International Journal of Psychophysiology 89 (2013) 252–258

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Modulation of gamma and spindle-range power by slow oscillations in scalp sleep EEG of children

Giovanni Piantoni [a], Rebecca G. Astill [a], Roy J.E.M. Raymann [a,b], José C. Vis [a,c], Joris E. Coppens [d], Eus J.W. Van Someren [a,e,f,*]

[a] Department of Sleep and Cognition, Netherlands Institute for Neuroscience, an institute of the Royal Netherlands Academy of Arts and Sciences, Amsterdam, The Netherlands
[b] Philips Group Innovation—Research, Brain, Body & Behavior Department, Eindhoven, The Netherlands
[c] Sleepvision, Berg en Dal, The Netherlands
[d] Department of Technology and Software Development, Netherlands Institute for Neuroscience, an institute of the Royal Netherlands Academy of Arts and Sciences, Amsterdam, The Netherlands
[e] Department of Integrative Neurophysiology, Center for Neurogenomics and Cognitive Research (CNCR), Neuroscience Campus Amsterdam, VU University, Amsterdam, The Netherlands
[f] Department of Medical Psychology, VU University Medical Center, Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 8 December 2012
Received in revised form 29 January 2013
Accepted 31 January 2013
Available online 8 February 2013

Keywords:
Sleep
Electroencephalography
Slow oscillation
Spindles
Gamma
Development
Synaptic density
Children

ABSTRACT

Deep sleep is characterized by slow waves of electrical activity in the cerebral cortex. They represent alternating down states and up states of, respectively, hyperpolarization with accompanying neuronal silence and depolarization during which neuronal firing resumes. The up states give rise to faster oscillations, notably spindles and gamma activity which appear to be of major importance to the role of sleep in brain function and cognition. Unfortunately, while spindles are easily detectable, gamma oscillations are of very small amplitude. No previous sleep study has succeeded in demonstrating modulations of gamma power along the time course of slow waves in human scalp EEG. As a consequence, progress in our understanding of the functional role of gamma modulation during sleep has been limited to animal studies and exceptional human studies, notably those of intracranial recordings in epileptic patients.

Because high synaptic density, which peaks some time before puberty depending on the brain region (Huttenlocher and Dabholkar, 1997), generates oscillations of larger amplitude, we considered that the best chance to demonstrate a modulation of gamma power by slow wave phase in regular scalp sleep EEG would be in school-aged children. Sleep EEG was recorded in 30 healthy children (aged 10.7 ± 0.8 years; mean ± s.d.). Time-frequency analysis was applied to evaluate the time course of spectral power along the development of a slow wave. Moreover, we attempted to modify sleep architecture and sleep characteristics through automated acoustic stimulation coupled to the occurrence of slow waves in one subset of the children.

Gamma power increased on the rising slope and positive peak of the slow wave. Gamma and spindle activity is strongly suppressed during the negative peak. There were no differences between the groups who received and did not receive acoustic stimulation in the sleep parameters and slow wave-locked time-frequency analysis. Our findings show, for the first time in scalp EEG in humans, that gamma activity is associated with the up-going slope and peak of the slow wave. We propose that studies in children provide a uniquely feasible opportunity to conduct investigations into the role of gamma during sleep.

1. Introduction

A most characteristic electrophysiological feature of non-rapid eye movement (NREM) sleep is the slow oscillation, visible on scalp electroencephalography (EEG) as a biphasic wave of high amplitude and a fundamental frequency of around 1 Hz (Achermann and Borbély, 1997). This slow oscillation, or slow wave, is the result of the alternation of periods of extended synchronization and desynchronization of the membrane potentials of numerous cerebral cortical neurons (Steriade et al., 1993). During the hyperpolarized phase, often called down state, neurons remain silent for up to a few hundred milliseconds. During the depolarized phase, also called up state, neuronal spike activity takes place, often including burst firing (Steriade et al., 1993).

* Corresponding author at: Department of Sleep and Cognition, Netherlands Institute for Neuroscience, Meibergdreef 47, 1105 BA Amsterdam, The Netherlands. Tel.: +31 20 5665500; fax: +31 20 5666121.
E-mail address: e.van.someren@nin.knaw.nl (E.J.W. Van Someren).

0167-8760/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpsycho.2013.01.017

Up states are associated with complex and widespread neuronal network activity throughout the brain (Volgushev et al., 2011), including high-frequency oscillations. Especially these oscillations, and their coalescence with slow oscillations, have been implicated in network communication and systems consolidation of memory traces (Diekelmann and Born, 2010; Mölle and Born, 2011; Schwindel and McNaughton, 2011; Van Someren et al., 2011). During the up states of slow oscillations, newly encoded memory representations are thought to be reactivated and redistributed, enabling a shift from temporary storage to long-term storage. Crucial for the dynamical formation of neuronal ensembles and altering of the synaptic connections during the up state is the co-occurring thalamocortical and cortico-cortical neuronal activity in higher frequency bands, notably the 10–15 Hz sleep spindles (Rosanova and Ulrich, 2005) and the >30 Hz gamma oscillations (Steriade et al., 1996; Mena-Segovia et al., 2008; Mena-Segovia and Bolam, 2011).

After the initial demonstration in cats and ferrets that the preferred occurrence of thalamocortical spindles and cortical gamma oscillatory activity is during the depolarizing phase of slow oscillations (Contreras and Steriade, 1995; Steriade, 2006), Mölle and colleagues showed a similar modulating effect of slow oscillations on spindles in the EEG of adult humans (Mölle et al., 2002; Mölle and Born, 2011). Whereas in humans intracortical recordings support a similar modulation of gamma activity by slow oscillations (Csercsa et al., 2010; Le Van Quyen et al., 2010; Valderrama et al., 2012) and magnetoencephalographic (MEG) recordings support concerted modulation of gamma and spindles (Ayoub et al., 2012), gamma modulation along the time course of a slow wave has not yet been demonstrated in human scalp EEG.

The lacking demonstration of such modulation of gamma activity along the time course of a slow wave in human scalp EEG is unfortunate, because it is especially these high frequency oscillations that have been attributed an important role in synchronizing and binding neuronal network activity to support neuronal network processes underlying cognition. Destexhe et al. (2007) proposed them to represent brief fragments of a wake-like state where effective communication between different neuronal systems can take place to support brain function and cognition. Given the proposed functional importance of gamma activity modulation by slow oscillations, it would be highly valuable to be able to measure and quantify them in the human sleep EEG. This was the major aim of the present study. As will be discussed below, we argued that the best chance of achieving this might be in the sleep EEG of children around the age of 11 years.

The expression of slow waves undergoes remarkable changes during development, both with respect to their topographical distribution (Jenni et al., 2005; Kurth et al., 2010; Tarokh et al., 2010), as well as with respect to their amplitude (Feinberg et al., 1990; Feinberg and Campbell, 2010). The amplitude of slow oscillations increases during childhood to peak shortly before puberty (Feinberg et al., 1990). A steep drop occurs during adolescence, decelerating at the age of about 17 years, after which the amplitude declines only slowly (Feinberg and Campbell, 2010). Interestingly, the initial inverted-U shape closely follows the developmental profile of cortical synaptic density (Huttenlocher, 1979; Huttenlocher and de Courten, 1987; Paus et al., 2008). The reason for this parallel is sought in the fact that the amplitude of slow oscillations reflects the degree of synchronization by which cortical neurons switch between up and down states (Ringli and Huber, 2011). Although receiving much less attention, the capacity of a densely connected neuronal network to synchronize its activity may not only be reflected in the amplitude of slow oscillations, but might as well lead to more pronounced oscillations in frequency bands other than the 0.5–4 Hz range. Indeed, power in the theta (4–8 Hz) range declined across puberty and early adolescence (Feinberg et al., 2011). Gaudreau et al. (2001) investigated NREM sleep EEG power in a wider range of frequency bands across the age range of 6 to 60 years. They report a much higher absolute power of theta (4.0–7.75 Hz), alpha (8.0–12.0 Hz) and beta (15.25–31.0 Hz) in the group of children in the range of 6 to10 years, as compared to the groups of adolescents (range 14 to 16 years), young adults (range 19 to 29 years) and middle aged adults (range 36 to 60 years). The largest values for spindle-range power (12.25–15.0 Hz) were found in the adolescent group, suggestive of an inverted-U shape peaking somewhere between the age of about 10 years and late adolescence. Jenni and Carskadon (2004) investigated developmental changes across the 0.6 to 25 Hz NREM-sleep power spectrum and found that children aged 9.6–12.9 years, as compared to children aged 11.8–15.9 years, had significantly higher absolute power not only in the low frequencies up to about 7 Hz, but also in the 12–13 Hz sigma range and 16–17 Hz low beta range. Recently, both Tarokh et al. (Tarokh and Carskadon, 2010; Tarokh et al., 2011) and Baker et al. (2012) applied a within-subject follow-up design rather than the above-mentioned cross-sectional approaches, to confirm that changes in the sleep EEG across adolescence were not restricted to the lower frequency bands, neither to NREM sleep only. Across adolescence, the sleep EEG power decreases over a wide range of frequencies, up to the beta range for at least some derivations. In summary, the above-mentioned developmental studies suggest that a wide range of cortical oscillations measured in the scalp EEG show their maximal signal-to-noise ratio in late childhood, around the age of 11, where the signal of interest is the amplitude of the oscillations and the noise reflects the noise floor of scalp EEG assessment. We argued that the sleep EEG of children around this age may thus provide an optimal opportunity to investigate modulations and associations between different frequency bands in human sleep.

The first aim of the present study was to investigate whether gamma modulation by slow waves can be demonstrated in the sleep EEG of children. We considered it more likely to demonstrate this phenomenon in children of about 11 years of age than in adults, arguing that the capacity of a densely connected neuronal network to synchronize its activity could result in more pronounced oscillations and a better signal to noise ratio in the gamma frequency range. The demonstration of gamma modulation during slow oscillations in scalp EEG recordings would open a door to noninvasive experimental studies on their functional relevance in humans. The integrated second aim of the present study was therefore to evaluate the feasibility and effects of selective mild acoustic perturbation of slow oscillations in children, one of the experimental approaches that we previously showed to affect slow oscillations in adults, using temperature manipulation (Raymann et al., 2008) and acoustic stimulation (Van Der Werf et al., 2009). A further aim of the present study was to evaluate whether the above-mentioned modulation of spindles by slow oscillations in the sleep of adults can be found as well in an earlier developmental stage.

2. Methods

2.1. Participants

Thirty-two children of an elementary school participated in the study. For ethical reasons, i.e. peer group interaction, no child was excluded from the recording session, whereas the data from two participants were discarded due to a diagnosis of pervasive developmental disorder-not otherwise specified. The data presented here thus represent 30 healthy children (19 females, aged 10.7 ± 0.8 years; mean $\pm$ s.d.). The Medical Ethics Committee of the VU University Medical Center, Amsterdam, The Netherlands, approved all procedures and written informed consent was obtained from the parents.

2.2. Procedure

Children were invited to simultaneously undergo a full polysomnography (PSG) during a full night while sleeping in a dedicated sleep lab built on location in a science museum. They were randomly