Untreated Sleep-Disordered Breathing: Links to Aging-Related Decline in Sleep-Dependent Memory Consolidation

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Abstract

Background: Increasing age is associated with a decline in cognition and motor skills, while at the same time exacerbating one’s risk of developing obstructive sleep apnea (OSA). OSA-related cognitive deficits are highly prevalent and can affect various memory systems including overnight memory consolidation on a motor sequence task. Thus, the aim of our study was to examine the effect of aging on sleep-dependent motor memory consolidation in patients with and without OSA.

Methods: We studied 44 patients (19–68 years) who had been referred by a physician for a baseline polysomnography (PSG) evaluation. Based on their PSG, patients were assigned either to the OSA group (AHI > 5/h), or control (Non-OSA) group (AHI < 5/h). All subjects performed the Psychomotor Vigilance Task (PVT) and the Motor Sequence Learning Task (MST) in the evening and again in the morning after their PSG.

Results: Despite similar learning in the evening, OSA subjects showed significantly less overnight improvement on the MST, both for immediate (OSA: −2.7% ± 2.8% vs. controls: 12.2% ± 3.5%; p = 0.002) and plateau improvement (OSA: 4.9% ± 2.3% vs. controls: 21.1% ± 4.0%; p = 0.001). Within the OSA group, there was a significant negative correlation between overnight MST improvement and age (r² = 0.3; p = 0.01), an effect that was not observed in the Non-OSA group (r² = 0.08; p = 0.23).

Conclusions: Consistent with previous research, healthy sleepers demonstrated a higher degree of sleep-dependent overnight improvement on the MST, an effect not mitigated by increasing age. However, the presence of untreated obstructive sleep apnea is associated with an aging-related cognitive deficit, otherwise not present in individuals without OSA. As other research has linked the presence of OSA to a higher likelihood of developing dementia, future studies are necessary to examine if the inhibition of memory consolidation is tied to the onset of neurodegenerative disease.

Introduction

The prevention and treatment of chronic diseases, especially those that are closely associated with aging, will be of growing importance as we expect the elderly population (those aged 65 years or older) to double from approximately 35 million today to more than 70 million by 2030, representing nearly 20 percent of the total U.S. population [1].

Increasing age has been associated with the risk of developing sleep-disordered breathing [2,3]. Depending on the definition and sample studied, sleep-disordered breathing is thought to affect 10–60% of the population [4,5,6]. These sleep disturbances in turn can theoretically accelerate the aging process [7] and are associated with serious health consequences, including an increased risk for cardiovascular disease [8,9,10,11,12,13], mortality [12,14,15,16,17,18,19], and the presence of cognitive deficits which clearly extend beyond those primarily associated with sleepiness [20,21,22,23,24,25,26]. In addition, evidence from a recent study linked the presence of untreated obstructive sleep apnea with an increased risk of developing dementia [27].

The link between sleep and memory has been supported by several human studies which have confirmed a role for sleep after training in benefiting long-term memory consolidation and enhancement [28,29]. In particular, these studies have determined that sleep following various tasks such as declarative paired associates, procedural motor memories, more complex category learning, and emotional memory tasks, can lead to enhanced performance [30,31,32,33,34,35].
Most studies thus far have been conducted on healthy young adults, but the importance of understanding how these processes affect the aging brain is increasingly recognized.

We have previously demonstrated that OSA-induced sleep fragmentation can affect off-line learning improvement on a motor sequence learning task in a young (mean age = 30.4 years) patient population [36]. OSA’s high prevalence in the elderly population, and research suggesting that OSA may have some adaptive benefits over time [37], raises questions about whether the cognitive consequence of OSA on off-line memory processes remain as significant with increasing age.

The aim of this study was thus to examine the effect of aging on sleep-dependent motor memory consolidation in subjects with and without OSA. This would allow us to test the hypothesis that OSA modulates aging-related off-line sleep-dependent memory processes and that this deficit is independent of circadian factors and differences in attention and vigilance.

