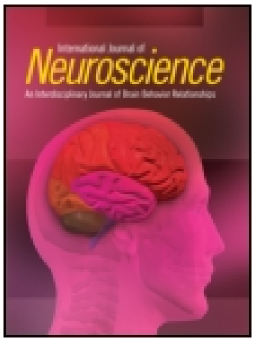

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SUBJECTIVE AND OBJECTIVE SLEEPINESS IN THE ACTIVE INDIVIDUAL

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Eight subjects were kept awake and active overnight in a sleep lab isolated from environmental time cues. Ambulatory EEG and EOG were continuously recorded and sleepiness ratings carried out every two hours as was a short EEG test session with eyes open for 5 min and closed for 2 min. The EEG was subjected to spectral analysis and the EOG was visually scored for slow rolling eye movements (SEM). Intrusions of SEM and of alpha and theta power density during waking, open-eyed activity strongly differentiated between high and low subjective sleepiness (the differentiation was poorer for closed eyes) and the mean intraindividual correlations between subjective and objective sleepiness were very high. Still, the covariation was curvilinear; physiological indices of sleepiness did not occur reliably until subjective perceptions fell between "sleepy" and "extremely sleepy-fighting sleep"; i.e. physiological changes due to sleepiness are not likely to occur until extreme sleepiness is encountered. The results support the notion that ambulatory EEG/EOG changes may be used to quantify sleepiness.

Keywords: sleepiness, spectral analysis, polysomnography, EEG, EOG, ratings

Recent analyses of spectacular accidents and catastrophes suggest that sleepiness may play an important role in such events (Mitler, et al., 1988). Systematic investigation of such links requires some objective measure of sleepiness. Dement & Carskadon (1982) have operationalized the latter concept as the speed with which an individual falls asleep, that is, proceeds from the EEG alpha activity (8–12 Hz) of relaxed alertness to the theta activity (4–8 Hz) of the first stage of sleep. This "sleep latency test" has become the established objective measure of sleepiness. This test, however, requires the subject to be lying down with eyes closed in a dark room, and is obviously ill suited for continuous monitoring of the active, open-eyed subject engaged in normal activity. The few studies available on active subjects with open eyes clearly indicate that alpha and theta activity of the EEG may reflect also sleepiness under such conditions (Fruhstorfer, Langanke, Meinzer, Peter, & Pfaff, 1977; O'Hanlon, & Kelley, 1977b), as well as reduced performance (Daniel, 1967; Horvath, Frantik, Kopriva, & Meissner, 1976; O'Hanlon, & Beatty, 1977a). However, then it is the appearance of alpha activity that signals alertness, in contrast to its disappearance, as is the case under conditions of closed eyes (Santamaria, & Chiappa, 1987).

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This paper is dedicated to the memory of our friend and colleague Lars Torsvall who died on the 10th August, 1989.
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In our own work we have brought EEG/EOG methods into the field for long term ambulatory recording of sleepiness in normal life situations. For this purpose we have used small portable 4-channel Medilog tape recorders to collect data and developed techniques for high speed spectral analysis by computer. In one study of train drivers we found that, during the night drive, rated sleepiness increased pronouncedly, as did alpha, theta, and delta power density as well as slow rolling eye movements (SEM) (Torsvall, & Åkerstedt, 1987). Furthermore, the intercorrelations between these variables were high. In particular, perceived sleepiness was closely reflected in increased alpha and theta activity, as well as in an increased number of SEMs.

However, in order to interpret EEG/EOG data from field studies in behavioral–operational terms one would need absolute criteria for critical levels of subjective and behavioral alertness obtained under well controlled conditions. In an initial experiment (Torsvall, & Åkerstedt, 1988) we therefore describe the changes accompanying the extreme sleepiness immediately precipitating an incident of "dozing off." This critical point was characterized by very large increases in alpha and theta power density as well as in slow eye movement activity. This study was strictly controlled with respect to head (and body) position, and no subjective ratings could be obtained since ratings would have interfered with the falling asleep process.

In the present experiment we sought to describe the EEG/EOG effects of severe sleepiness under more natural, ad lib. conditions and to compare these to controlled conditions. A second purpose was to study the correspondence between EEG/EOG changes and subjective sleepiness.

METHODS

Eight male subjects (age 25–47 years of age) were recruited from the institutes involved and participated on normal paid work time (including overtime). The experiment took place in a sleep laboratory which was isolated from all environmental time cues (no clocks, radio, TV or natural light). The subjects arrived at the laboratory at 2000h, were equipped with a recording device and received practice at the various tasks. The recording was started at 2230h and continued to 1100h the next day. During most of this time the subjects were allowed to carry out their own preferred activities such as reading, writing or pursuing hobbies. Lying down, sleeping, or vigorous physical activity were not allowed. An experimenter monitored the behavior to ensure compliance. Every two hours the subjects rated their sleepiness, carried out a 7 min EEG/EOG test and had a small snack.

The electrophysiological recording was carried out using a portable 4-channel tape recorder (Medilog). The EEG was obtained from a CzOz derivation and the EOG from an oblique bipolar derivation. For the EEG/EOG test the subject was seated in a straight-backed chair focussing on a spot at eye level at a distance of one meter. After five minutes the subject was asked to close his eyes while remaining seated in the same position for two additional minutes. The five minutes of open eyes was compromise between wanting to ensure that the activation resulting from being transferred to the test situation would have subsided and wanting to avoid exposing the subject to a long monotonous situation. The two minutes of closed eyes was chosen since we were interested mainly in the early effects of eye closure and since we wanted to avoid allowing the subjects any sleep (the subjects could not be monitored since they were recorded in an ambulatory state and were not connected to any display equipment).

Before the test the subjects rated their sleepiness on two scales. One was a 100 mm visual analog scale (VAS) from "very sleepy" to "very alert." The other one was a 9 point verbally anchored scale (Karolinska Sleepiness Scale – KSS) with the following steps: "extremely alert" (score = 1), "alert" (3), "neither alert nor sleepy" (5), "sleepy—but no difficulty remaining awake" (7), "Extremely sleepy—fighting sleep" (9). The steps in between had a scale value but no verbal label.

The EEG and EOG were first replayed on paper and artifacts were identified for removal from computations. The EEG was then fed through a spectrum analyzer (Princeton Instruments) at 30 times the recording speed. The analysis epoch was set to 15 seconds and the resulting power spectra were stored and smoothed in a PDP 11/23 computer. All tapes used were calibrated using a 50 μV sine wave at 1.7 Hz. For each interval we integrated the power density across each 1 Hz band as well as across the conventional (and previously used) 0.5–3.9 Hz (delta), 4–7.9 Hz (theta), 8–12 Hz (alpha), and 13–32 Hz (beta) bands. The obtained values were then used to compute means across various time intervals as described in the results section.

The EOG was visually analyzed for slow eye movements. These were defined as involving a > 1 second slow, rolling excursion of the EOG (SEM) of at least 100 μV amplitude. The parameter obtained was the percentage of time in each minute occupied by SEMs.

The main interest of the present study was focussed on effects during conditions with open eyes. For comparative purposes, however, some of the analyses were also carried out for the 2 min test situation with eyes closed. The temporal effects were evaluated using the Friedman "ANOVA" (Siegel, 1959). For pairwise comparisons was used the Wilcoxon matched pairs signed ranks test (Siegel, 1959). Nonparametric tests were used because of skewed distributions. For mean intraindividual correlations students t-test was used after z-transformation.

RESULTS

Variation Over Time

To describe the variation over time we computed mean values for each EEG/EOG test situation from 2300h to 1100h as well as for the last 30 minutes of ad lib. activity immediately before each test session. The ratings were carried out in between these two measurements. All EEG values were expressed in relation to the value obtained at the 2300h test condition with open eyes (= 1), and SEMs were expressed as percentage of time scored.

