Transient synchronization of hippocampo-striato-thalamo-cortical networks during sleep spindle oscillations induces motor memory consolidation

Arnaud Boutin a,b,*, Basile Pinsard a,b,c, Arnaud Bore a, Julie Carrier a,b,d, Stuart M. Fogel e, Julien Doyon a,b,**

a Unité de Neuroimagerie Fonctionnelle, C.R.I.U.G.M., Montréal, QC, Canada
b Université de Montréal, Montréal, QC, Canada
c Sorbonne Universités, UPMC Université Paris 06, CNRS, INSERM, Laboratoire d’Imagerie Biomédicale, Paris, France
d Center for Advanced Research in Sleep Medicine, Hôpital du Sacré-Coeur de Montréal, Montréal, Canada
e School of Psychology, University of Ottawa, Ottawa, Canada

ARTICLE INFO

Keywords:
- Hippocampus
- Memory consolidation
- Motor sequence learning
- Sleep
- Spindles
- fMRI
- EEG

ABSTRACT

Sleep benefits motor memory consolidation. This mnemonic process is thought to be mediated by thalamo-cortical spindle activity during NREM-stage2 sleep episodes as well as changes in striatal and hippocampal activity. However, direct experimental evidence supporting the contribution of such sleep-dependent physiological mechanisms to motor memory consolidation in humans is lacking. In the present study, we combined EEG and fMRI sleep recordings following practice of a motor sequence learning (MSL) task to determine whether spindle oscillations support sleep-dependent motor memory consolidation by transiently synchronizing and coordinating specialized cortical and subcortical networks. To that end, we conducted EEG source reconstruction on spindle epochs in both cortical and subcortical regions using novel deep-source localization techniques. Coherence-based metrics were adopted to estimate functional connectivity between cortical and subcortical structures over specific frequency bands. Our findings not only confirm the critical and functional role of NREM-stage2 sleep spindles in motor skill consolidation, but provide first-time evidence that spindle oscillations (11–17 Hz) may be involved in sleep-dependent motor memory consolidation by locally reactivating and functionally binding specific task-relevant cortical and subcortical regions within networks including the hippocampus, putamen, thalamus and motor-related cortical regions.

Introduction

Sleep in humans is characterized by a loss of consciousness and absence of behavioral control. The shutting down of the human brain to external inputs when falling asleep is believed to serve mnemonic functions, such as memory consolidation mechanisms (see (Diekelmann and Born, 2010; Rasch and Born, 2013; Stickgold and Walker, 2005) for reviews). Conceptually, consolidation refers to the process during which newly acquired and initially labile memories encoded during wakefulness are thought to be reprocessed and transformed into more stable representations that are then integrated into pre-existing memory networks during sleep (Dudai, 2012; Dudai et al., 2015). There is accumulating evidence that sleep contributes to the consolidation of anatomically and functionally distinct declarative/procedural memory systems (see (Albouy et al., 2013a; Genzel et al., 2014) for reviews). However, one of the unsolved most current issue in the sleep/memory research domain relates to the question whether sleep is involved in overnight consolidation of both types of memory information in an unspecific manner, or whether particular sleep-related oscillatory patterns are involved in this mnemonic process by selectively reactivating and consolidating specific memories. In the present study, we aimed to give some insights into the neurophysiological mechanisms underlying this active sleep-mediated processing and strengthening of newly acquired memory traces with regards to motor sequence learning (MSL).