Methods

Ethics Statement
All participants provided written informed consent. The study was approved by the Partners’ Institutional Review Board.

Participants
We recruited 44 participants (19–68 years) who had been referred by a physician for a baseline polysomnography (PSG) evaluation. Post PSG, based on their apnea-hypopnea index (AHI), patients were assigned to either the OSA group (AHI>5/h), or Control/Non-OSA group (AHI<5/h).

Exclusion criteria
Subjects were excluded if they (1) were found to have a periodic limb movement index of >15/h based on their PSG, (2) had another diagnosed sleep or circadian disorder, (3) had a history of alcohol, narcotic, or other drug abuse, (4) had a history of a medical, neurologic or psychiatric disorder (other than OSA and treated hypertension) that could influence excessive daytime sleepiness, (5) used medications known to have an effect on sleep and daytime vigilance (e.g., psychoactive drugs or medications, sedatives or hypnotics, including SSRIs), or (6) were left-handed.

Study procedures
In the evening between 8 and 9 PM, all subjects performed the psychomotor vigilance task (PVT) and then trained on the motor sequence task (MST [38,39]). Subjects were randomized to one of two sequences in the evening: 4-2-3-1-4 (sequence A) or 2-4-1-3-2 (sequence B). After training, participants spent the night in the laboratory and underwent standard polysomnographic sleep recording. The next morning between 6:30 and 7:30 AM subjects repeated the PVT and were tested on the MST. After a 10-minute break, they learned the second MST sequence, again with 12 trials, to control for circadian effects of motor sequence learning. Learning the motor sequence task is sequence specific, with no transfer of learning to new sequences [30]. This study design was performed using BrainVision Analyzer 2.0 (BrainProducts, Munich Germany). Artifacts were automatically detected and removed and EEG data were filtered at 0.5–33 Hz. Artifact rejection was confirmed by visual inspection. Power spectral density (μV²/Hz) was calculated for Fast Fourier Transform (FFT), applying a Hanning window to 5 s epochs of sleep (N2 and N3) with 50% overlap.

An arrhythmic study, spindle analysis (number and density) was performed for stage 2 sleep manually and using a wavelet-based algorithm that was developed and previously applied by Wamsley et al. [41]. Data were pre-processed and analyzed using BrainVision Analyzer 2.0 and MatLab R2009b (The MathWorks, Natick MA).

Statistical analysis
Unpaired t-tests were performed to compare the demographic, questionnaire and primary PSG-derived sleep data between OSA patients and healthy controls. MST improvement for each subject was calculated as a percent change in performance speed from initial evening training to subsequent morning retesting, and compared between OSA patients and controls using an a t-test. Simple and multiple logistic regression analyses were performed to examine the association of AHI, sleep spindles and arousal index with overnight performance changes. Statistical analysis was performed using JMP Version 8 (SAS Institute Inc., Cary, NC). A p-value of <0.05 was considered significant. Variability is expressed as standard errors of the mean (SEM).

Results

There was no significant group difference in age means, age range or body mass index (BMI) between the OSA and Non-OSA group (Table 1). The groups also did not differ significantly on any measure of sleep architecture or sleep quality, including total sleep time, sleep stage distribution, wake time after sleep onset, or the number of awakenings. There was, however, a trend toward more total sleep time in the controls (344 vs. 322 min; p = 0.07).

As expected, significant differences were present in all variables related to sleep-disordered breathing, including oxygen nadir (91.6±0.6% vs. 86.1±1.0, p<0.001), AHI (1.7±0.3 vs. 11.3±2.0, p<0.001), and arousal index (18.7±1.5 vs. 23.8±2.4, p = 0.02). In addition, subjective sleepiness variables assessed with the Epworth Sleepiness Scale (ESS) and Stanford Sleepiness Scale revealed no significant group differences.
controls (mean RT: p = 0.39; lapses: p = 0.37). In summary, there

OSA group (mean RT: p = 0.47; lapses: p = 0.85) or among

the morning sessions showed no significant difference in either the

p = 0.68). Within-subject comparisons between the evening and

p = 0.73) or in the morning (mean RT = 429.9

2.5, controls = 7.0

2.4; p = 0.774; lapses = 8.9±2.4

2.3; p = 0.05; Table 2), but not at frontal

or occipital electrodes. OSA patients also exhibited a significantly

smaller total number of sleep spindles at C4 (p = 0.03), but not at

other electrodes.

