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Research report

Wakefulness–sleep transition: Emerging electroencephalographic similarities with the rapid eye movement phase

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Abstract

The covert-rapid eye movement (REM) sleep hypothesis of dreaming suggests that elements of REM sleep emerge during sleep onset, leading to vivid hypnagogic imagery. We tested the physiological part of this hypothesis by analysing scalp-recorded electroencephalograms of 15 human subjects during wake–sleep transition and subsequent night time sleep. Wake–sleep transition was categorised semi-automatically as alpha activity, alpha dropout and as early Stage 2 sleep. The slow oscillation, the slow and the fast subdivisions of the delta and the theta frequencies respectively, as well as alpha and sigma bands were analysed. The similarity of individual-specific wake–sleep transition periods and the whole night Stage 2 or REM sleep periods was expressed in a composite similarity measure covering the spectral power of all analysed frequency bands and in frequency-specific similarities related to power values in single bands. A significant increase in composite similarity with the whole night REM sleep emerged in the period of alpha dropout and diminished in early Stage 2 sleep. The alpha dropout period was more similar to whole night REM sleep than to whole night Stage 2 sleep. These region-independent effects were mirrored in region-specific manner by frequency bands of the delta-slow theta range. Findings are in accordance with the covert REM sleep hypothesis, with previous electrocorticographic results and with the frequency range of the sawtooth waves in humans.

Keywords: Sleep stages; Polysomnography; Delta rhythm; Theta rhythm; Alpha rhythm; Hypnagogic hallucinations

1. Introduction

Wakefulness, non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep are naturally occurring states of consciousness, differing substantially in chemical, electrical and metabolic brain processes, as well as in the characteristic subjective experiences accompanying them [9]. Although the core physiological features of these states could explain many of their phenomenological differences, the transition between wakefulness and sleep is still a kind of no mans land, as this poorly characterized period unifies some apparently unrelated features of wakefulness, NREM sleep and REM sleep. On the macrostructural level Stage 1 sleep is regarded as light NREM sleep [15]. Some quantitative EEG analyses revealed a continuous increase in NREM sleep-specific activity during this sleep stage, thus suggesting its NREM sleep-like physiology [4]. However, at the subjective level the transition between wakefulness and sleep is non-continuous, possessing transiently some characteristic features of REM sleep: i.e. vivid and bizarre hallucinatory activity [7], the dream-like quality of which depends on REM sleep pressure [13]. Moreover, frequent episodes of NREM sleep with low muscle tone were detected at sleep onset which may represent early manifestations of REM sleep [18]. However, a functional neuroimaging study concluded that the hypnagogic hallucinatory experience is in fact the dreaming state of wakefulness and not sleep [11]. Detailed EEG analyses of wakefulness–sleep transition (WST) revealed a quite complex picture consisting of nine stages with different electrophysiological features. Almost all of the nine stages could be accompanied by hypnagogic experiences, but the highest incidence was found in the fifth stage, characterized by theta activity appearing after alpha dropout/EEG flattening and before vertex sharp waves/sleep spindling [10]. The question arises if this transitional period shares some EEG features of REM sleep and if yes, what are these features? The covert REM sleep hypothesis of dreaming suggests that hidden REM-like physiological elements appear in different parts of the sleep process determining the concomitant increase in vivid, REM-type mental activity

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[12]. WST could cover such states. A parahippocampal electrocorticographic analysis of WST in epileptic patients, revealed a transitional increase in REM-like 1.5–3 Hz activity after alpha dropout, before definitive sleep spindling [1]. We hypothesize that there is a transient increase in REM-likeness of the scalp-recorded EEG activity after the alpha dropout period of WST, that is, the pre-spindle EEG shares more similarity with REM sleep than either the previous wakefulness or the subsequent NREM sleep EEG. Moreover, we hypothesize that the EEG of this transitional period is more similar to REM sleep than to Stage 2 sleep EEG.

2. Methods

2.1. Subjects and procedures

Fifteen healthy subjects free of drugs and medications as assessed by an interview and questionnaires on sleeping habits and health participated in the study (age: 17–55 years, mean: 29.07 ± 10.16 years, eight males and seven females). Subjects were paid volunteers and signed an informed consent. The study was accepted by the Ethical Committee of the Semmelweis University. Sleep was recorded in the sleep laboratory for two consecutive nights. The timing of lights off was determined by subjects' habit, and the awakenings were spontaneous. Sleep was recorded by standard polysomnography, including electroencephalography (recording sites: Fp1, Fp2, F3, F4, Fz, F7, F8, C3, C4, Cz, P3, P4, T3, T4, T5, T6, O1, O2), left- and right electro-oculography (EOG), bipolar submental electromyography (EMG) and electrocardiography (ECG). EEG electrodes were referred to the contralateral mastoid. We used the right mastoid as a reference for the midline EEG electrodes. Impedances for the EEG electrodes were kept below 5 kΩ. Signals were collected, pre-filtered, amplified and digitized at a sampling rate of 249 Hz/channel by using the 30 channel Flat Style SLEEP La Mont Headbox with implemented second order filters at 0.5 Hz (high pass) and 70 Hz (low pass) as well as the HBX32-SLP 32 channel preamplifier (La Mont Medical Inc. USA). An additional 50 Hz digital notch filtering performed by the DataLab acquisition software (Medcare, Iceland) was carried out before data analysis.

2.2. EEG analyses

Wakefulness and sleep stages of the second night recordings were identified manually according to the standardised criteria [15]. Scored recordings were ravelled in 4 s epochs. Epochs containing artefacts were excluded from further analyses. This was done by visual inspection of the EEG, EMG, EOG and ECG signals. Epochs of the WST period were categorised into three substages (Fig. 1): the alpha-dominated state contained 1 min (15 epochs) of visually striking posterior alpha activity in pre-sleep wakefulness (manually-selected baseline) plus the subsequent pre-Stage 2 epochs containing more than 50% alpha activity of baseline (WSTa); the alpha dropout periods contained less than 50% alpha activity of the baseline in the pre-Stage 2 period (WSTs1); the early Stage 2 sleep contained 1 min of NREM Stage 2 sleep from the first visually detectable K-complex or sleep spindle (WSTs2). The selection of epochs containing more or less than 50% of the baseline 1 min alpha activity was performed in a derivation-specific manner (each EEG derivations' pre-Stage 2 epochs were categorised on the basis of that specific channels' baseline alpha activity). The amount of EEG derivation-specific alpha activity in pre-Stage 2 epochs was determined automatically by fast-Fourier transformation (FFT) as described below.

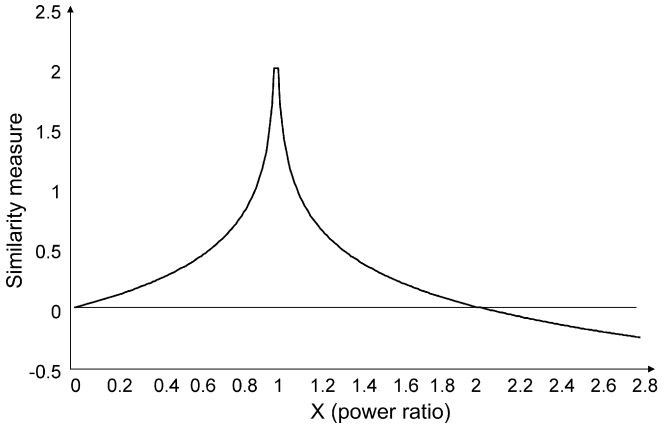

Fig. 2. The similarity measure as a function of the power ratio. Higher similarities (ratios close to 1) result in higher similarity measures.

Epochs of the EEG derivations F3, F4, Fz, C3, C4, Cz, P3, P4, O1, O2, T3 and T4 were Hanning-tapered and zero-padded to 4096 points (16.45 s) then subjected to FFT in order to calculate the average power spectra of the whole night Stage 2 sleep, REM sleep and of the WST substages. The above analyses resulted in periodograms of 0.06 Hz resolution. For purposes of comparability we divided the low frequency EEG bands in subdivisions which closely correspond to those used in a previous study [1]. This was done by finding the closest frequency bin to the frequency limits used in that study. These were the slow oscillation (0.48–1.27 Hz), and the alternating ~1.25–1.50 Hz wide subdivisions of the delta/theta ranges as follows: Delta-1: 1.51–2.97 Hz; Delta-2: 3.22–4.49 Hz; Theta-1: 4.74–6.26 Hz; Theta-2: 6.50–7.72 Hz. Additionally alpha (8.02–11.97 Hz) and sigma (12.27–15.01 Hz) bands were also analysed.

In order to detect the similarities of WST substages with Stage 2 and REM sleep each individuals, each WST power value was divided by the respective value of the REM and Stage 2 sleep power spectra. Resulting ratios (x) were subjected to a data transformation expressing the absolute distance from complete similarity ($|1-x|$) and inverted ($1/|1-x|$) to get higher values for higher similarity. As this function is an exponential one it was log-transformed: Similarity measure = $\log_{10}(1/|1-x|)$. Although there was no case of complete similarity ($x=1$) in our data, this possibility would cause a problem of division by zero. Therefore we handled this possibility by redefining the function for x values falling between 0.99 and 1.01. Similarity measures for x values in this range were given a constant value of 2.00, which is equal to the output of the similarity formula at $x=0.99$ and $x=1.01$ (Fig. 2).

Data from the 12 recording sites were grouped by averaging the scores from three brain regions: fronto-central: F3, F4, Fz, C3, C4, Cz; parieto-occipital: P3, P4, O1, O2; and temporal: T3, T4. In addition, these frequency-specific

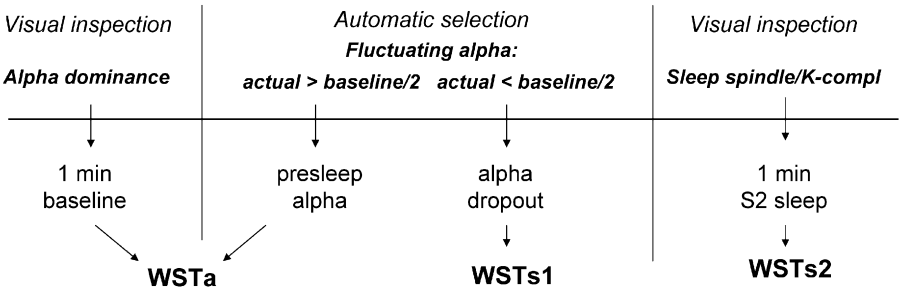

Fig. 1. Semi-automatic categorisation of the wakefulness–sleep transition (WST) period in three substages. WSTa—alpha-dominated EEG activity before sleep; WSTs1—periods of diminishing EEG alpha activity; WSTs2—early Stage 2 sleep.