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Increased periodic arousal fluctuations during non-REM sleep are associated to superior memory

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Abstract

Sleep has been implicated in the plastic cerebral changes that underlie learning and memory. The scientific investigation of people with exceptional memory has been relatively neglected. We report the results of a polysomnographic investigation of an individual with superior memory performance. The sleep structure, in terms of sleep induction and maintenance, as well as non-REM and REM sleep percentages, were normal. The main finding was an increased number of periodic arousal fluctuations during non-REM sleep (measured as cyclic alternating pattern, CAP) during two consecutive nights (7–8 S.D. units above that observed in age-matched controls). Since CAP rate reflects the structural organization of non-REM sleep, this observation supports the hypothesis of a link between non-REM sleep and declarative memory performance.

Keywords: Memory; Sleep; Arousals; Cyclic alternating pattern (CAP)

1. Introduction

Behavioral studies of sleep and learning in humans and animals, and neurocognitive studies of information processing during sleep provide evidence for a relationship between sleep, learning and memory. The fact that some individuals can accomplish extraordinary memory feats is well-known.

The scientific investigation of people with exceptional memory has been relatively neglected, with some remarkable exceptions [27]. A recent study of a group of ten superior memorizers [12] failed to detect differences in brain structure, as assessed with magnetic resonance imaging morphometry, in comparison to matched controls; however, a functional imaging study during a memory task indicated an increased recruitment of areas, such as the hippocampal formation, engaged in spatial memory.

The latter finding was interpreted as reflecting the use of specific strategies involving spatial learning by superior memorizers. We have had the opportunity to collaborate with one superior memorizer in the investigation of the psychological and neurological correlates of his exceptional performances. Given the evidence for a relationship between sleep and memory performance [2], as part of the evaluation we performed a polysomnographic study. In our evaluation we included the arousals that interrupt sleep continuity. The scoring of arousals relies on transient EEG changes mostly characterized by patterns of wakefulness. However, in this standard scoring the abrupt appearance of slow wave activities is basically neglected, even if it has been demonstrated that autonomic changes may occur in concomitance with these EEG changes. In recent years, some authors have identified the cyclic alternating pattern (CAP) that is involved in the structural organization of non-REM sleep. CAP is identified by repetitive stereotyped EEG patterns lasting 10–60 s and separated by time-equivalent intervals of background activity [4,23]. CAP corresponds to a prolonged oscillation of the arousal level between two reciprocal functional states termed phase A (greater arousal; clusters of EEG transients) and phase B (lesser arousal; interval between the successive clusters); the complementary condition non-CAP is closely related to a degree of stability in sleep depth. We report here the polysomnographic results obtained in our superior memorizer.

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2. Materials and methods

We evaluated an individual with superior memory performance. The participant gave his written informed consent to the study. The main results of the standard psychometric assessment are reported in Table 1.

We were not able to find the upper limit of his performance on short-term memory (span) tasks. His performance was also superior in the case of verbal episodic learning tasks; only for an incidental visuo-spatial memory test his performance was comparable to high-scoring controls.

In our subject polysomnography was performed for two consecutive nights. The following signals were recorded using the Grass Telefactor Heritage Digital PSG equipment: 5 EEG leads (C3-A2,F3-T3, T3-O1, F3-C3, C3-O1), 2 EOG leads (ROC-A2, LOC-A2), three EMG leads (chin, right and left tibial), one ECG derivation, nasal and oral airflow (through nasal and oral thermistors), toracic and abdominal efforts (through piezoelectric belts). For the control group, published data of young adults (aged 20–39 years) have been considered [15]. The total recording time for our superior memorizer as well as for the controls was 500 min.

Concerning the polysomnographic data, the traditional parameters of sleep induction and maintenance, and of sleep architecture were considered, as well as the sleep microstructure (CAP). As previously mentioned, CAP corresponds to a prolonged oscillation of the arousal level between two reciprocal functional states termed phase A and phase B. On the basis of their morphological features, the phases A in human sleep are classified in subtypes A1 (characterized by EEG synchronized patterns), subtypes A2 (including a balanced mixture of EEG synchrony and desynchrony), and subtypes A3 (mostly composed of EEG desynchronized features). CAP time is the temporal sum of all CAP sequences. The percentage ratio of CAP time to sleep time is referred as the CAP rate. CAP rate may be measured in the total non-REM sleep and in the single non-REM stages.

Table 1
Neuropsychological assessment

Neuropsychological assessment	Score	Range	Control data[a]
Raven's colored PM	35/36	0–36	>31
Digit span		–	>5.25
Forward	20		
Reverse	20		
Corsi spatial span		–	>4.5
Forward	12		
Reverse	12		
California verbal learning test			
Average learning	80	0–80	48.6 ± 10.4[b]
Delayed recall	16	0–16	9.9 ± 3.5[b]
Logical memory			
Immediate recall			
Hierarchical score	50.5	0–75.5	
Non-hierarchical score	50.5		>32
Delayed recall			>14.5
Hierarchical score	55		
Non-hierarchical score	62.5		
Loss of information (%)			
Hierarchical score	−9.1		2.73 (5.84)[b]
Rey–Osterreith's figure			
Copy	36	0–36	32.41
Delayed recall	27.5		14.74

[a] Above the median of the control sample.
[b] Mean ± S.D. of the control sample

3. Results

Table 2 shows the results obtained for the traditional sleep parameters.

The sleep structure of our subject, in terms of sleep induction and maintenance, as well as non-REM and REM sleep duration, were normal.

Table 3 shows the data obtained by microstructural analysis of sleep (CAP parameters).