Figure 1 shows that both types of *rating scales* varied significantly across time (Friedman χ^2 for df:6 = 29, $p < .001$ for both variables). Their mean intraindividual correlation was (after z transformation) $r = .93 + 0.02$ ($t = 40.6$; $p < .00001$) with a regression of $y = .0852X + 1.12$.

Also SEM (30, $p < .001$) and alpha (25, $p < .001$) and theta (26, $p < .001$) power density from the test condition with *open eyes* varied significantly over time with peak values between 0500h and 0900h (Fig. 1). Delta and beta power did not exhibit any significant variation over time.

For the *ambulatory* condition there was a significant variation over time for both alpha (29, $p < .001$) and theta (14, $p < .05$) power density with peaks during the morning. SEM turned out to be very difficult to score and is not included in this presentation. No significant difference in level was found between the ambulatory and test conditions (Wilcoxon). The mean intraindividual correlations (across time) reached $r = .53 \pm 0.13$ ($t = 4.0$, $p < .01$) for alpha power and $r = .45 \pm 0.15$ ($t = 2.9$, $p < .05$) for theta power.

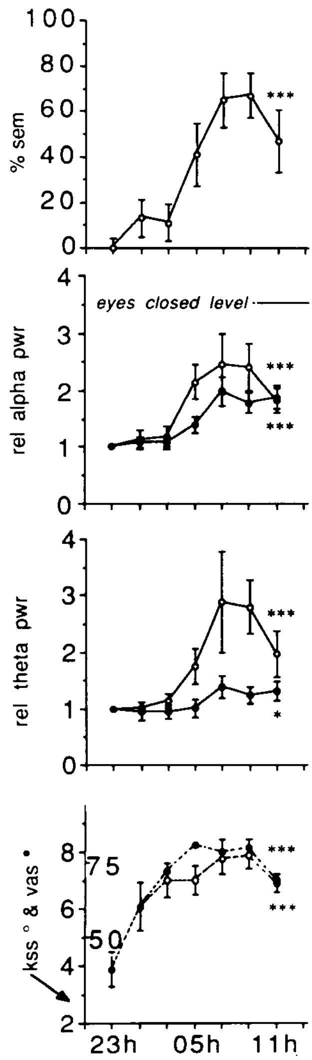

FIGURE 1 Mean (+ —standard error) for all variables at 2 hour intervals. In the three upper panels filled circles represent the ambulatory conditions and open circles the test session with open eyes
In the lower panel filled circles (with broken lines) indicate results on the VAS scale and open circles results on the KSS scale. $^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$ for the Friedman nonparametric Anova across time.

For the *eyes closed* condition (not in the figure) the variation over time was weakly significant for alpha (15, $p < .05$) and theta (15, $p < .05$) power density as well as for SEM (14, $p < .05$). Delta and beta power density did not vary significantly.

Relations Between Subjective and Physiological Variables

To illustrate the difference in EEG/EOG parameters between high and low sleepiness we selected the *test situations* with maximum and minimum sleepiness, respectively, and contrasted them. The scale values were 8.6(.3) vs 3.1(.6) and 89(7) vs 34(6) for the

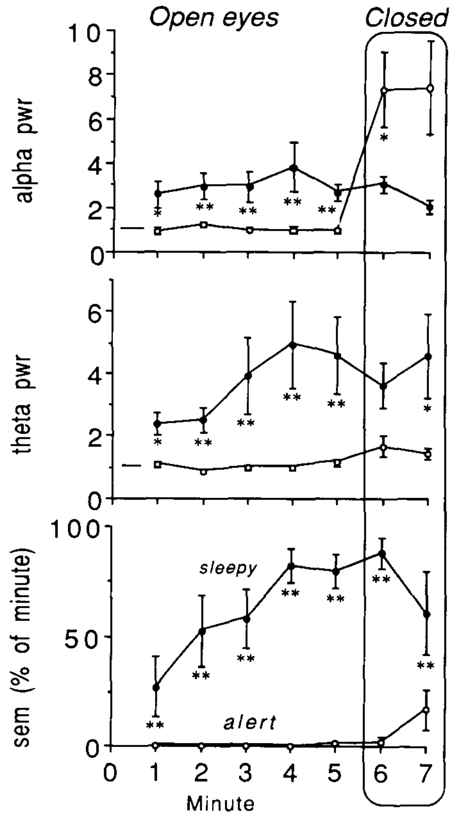

FIGURE 2 Mean (+ − standard error) for EEG and EOG variables during the 5 minutes with open eyes and 2 minutes with closed eyes for the most sleepy and most alert condition
Asterisks indicate significant deviation according to the Wilcoxon test (maximum level for 7 *df* $p < .01$).

KSS and VAS, respectively. On the KSS scale the maximum value comes very close to the verbal anchor "extremely sleepy, fighting sleep," whereas the minimum value corresponds to the rating "alert."

As in previous studies, power density for the conventional bands was expressed as a proportion of the value with eyes open during the 2300h test situation. SEMs were expressed as the percentage of each minute occupied by SEMs. Figure 2 shows that the alert condition was characterized by a low alpha power density with eyes open, followed by a strong increase upon eye closure. Theta power density and the proportion of SEM were very low throughout both the 5 minutes with eyes open and the 2 minutes with eyes closed. In contrast, the condition with maximum sleepiness showed a strong and significant (Wilcoxon) increase in all three parameters for the 5 minutes with open eyes. This effect disappeared somewhat during eye closure. For alpha power the usual enhancement by eye closure actually failed to appear. No significant effects were seen for beta or delta power density.

To obtain a higher resolution for the EEG changes we also carried out an analysis similar to the one above but for individual *1 Hz bands*. Means were computed across the five minutes of open eyes and the two minutes of closed eyes, respectively. Under the open eyes condition there was a significant ($p < .05$) increase in power density

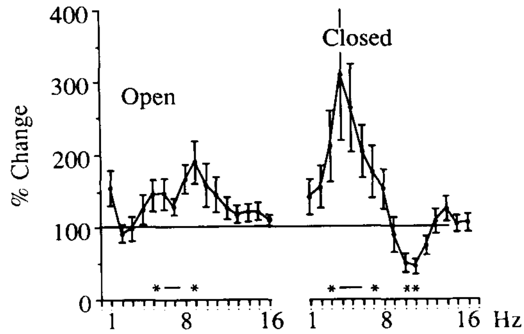

FIGURE 3 Mean (+ −standard error) deviation of the most sleepy condition from the most alert condition for the power density spectrum in 1 Hz bands
Asterisks indicate significant difference between conditions (Wilcoxon).

for all bands from 5 to 9 Hz, the maximum increase reaching 90% for the 9 Hz band (Figure 3). Under the closed eyes condition there was a significant increase in the 3 to 7 Hz bands and a significant *decrease* in the 10 and 11 Hz bands. The increase reached a maximum of 140% at 4 Hz and the decrease a maximum of 60% at 11 Hz.

As a further check on the association between subjective sleepiness and the EEG/EOG variables *intraindividual correlations* were computed (Table 1). All conditions and variables showed significant mean correlations except for theta power with closed eyes. Delta and beta power density were not entered in the computations since they did not differ significantly between the sleepy and alert conditions. The correlations using the VAS scale were virtually identical to those with the KSS scale.

Figure 4 shows a more detailed analysis of the relation between subjective and physiological sleepiness. Five "bins" were constructed from the rating scales: 0–45, 46–65, 66–75, 76–85, 86–100 for the visual analog scale, corresponding to 1–4, 5–6, 7, 8, and 9 for the KSS scale. For each bin the corresponding EEG/EOG data were averaged and subjected to a Friedman nonparametric "analysis of variance" across the five bins. All variables from the test session with open eyes and the ambulatory condition, except theta activity during the latter, showed a significant variation across the different levels of subjective sleepiness. However, all variables showed a significant difference between maximum and minimum sleepiness (Wilcoxon, $z > 2.20$, $p <$

TABLE 1
Mean intraindividual correlations (standard error) between ratings and EEG/EOG variables, as well as associated probabilities for t-test against the null hypothesis (after z-transformation).

	KSS	VAS
alpha open	.53(.15)**	.53(.16)*
theta open	.53(.11)***	.52(.08)***
SEM open	.65(.04)***	.61(.05)***
alpha amb	.50(.04)***	.49(.05)***
theta amb	.29(.09)*	.53(.10)**
alpha closed	.56(.20)*	.51(.20)*
theta closed	.43(.19)	.43(.17)*
SEM closed	.57(.12)**	.46(.13)**

*$p < .05$, **$p < .01$, ***$p < .001$.

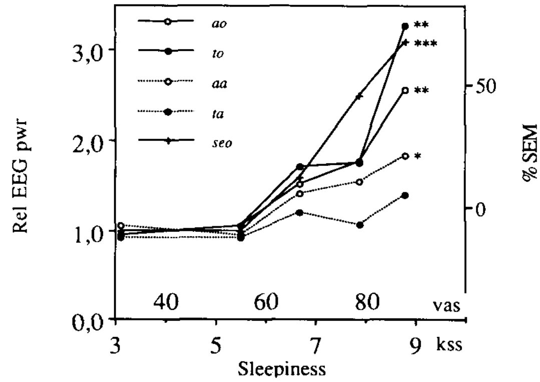

FIGURE 4 Mean level for EEG and EOG variables at different bins of subjective sleepiness. ao = alpha power with open eyes, to = dito theta, seo = dito sem; aa = alpha power during the ambulatory condition, ta dito theta, Asterisks indicate level of significance according to the Friedman nonparametric Anova computed across the 5 bins (4 *df*).

.05). From the figure it is evident that no EEG/EOG changes occurred until level 7 or 70 is reached on the KSS and VAS scales, respectively. For the test session with closed eyes only SEM showed a significant variation across bins ($\chi^2 = 13.6, p < .01$).

DISCUSSION

The EEG results clearly demonstrate that subjective sleepiness is reflected in increased levels of energy in the alpha and theta bands under the condition of open eyes. These results agree with earlier work (Daniel, 1967; Fruhstorfer, et al., 1977; Horvath, et al., 1976; O'Hanlon, et al., 1977a; O'Hanlon, et al., 1977b; Torsvall, et al., 1987; Torsvall, et al., 1988).

In addition, we found that the changes in the EEG did not appear until the subjective sleepiness is considerable, i.e., not until the subject rates himself as "sleepy" or close to "very sleepy, fighting sleep." This means that the EEG changes do not appear until the subjective symptoms of sleepiness become manifest, for example, as difficulties keeping ones eyes open, as an inability to focus, or as itching eyes, etc. Thus, one should not expect to find any relation between EEG alpha or theta activity on the one hand and subjective sleepiness or performance on the other if sleepiness only varies within the normal daily range (from "alert" to "somewhat sleepy").

At maximum sleepiness the test session with open eyes demonstrated that the EEG changes were already present during the first minute, although some increase across the five minutes was seen, particularly for theta power. The eyes closed condition was less efficient in differentiating the sleepy and alert states. One reason for this is probably that the falling asleep process started immediately upon eye closure and that this process proceeds with different speeds in different individuals. Still, the speed was impressive since the normal increase in alpha activity upon eye closure failed to appear, or rather was so rapidly replaced by theta activity that the one minute mean values failed to show any change. The results clearly suggest that conditions with open eyes are more likely to respond reliably to severe sleepiness than conditions with closed eyes.