Human sleep architecture depicts the cyclic occurrence of non-rapid-eye-movement (NREM) and rapid-eye-movement (REM) sleep episodes, each defined by specific neurobiological mechanisms and memory processes (see (Rasch and Born, 2013; Genzel et al., 2014; Walker and...
night of sleep (e.g., (Barakat et al., 2013; Fogel et al., 2017b)). Hence, in
been exclusively indirect, with studies mainly reporting correlations
recent evidence in rodents of spindle-triggered reactivations of
mediating the active reprocessing and strengthening of memory traces
ories, it is tempting to speculate that thalamo-cortical NREM2 sleep
dynamics, i.e., the expression of idiosyncratic/generic reactivation of a
hemisphere contralateral to the learned motor skill (Nishida and Walker,
2016; Nishida and Walker, 2007; Barakat et al., 2011), see (Fogel and
Peigneux, 2015; Rasch and Born, 2008) for reviews).
Recent findings have also revealed that MSL-dependent reshaping of
sleep architecture and spindle activity (i.e., extended NREM2 sleep pe-
riods; see (Fogel and Smith, 2011) for a review, as well as changes in striatal
(Debas et al., 2010, 2014), see (Doyon et al., 2003, 2009; Doyon
and Benali, 2005) for reviews) and hippocampal activity (Albouy et al.,
2008, 2013b, 2015) may underlie motor memory consolidation. For
instance, studies using MSL tasks have revealed that the magnitude of
overnight performance improvements correlates with increased spindle
activity (i.e., frequency, amplitude, density [spindles/minute], sigma
power) and the average duration of NREM2 sleep ((Laventure et al.,
2016; Nishida and Walker, 2007; Barakat et al., 2011), see (Fogel
and Smith, 2011) for a review). Neuroimaging data have further revealed that
such sleep-related motor memory enhancements are mediated by inter-
hemispheric regulations, associated with regionally-specific reorganiza-
tion expressed by lateralized increased spindle and brain activity in the
hemisphere contralateral to the learned motor skill (Nishida and Walker,
2007). However, previous research did not focus on the transient evoked
response elicited during sleep spindles, or their spatial and temporal
dynamics, i.e., the expression of idiosyncratic/generic reactivation of a
post-learning neural network.
In agreement with the basic tenets of prevailing neuroscience the-
ories, it is tempting to speculate that thalamo-cortical NREM2 sleep
spindle activity constitutes an unconscious endogenous brain mechanism
mediating the active reprocessing and strengthening of memory traces
acquired during daytime learning (see Ramanathan et al. (2015) for
recent evidence in rodents of spindle-triggered reactivations of
task-related neural patterns during NREM sleep). However, to the best
of our knowledge, evidence supporting this theoretical view in humans has
been exclusively indirect, with studies mainly reporting correlations
between sleep spindle characteristics and changes in brain activity after a
night of sleep (e.g., (Barakat et al., 2013; Fogel et al., 2017b)). Hence,
in the present study we sought to determine the functional contribution of
sleep spindles in the strengthening of procedural memories. To that end,
simultaneous EEG-fMRI sleep data were recorded following practice of a
MSL task and a simple motor control task (CTRL), which were adminis-
tered one week apart in a within-subject design (order counterbalanced
across participants). Yet, it is important to note that the fMRI data of the
present data set were previously published ((Fogel et al., 2017a; Vahtak
et al., 2017b)), and thus that only the EEG data were analyzed and re-
ported in the present study. Using novel EEG pre-processing and source
reconstruction methods, we sought to determine whether regionally-specific sleep spindle modulations support active reprocessing of
a memory trace, hence favoring motor skill consolidation. We hy-
pothesized that task-relevant activity patterns would emerge time-locked
with spindle oscillations over localized (sensorimotor) brain regions during
post-learning sleep, with spindle-triggered activation patterns correlating
with the expression of overnight performance improvements. Moreover,
while direct evidence supporting the theoretical hypothesis of inter-
hemispheric regulation is scarce, further topographical EEG examination
would provide new insights into the contribution of local modulations of
sleep spindles upon motor memory consolidation (i.e., interhemispheric
differences in terms of spindle frequency, amplitude, duration and
density).
Furthermore, deep brain source reconstruction analysis, derived from
EEG signals, offers high temporal and spectral resolution for quantifica-
tion of both surface and subcortical neural activity. This can serve as
a novel and effective method for characterizing the information-processing
mechanisms underlying transient spindle activity over specific brain re-
gions and frequency bands, the latter being crucial for understanding the
role of sleep spindles in motor skill consolidation. Hence, we further
aimed at investigating whether distinctive patterns of coherence (func-
tional connectivity) over specific brain regions and frequency bands
support sleep-dependent motor memory consolidation (see also Mary
et al. (2017a,b), for a similar methodological approach for source
reconstruction and frequency-specific functional connectivity analyses).
To determine the degree of connectivity or synchronzation between
distinct brain regions at specific frequencies, we computed the imaginary
part of coherence (iCoherence), a measure of functional connectivity that is
insensitive to the volume conduction artefacts mainly affecting real
coherence (Nolte et al., 2004; Garcia Dominguez et al., 2013). Thus,
while rhythmic neuronal activity in the theta and alpha range has been
shown to underlie the encoding and successful retrieval of non-motoric
memories by sustaining hippocampal connectivity with striatal and
prefrontal cortical regions ((Benchenane et al., 2010; Herweg et al.,
2016), see (Dudai et al., 2015) for a review), we hypothesized that EEG
spindle-band coherence would be the mechanism supporting sleep-
dependent MSL consolidation by coordinating a functional network
integrating the striatum with the hippocampus and motor-related
cortical circuitry (see (Albouy et al., 2013a; King et al., 2017) for
reviews).
Materials and methods
Ethics statement
The study protocol was approved by the Research Ethics Board of the
“Regroupement en Neuroimagerie du Québec” (RNQ). Before participa-
tion, all subjects provided written informed consent and received
financial compensation for their participation in this study.
Participants and procedure
Thirty healthy volunteers (mean age: 25.6 ± 3.6 years, 20 females) were
recruited through local advertisements. All participants included in
the study fulfilled the following inclusion criteria: right-hand
dominant (Edinburgh Handedness Inventory; (Oldfield, 1971)),
non-smoker, non-musician or typist, medication-free, no history of
mental illness, no signs of mood disorders (Self-Rated Score ≤ 8 on the
Beck Depression (Beck et al., 1974) and Anxiety Inventories (Beck
et al., 1988)), Body Mass Index ≤ 25, and no sleep disturbances
(Pittsburgh Sleep Quality Index Global Score < 5; (Buysse et al., 1989)).
Participants categorized as extreme morning or evening types (Horne
Ostberg Morningness-Eveningness Scale; (Horne and Ostberg, 1976),
shift-workers or those who experienced a trans-meridian trip less than
3 months prior to the experiment, were excluded. Furthermore, we also
excluded participants exhibiting signs of excessive daytime sleepiness
(<9 on the Epworth Sleepiness Scale; (Johns, 1991)). Participants were
asked to maintain a regular sleep-wake cycle (bedtime between
10:00pm–1:00am, wake-time between 07:00am–10:00am) to ensure
that they were not sleep-deprived. Compliance to the schedule was
assessed using both sleep logs and wrist-worn actigraphs (Actiwatch 2,
دریافت فوری متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات