	0.060
REM	0.327	0.312	0.317	0.284	0.311	0.349	0.337	0.260
	0.146	0.088	0.190	0.182	0.107	0.135	0.156	0.134

TST, total sleep time; L, sleep latency; WASO, wakefulness after sleep onset; TAP, transient activation phase. Pairwise comparisons between reference night and the seven treatment nights are indicated by asterisks: *$p < 0.05$; **$p < 0.01$, ***$p < 0.001$ or less.

TABLE 3. *Means and standard deviations of the sleep structure for reference night and for the different experimental conditions*

	Night after undisturbed day				Night after disturbed day			
Night	20°C	20°C + noise	35°C	35°C + noise	20°C	20°C + noise	35°C	35°C + noise
SWS (%)	22.2	20.6	21.4	22.0	23.8	20.3	19.3	16.1
	0.5	0.5	1.4	0.9	0.4	0.8	0.7	0.4
REM (%)	27.3	22.0	23.8	23.4	24.6	23.3	21.5	21.0
	0.3	0.5	0.4	0.4	0.3	0.1	0.2	0.4
Stage 2 (%)	46.4	50.8	48.1	46.3	45.8	50.8	51.3	53.4
	7.9	6.4	8.2	9.0	8.2	6.7	6.0	5.6
REM latency (min)	80.4	97.4	87.4	104.0	96.3	106.7	116.2	112.7
	20.4	45.2	26.6	20.8	28.0	51.2	48.1	56.9
REM episode length (min)	41.4	25.9*	26.0*	26.7**	30.0	29.6*	24.4*	30.9
	13.5	6.6	7.7	6.3	17.1	5.2	10.9	10.7
REM cycle length (min)	113.5	101.6	116.2	122.7	118.7	113.1	111.0	123.5
	26.9	8.8	21.4	43.5	47.3	18.3	43.7	23.0
Barycentric point for								
SWS (min)	160.9	154.7	180.5	184.5	135.6	167.2	181.2	192.0
	63.0	33.1	32.4	28.4	20.1	32.2	62.5	64.4
REM (min)	305.9	301.4	293.0	278.7	294.9	306.1	294.4	275.0
	37.7	27.8	33.8	27.2	22.6	32.7	18.4	36.2

The durations of SWS and REM sleep are in percentage of total sleep time. Pairwise comparisons between reference night and the seven treatment nights are indicated by asterisks: *$p < 0.05$; **$p < 0.01$.

TABLE 4. *Results of the analysis of variance with means, F, and p values*

	Means		*F* values	p values
Main effects of noise	No noise	Noise		
Number of stage changes	89.8	108.0	8.20	0.024
Number of stage changes toward awakening	27.9	35.5	8.38	0.023
Number of stage 1 episodes	25.2	32.0	5.82	0.047
Main effects of air temperature (T)	20°C	35°C		
TST (min)	448.5	420.3	7.19	0.031
Number of stage changes	92.8	105.0	27.49	0.001
Number of stage changes toward awakening	26.6	36.9	39.29	0.001
Number of WASO	10.5	20.0	13.23	0.008
Number of stage 1 episodes	26.5	30.7	38.30	0.001
Duration (%) of WASO	6.3	13.7	16.17	0.005
Duration (%) of stage 1 episode	4.4	6.8	18.46	0.004
Frequency TAP				
TST	0.251	0.303	5.86	0.046
SWS	0.090	0.144	11.10	0.013
Stage 2	0.277	0.350	10.25	0.015
Main effects of Day	Undisturbed	Disturbed		
Number of stage changes	92.7	105.0	8.37	0.040
	Interactions			
Number of stage changes	N × D		9.04	0.020
Number of stage changes toward awakening	N × D		6.51	0.038
Duration of stage 1	N × D		8.53	0.022
Barycentric point SWS (min)	N × D		8.38	0.023
REM cycle length (min)	N × T		5.74	0.048
REM episode length (min)	N × T		9.62	0.017
Frequency TAP during REM	N × T		12.68	0.009
Number of stage 1 episode	D × T		9.64	0.017

For definitions of sleep variables see Tables 2 and 3.

ings, sleep stage changes, changes toward wakening, duration of wakefulness, and TAP frequency) were examined by thirds of night. The ANOVA results are shown in Table 5. No within-night adaptation occurred. All sleep quality measures indicated that poorer sleep was present during the second and third parts of the night. Only frequency of TAPs showed a significant change in all thirds of the night.

Pairwise comparisons

The ANOVA indicated that the presence of heat and noise during the day did not reduce or intensify the impact of nighttime heat and/or noise on sleep except for number of stage changes. Pairwise comparisons of sleep following disturbed day versus undisturbed day gave similar results.

The relative effects of heat and of noise on sleep were examined by comparing sleep measures during exposure to noise and exposure to heat following an undisturbed day. Results indicated that heat when compared to noise reduced TST (p = 0.028). None of the other sleep measures showed a significant difference.

The relative effects of the seven treatment conditions were examined by comparing appropriate sleep measures for each treatment condition with those for the reference night. The asterisks beside mean values in Tables 2 and 3 denote significant differences when the sleep measures for the treatment nights were compared to the reference night. The asterisks in Table 2 clearly indicate the disruption of sleep caused by noise alone and heat alone and when they were combined. The pattern of disruption was the same regardless of whether the preceding day was disturbed or not, especially for heat and heat plus noise. In all instances except one, frequency of TAPs in TST following an undisturbed day, the disruption of sleep caused by heat plus noise was present when heat alone was present. In this single instance, the p value was 0.055. In seven instances, noise alone did not produce the significant change in a sleep measure that was seen during heat or heat plus noise. The ANOVA indicated that only three *F* values related to the architecture of sleep were significant. Of these three, REM cycle and REM episode length and barycentric point SWS, only REM episode length was significantly reduced by noise and heat when compared to the reference night.

Subjective evaluation of sleep

Five questions on the morning sleep questionnaire pertaining to the previous night sleep were examined. These five were estimates of sleep latency in minute, number of awakenings, and three questions pertaining to quality of sleep: profound versus superficial, calm versus agitated, restful versus ineffective. The words of each pair anchored a line divided into seven steps and the subject had to say whether his sleep was very, some, a little, or neutral with respect to each adjective. The ANOVA indicated that there were significant *F* values for T_a for all five questions but no significant *F* values for the other two factors, noise and day. The respective *F* and p values were 4.93, p = 0.002; 6.90, p = 0.03; 7.96, p = 0.03; 14.2, p = 0.007; and 10.1, p = 0.02. The only significant interaction was T_a with noise for WASO. In the no noise condition, a T_a of 35°C produced more awakenings than a T_a of 20°C, but when noise was present awakenings were similar for both temperatures.

Pairwise comparisons of treatment nights with the

TABLE 5. *Analysis of variance for thirds of night*

	Thirds of night								
	First			Second			Third		
	Effect	*F*	p	Effect	*F*	p	Effect	*F*	p
Number of awakenings			ns	T	7.14	0.032	N × D	9.37	0.018
Number of stage changes			ns	T	7.45	0.029	T	13.82	0.007
				N	9.94	0.016	N × D	7.47	0.029
Number of stage changes toward awakening			ns	T	19.08	0.003	T	19.73	0.003
				N	7.41	0.030			
Duration of awakenings			ns				T	9.80	0.017
							N × D	8.85	0.021
Frequency TAP in total sleep	T	7.59	0.028	T	6.35	0.040	N × T	5.73	0.048

The different effects T, temperature; N, noise; D, day; and the interactions are reported with *F* and p values. TAP, frequency of transient activation phase for overall night sleep. ns = nonsignificant.

reference night indicated that for each of the five questions there was a significant impairment of sleep when heat alone and when heat plus noise were present regardless of whether the day was disturbed or undisturbed. When nights with noise were compared with nights with heat, subjects rated their sleep as more superficial and less effective when exposed to heat. There were no significant noise versus heat differences on the other three questions.

DISCUSSION

Regardless of whether the day was disturbed or not, at night under thermoneutral conditions T_{es} and $\bar{T}_{sk}$ followed a circadian pattern. Nighttime T_a of 35°C attenuated the circadian lows, and when a disturbed day preceded heat at night the circadian rhythm was abolished. Our results clearly stress the importance of daytime exposure to heat on the response patterns of both T_{es} and $\bar{T}_{sk}$ temperatures recorded during the subsequent night. However, the mean levels of body temperatures calculated for the entire night were not affected by daytime exposure to heat. The 5-h period of wakefulness in T_a 20°C prior to bedtime appears to be sufficient to eliminate the body heat accumulated during the day. This is supported by the finding that body temperatures at bedtime (11 p.m.) were not significantly affected by the diurnal conditions.

It seems that thermoregulatory mechanisms enhanced by daytime exposure to heat only modify the response patterns of $\bar{T}_{sk}$ and T_{es} of the subsequent night without affecting their mean levels. This might be explained by the fact that in our experimental condition, in dry moderate heat exposure, body temperatures will not be different from one experimental condition to another as long as the evaporative sweating is adjusted to dissipate the body heat storage.

Effects of heat and noise on sleep measures

Analysis of sleep variables showed that heat was more disruptive to sleep than was noise. The thermal load had a larger impact on the EEG measures of sleep quality than on sleep architecture. The morning questionnaires, which examined subjective estimates of sleep quality, confirmed the EEG findings. Previous investigators have generally reported that heat induces an increase in the number of awakenings and the time spent awake and decreases in SWS and REM sleep (5,6,21,22). Our findings partly support these observations. The disruptive effect of heat was clearly demonstrated by marked increases in TAPs recorded in stage 2 and in SWS, i.e., no clear change was observed in SWS and in REM sleep amounts, which is in agreement with the findings by Hénane et al. (20) and with our previous investigation (23).

Ambient temperature also interacted with noise at night. At 35°C T_a, REM episode length decreased in no noise condition whereas REM cycle lengths were unchanged. When noise was present at night, T_a did not modify the durations of REM episodes but reduced the length of REM sleep cycles. Muzet et al. (24) have suggested that the mechanisms underlying REM sleep rhythmicity might be separated from those responsible for REM maintenance. Our finding in the present experiment that these two REM sleep measures responded in opposite ways support their hypothesis. Szymusiak et al. (25) and Haskell et al. (26), however, suggested that the REM sleep changes may not reflect a specific influence of heat and probably result from a general disruption of sleep.

The sleep measures showing significant changes when only noise was present were number of stage changes, number of changes toward awakening, and number of stage 1 episodes. Thus, relative to heat, sleep appears to be more resistant to the type of traffic noise used in this experiment. This finding supports those reported by others showing that only sleep stability decreases with noise (2,3). The analysis by thirds of night showed that the arousing effects of exposure to heat and noise as reflected in frequency of TAPs were present throughout the night reflecting the sensitivity of TAPs to external disturbances. For other measures of sleep quality, significant impairment was seen in the second and third parts of the night. Adaptation did not occur and no within-night recovery mechanisms seem to exist that would protect sleep quality. Quite the opposite occurred. The shift to lower arousal levels during the latter part of the night appeared to interact with the disturbing effects of noise and heat and sleep quality was most impaired during the last third of the night.

The effect of daytime disturbance on sleep measures

Daytime exposure to combined heat and noise had little impact on the subsequent night's sleep. After a disturbed day, only sleep stability, as indicated by the increased number of stage changes, was significantly altered when compared to sleep following nondisturbed day. SWS and REM sleep durations were not significantly modified by daytime heat exposure. In contrast to our findings of minimal impact of daytime disturbance, Blois et al. (7) reported that daytime noise reduced total sleep time and REM sleep and Fruhstorfer et al. (8) reported increased SWS with a concomitant decrease in stage 2. Later Fruhstorfer et al. (27) reported that daytime exposure of 12 h duration ending 2 h before bedtime caused strained wakefulness and intensified fatigue. The need for recovery could be at the origin of the SWS increase observed during the second sleep cycle. These discrepant results might be explained by the different duration of noise exposure and/or by the elapsed time between the end of exposure to bedtime. In the present study, the ensuing period of wakefulness (5 h) following the daytime exposure could be sufficient to eliminate the fatigue induced by heat and noise exposure as the sleep disturbances are minimal. Similar findings have been reported by Bunnell et al. (12) when subjects were daily exposed to ambient heat. The data of the present study also showed that the effects of daytime exposure to heat and noise on subsequent sleep did not significantly potentiate the effects of these disturbances when presented at night.

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