Continuous Probabilistic Modeling of the Sleep Process

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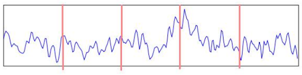
Introduction

We present a continuous probabilistic sleep model. We describe sleep stages via posterior probabilities of a finite number of states, not necessarily reflecting the standardized Rechtschaffen and Kales (RK) sleep stages. Our goal is to overcome existing limits of the RK rules by using a **finer temporal resolution** (3 sec instead of 30 sec), a **finer sleep structure resolution** (from 10 up to 35 states instead of Wake, N1, N2, N3, REM) and **continuous sleep profiling** instead of the discrete RK staging.

We contrast statistics derived from the state posteriors with the objective results of psychometric tests and questionnaires reflecting the quality of sleep. In addition, we re-combine states with the aim to define areas of higher correlations to sleep quality. We demonstrate that these statistics are in general superior to their counterparts defined by the RK labels.

Methods

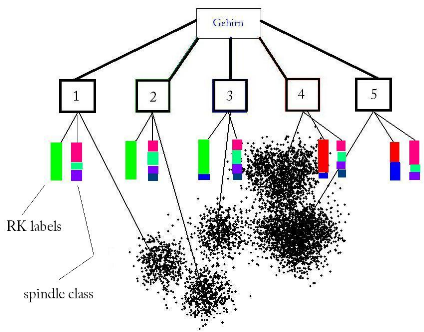
We use the C3-M2 (and C4-M2 as a substitute) EEG channel. To unify laboratory differences we downsample data to 100 Hz and bandpass filter data with a Butterworth filter of order 8 and a frequency range of 0.4 to 40 Hz.



For each 3 sec segment a AR(10) model is fitted:
$X_t = a_1 X_{t-1} + a_2 X_{t-2} + \ldots + a_{10} X_{t-10} + e_t$
To each 3 sec interval a value $s \in \{0, 1, 2, 3\}$ is assigned (0: no spindle, 1,2,3: spindle with increasing certainty). The RK labels c are assigned by the automatic sleep scoring system, Somnolyzer24x7, to each 30 sec long data segment.

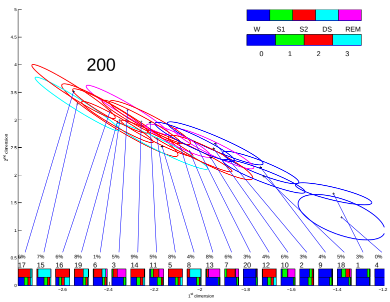
The separator model (SM; that is, the Gaussian Mixture Model with 2 attached class labels) assumes the existence of a latent variable Z with K possible states and

$$p(a, c, s) = \sum_{z=1}^{K} p(z) p(a|z) p_R(c|z) p_S(s|z)$$



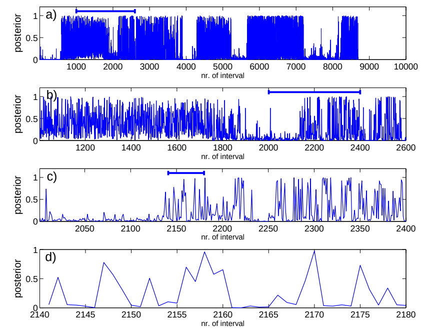
Fitting of a model

Two night PSG recordings of 175 healthy subjects between 20 and 95 were used. The RK scorings were available for each recording. Models were fitted using the EM algorithm.



The fitted Gaussians $p(a|z)$ (2 of 10 dimensions) and fitted RK and spindle class probabilities are depicted (K=20). Bootstrap simulations showed that the number K can be as high as 35 (criterion: likelihood or conditional log-likelihood on independent test sets).

Applying a model



Posteriors for a subset merging Deep Sleep and spindle-rich N2 states.

Applying a model means to present an observation (a, s) and to calculate the posteriors

$$p(z|a, s) = \frac{p(z) p(a|z) p_S(s|z)}{\sum_k p(k) p(a|k) p_S(s|k)}$$

or the RK posteriors

$$p(c|a, s) = \sum_{z=1}^{K} p(z|a, s) p_R(c|z)$$

Application: Maximize correlations with subset approach

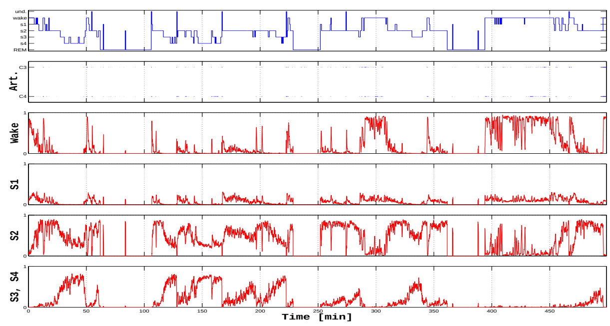
We consider 'Relative Time Spent (RTS)' in a certain state (sum of posteriors of this state over the night/number of intervals). For each sleep quality variable (SQV) we find a subset with the maximum correlation of RTS (subset) to SQV. We performed 50 runs with independent Bootstrap samples for training (fit the model), evaluating (choose the subset) and testing (judge the performance).

Var	SRAW	SRK	SORIG	RAW	RK	ORIG	
age	0.775	0.601 (0)	0.511 (0)	0.664 (0)	0.576 (0)	0.477 (0)	Average absolute correlations on the test set
psqi	0.253	0.098 (1)	0.122 (3)	0.149 (7)	0.088 (2)	0.108 (4)	
tot	0.361	0.316 (9)	0.368 (29) *	0.278 (5)	0.317 (9)	0.365 (29) *	(S)RAW: (subsets of) raw posteriors
s_qua	0.380	0.342 (8)	0.414 (31) *	0.283 (2)	0.341 (7)	0.371 (18) *	(S)RK: (Subsets of) RK posteriors
a_qua	0.242	0.151 (4)	0.182 (8)	0.146 (5)	0.125 (2)	0.182 (8)	(S)ORIG: (Subsets of) RK original
s_com	0.416	0.269 (0)	0.313 (0)	0.342 (4)	0.268 (0)	0.313 (0)	
sys_e	0.527	0.453 (0)	0.341 (0)	0.425 (0)	0.384 (0)	0.321 (0)	(): number of equal or larger correlations
drive	0.275	0.219 (8)	0.166 (4)	0.172 (2)	0.175 (3)	0.123 (0)	than SRAW
mood	0.208	0.160 (6)	0.222 (31) *	0.101 (3)	0.124 (2)	0.158 (13)	
aff	0.239	0.112 (1)	0.141 (6)	0.111 (2)	0.077 (1)	0.117 (3)	*: not significantly different from SRAW
drows	0.280	0.218 (6)	0.210 (4)	0.171 (3)	0.191 (4)	0.201 (6)	
num_m	0.458	0.286 (0)	0.204 (0)	0.420 (5)	0.282 (0)	0.199 (0)	+: different, but more often larger correlations
fma_r	0.507	0.346 (0)	0.295 (0)	0.392 (1)	0.350 (0)	0.290 (0)	

Application: Psychometric Variables & Factor Scores

Factor analysis was applied to 23 external criteria of sleep (psychometric variables). Three distinct factor scores (FS) were observed and extracted. The FS were correlated with features extracted from both the discrete RK and continuous SM sleep profiles.

Var	FS1	FS2	FS3
age	-0.010	**-0.605**	**+0.423**
psqi	**+0.238**	+0.036	+0.133
s_qua	**+0.234**	-0.133	+0.028
a_qua	**+0.542**	-0.168	+0.009
s_com	**+0.308**	-0.142	+0.133
num_m	+0.009	**+0.506**	-0.144
wb_e	**+0.433**	+0.158	-0.060
wb_m	**+0.704**	+0.141	-0.034
pul_m	-0.020	-0.027	+0.028
pul_e	-0.139	-0.064	-0.034
sys_m	+0.097	**-0.338**	**+0.771**
sys_e	+0.024	**-0.256**	**+0.831**
dia_m	+0.133	-0.033	**+0.710**
dia_e	+0.066	+0.105	**+0.731**
drive	**+0.845**	+0.037	-0.049
mood	**-0.686**	+0.081	+0.093
aff	**-0.663**	+0.164	+0.036
drows	**+0.819**	+0.075	-0.119
ad_ts	-0.088	**+0.586**	-0.160
ad_sv	+0.018	-0.002	-0.038
errp	+0.003	-0.174	-0.047
fma_r	-0.021	**+0.941**	-0.050
fma_l	+0.008	**+0.883**	+0.018



Var	1st SM	2nd SM	3rd SM	1st RK	2nd RK	3rd RK
s_qua	-.41 eff	+.40 wtsp	+.40 aW	-.41 eff	+.41 wtsp	-.34 tst
FS2	+.42 aS2	-.39 aS1	+.38 aS2q4	-.34 fw	-.33 wtsp	+.33 slR
FS3	-.39 aD	-.37 a2D	+.36 aS1q2	-.36 S4	-.35 tstS4	-.30 D

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