An increased CAP rate was observed in two consecutive nights. The percentage of CAP rate was 7–8 S.D. units above

Table 2
Macrostructural sleep findings

	Controls ($n = 10$)	Night 1–Night 2
Sleep latency	16 (14)	20–12
Total sleep time	455 (33)	448–472
Sleep efficiency	91 (7)	89.6–94.4
WASO	12 (8)	18–7
Stage 1 NREM	21 (12)	14–25
Stage 2 NREM	219 (37)	237–233
Stage 3 NREM	36 (13)	32–30
Stage 4 NREM	61 (16)	66–75
REM	118 (19)	113–109
REM latency	76 (20)	87–83

WASO: wake after sleep onset. Standard deviations in parentheses. All variables are expressed in minutes.

Table 3
CAP (microstructural) findings throughout non-REM sleep

	Controls ($n = 10$)	Night 1–Night 2
NREM		
CAP rate (%)	31.9 (7)	63.2–64.5
CAP cycles (n)	233 (74)	379–384
STAGE 1		
CAP rate (%)	38.3 (16.4)	39.3–38.2
STAGE 2		
CAP rate (%)	32.6 (6.4)	66.5–70.7
STAGE 3		
CAP rate (%)	44 (16.3)	78.3–79.1
STAGE 4		
CAP rate (%)	24.4 (11.5)	68.7–69.8
A_1 subtypes (% of phases A)	61.4	68.2–69.1
A_2 subtypes (% of phases A)	27.9	20.4–23.8
A_3 subtypes (% of phases A)	10.7	11.4–7.1

Standard deviations in parentheses.

that observed in an age-matched sample of controls. Possible causes of sleep fragmentation with increased CAP rate, as sleep apneas or periodic limb movements (PLM), have been excluded. In fact, our subject had a PLM index = 1.8 in the first night and =1.2 in the second night. The apnea/hyponea index was 1.4 and 1.1, respectively.

In the evaluation of the distribution of the different phase A subtypes, the contribution of phase A1 was relatively increased.

4. Discussion

Several studies have investigated the hypothesis that sleep may promote learning and memory [6,10,11,19]. There are experimental results suggesting a role for sleep in synaptic plasticity [1]. Neuronal activity in REM sleep is substantially similar to that observed in waking [9]: neocortical pyramidal neurons, as well as hippocampal neurons, are tonically depolarised. In non-REM sleep, neocortical pyramidal neurons are less active and responsive than in waking or REM sleep. They are generally firing single action potentials or bursts at fairly regular intervals, with a long after-hyperpolarization following each depolarisation [21,22].

Several investigators have reported REM-sleep augmentation in animals following a variety of learning or exposure to enriched environments tasks [1,8]. Animal studies have also shown changes in non-REM sleep amounts and architecture in the same experimental conditions. An increased number of episodes with transition of non-REM sleep to REM sleep (transitional sleep states) positively correlated with task acquisition [13,20].

Human studies, based on different methodologies, have in general supported the relationship between sleep and memory performance [14]. Both REM and non-REM sleep have been shown to be involved in human memory function [16]. In particular, it has been claimed that early sleep, dominated by the slow wave sleep (SWS, stage 3 and 4 non-REM), is specifically linked to the consolidation of declarative memory, while late sleep, in which REM prevails, is necessary for non-declarative (procedural) memory [17,18]. Recent evidence provides partial support to this distinction. For instance, increased EEG spindles have been reported after extensive training on a verbal learning task [7]. However, a classic procedural task such as maze learning has also been shown to increase stage 2 non-REM and EEG spindles in subsequent sleep [16]. Further, Walker et al [26] reported that stage 2 non-REM, which is particularly rich in EEG spindles, is positively correlated with the acquisition of a motor skill.

Taken together, these data underline the important contribution of non-REM sleep to memory performance. The quantitative evaluation of spontaneous periodic sleep EEG oscillations represents an important contribution of human clinical neurophysiology to the investigation of non-REM sleep. The classical approach to sleep macrostructure may fail to recognize these EEG microstructural changes. In recent years, some authors have identified the CAP that is involved in the structural organization of non-REM sleep [23].

Our study shows the possible role of sleep microstructure in individuals with superior memory and provides further support to the link between non-REM sleep and declarative memory. The large increase in CAP rate in our subject provides further evidence for the link between non-REM sleep and memory. In the evaluation of the distribution of the different phase A subtypes, the contribution of phase A1, the component of CAP related to the achievement and maintenance of slow wave sleep [5], was relatively increased in our superior memorizer. Slow wave and sleep spindles during non-REM sleep seem to generate conditions for increasing the synaptic efficacy by inducing long-term potentiation and for consolidating memory traces acquired during wakefulness [22]. Sequences of K-complexes and slow wave bursts characterize the A1 subtypes of CAP. The A1 subtypes coincide with the slow oscillations inducing progressive amplitude increase of the EEG signal linked to the build-up and maintenance of deep non-REM sleep [3]. Our data reinforce the evidence of the important contribution of non-REM sleep to memory performance, by means of the various types of SWS oscillations favoring brain plasticity [14].

The relationship between non-REM sleep and memory performance is also supported by pharmacological evidence in humans. The majority of antidepressant drugs, which drastically reduce the amount of REM sleep, do not induce any deleterious effect on memory [25]. Interestingly, hypnotic compounds that reduce the periodic arousal fluctuations measured as CAP, affect memory and learning [24].

In conclusion, the present investigation adds another line of evidence, derived from the unusual area of “exceptional” abilities. The observation leads itself to different interpretations: the unusually high CAP rate may be considered as a neurophysiological signature of an increased consolidation load, or as evidence for a peculiar organization of brain processes in a superior memorizer. The scientific investigation of exceptionally gifted individuals may represent a privileged avenue into these basic questions.

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