The ambulatory condition showed responses to sleepiness similar to those of the test session. The conditions were reasonably well correlated considering the fact that the values from the ambulatory condition were obtained after averaging across 30 minutes, thus probably involving considerable variation in sleepiness. The latter probably also contributed to the weaker ability to differentiate between alertness and sleepiness. This weaker ability to differentiate also raises the question of whether averaging power values across time is the optimal approach to identifying sleepiness in ambulatory subjects. Still, the percentage increase from baseline for both EEG parameters (80% and 40% for alpha and theta power, respectively) were remarkably similar to those from the study of train drivers (Torsvall, et al., 1987). Possibly, the values obtained could serve as rough criteria of sleepiness in field studies.

Although it is rather difficult to determine which variable was most successful at differentiating sleepiness from alertness it seems that SEM during the test session with eyes open is most sensitive. The correlation with subjective sleepiness was close and the increase during the five minutes was dramatic. Towards the end the EOG was dominated by slow undulating patterns. Similar SEM activity was seen in our previous laboratory study (Torsvall, et al., 1988) and in our study of train drivers (Torsvall, et al., 1987).

The pattern of slow eye movements during sleepiness with "open eyes" suggest that the session tended to become a session with alternation between open and almost closed eyes. This, presumably, was one of the major reasons for the increase in alpha activity. In one of our previous studies (Torsvall, & Åkerstedt, 1985) we demonstrated that the increase in alpha power density during sleepiness corresponded to a 10-fold increase in blink duration. Incidentially, the same study demonstrated that theta activity was not affected by blink duration whereas delta activity approximately doubled when blink duration increased from 0.2 to 2.0 seconds.

If only the test session were considered one would be tempted to draw the conclusion that SEM would be the parameter of choice to identify sleepiness. SEM could not, however, be scored reliably for the ambulatory condition since blinks and rapid eye movement interfered. The reason that we were able to score this variable in the study of ad lib. train drivers was probably that the drivers were seated during the recording and were keeping their eyes focussed on the track ahead. Thus, it seems that SEM may be difficult to use in many ad lib. ambulatory conditions.

One particular problem in studies of the present type tends to be the differences between individuals. In the present study three out of eight individuals showed responses to sleepiness that deviated from the expected. One subject was unable to maintain alpha activity for more than 30 to 40 seconds with closed eyes. However, with increasing sleepiness the subject would start to oscillate between alertness and sleepiness, leading to an oscillation in the EEG between alpha and theta activity. As a consequence the amount of alpha activity with eyes closed would in this subject *increase* with increasing sleepiness. Another subject suffered from borderline excessive daytime sleepiness and showed much alpha activity with eyes open, even when at maximum alertness. When maximally sleepy this subject, still with his eyes open, shifted from alpha to theta activity and thus showed a *decrease* in alpha activity. A third subject had a very large amplitude alpha activity which spread into the (formal) theta band. When this subject closed his eyes while sleepy there was the expected reduction of alpha activity, but also a *decrease* in the theta activity that had previously been inflated by the "overflow" of alpha activity into the theta band. These observations suggest the need for individual "calibration" of sleepiness effects during the initial parts of a study of EEG effects of sleepiness.

The need for another subdivision than the traditional into theta and alpha bands is also supported by the analysis based on 1 Hz bands. Thus, we found that the increase due to high sleepiness in subjects with their eyes open affected the band from 5 to 9 Hz. During the eyes closed condition power increased in the 3 to 7 Hz band and decreased in the 10 to 11 Hz band. Clearly, a more flexible approach in selecting bands might improve the precision of EEG parameters as indicators of sleepiness.

In conclusion, we have found that the EEG and EOG during conditions of open eyes sensitively identify states of severe sleepiness, and that at least the EEG parameters may be used successfully for this purpose in ambulatory subjects.

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