Comparing spindles in the OSA to the non-OSA group using a

simple ANOVA, but adding age as a covariate, reveals a

significant effect for group (p = 0.01) but not for age (p = 0.27).

Interestingly, central spindle activity (C3 and C4) was significa-
cantly correlated with immediate improvement for OSA patients

(r² = 0.12, p = 0.02), but not for the Non-OSA group (r² = 0.03,

p = 0.29).

MST Improvement and Age

Within the OSA group, there was a significant negative

correlation between overnight MST improvement and age

(r² = 0.3; p = 0.01), an effect that was not observed in the Non-

OSA group (r² = 0.08; p = 0.23). (Figures 2A and 2B)

Both groups had similar age distributions with the number of

subjects under 35 being 8 in the OSA and 11 in the non-OSA
group. Comparing the data points in the regression plots between

groups shows that all of the OSA patients lie below the mean

regression line for non-OSA patients (binomial distribution).

Sleep and Age

Multiple linear regression analysis was conducted to assess the

effect of age on the sleep parameters AHI, arousal index, and

C3+C4 sleep spindle density. For OSA patients, age had a

significant positive correlation with central spindle density

(p = 0.02), but not with arousal index (p = 0.13) or AHI

(p = 0.39). For the Non-OSA group, age was positively correlated

with the arousal index (p = 0.04), but not with central spindle

density (p = 0.87) or AHI (p = 0.17).

Age, spindle density, AHI and arousal index were then entered

into a regression model as predictor variables for overnight MST

plateau improvement.

For the OSA group, the regression model (R² = 0.59) was

statistically significant for AHI (p = 0.01), arousal index

(p<0.0001) and age (p<0.0001), but not for central spindle

density.

In contrast, for the Non-OSA group, only arousal index

(p = 0.001) contributed significantly to overnight MST improve-

ment (R² = 0.34).

Discussion

Even healthy aging is associated with distinct changes in sleep

architecture and sleep efficiency [43,44]. Sleep changes include

Table 1. Demographic and sleep data.

<table>
<thead>
<tr>
<th></th>
<th>No OSA (n = 20)</th>
<th>OSA (n = 20)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>35.3±2.6</td>
<td>41.1±1.0</td>
<td>0.16</td>
</tr>
<tr>
<td>Age-range</td>
<td>19—26</td>
<td>22—67</td>
<td></td>
</tr>
<tr>
<td>BMI (Kg/m²)</td>
<td>27.9±1.7</td>
<td>29.0±1.4</td>
<td>0.63</td>
</tr>
<tr>
<td>Epworth Sleepiness Scale</td>
<td>9.3±1.3</td>
<td>9.0±1.2</td>
<td>0.89</td>
</tr>
<tr>
<td>Stanford Sleepiness Scale PM</td>
<td>3.5±0.3</td>
<td>3.1±0.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Stanford Sleepiness Scale AM</td>
<td>3.0±0.3</td>
<td>3.4±0.3</td>
<td>0.33</td>
</tr>
<tr>
<td>Typing assessment (hr/week)</td>
<td>16.9±5.3</td>
<td>34.2±8.8</td>
<td>0.11</td>
</tr>
<tr>
<td>TST (min)</td>
<td>344.1±7.5</td>
<td>322.4±8.7</td>
<td>0.07</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td>85.9±2.2</td>
<td>83.8±1.8</td>
<td>0.45</td>
</tr>
<tr>
<td>N1%</td>
<td>8.5%±0.9%</td>
<td>8.5%±1.2%</td>
<td>0.97</td>
</tr>
<tr>
<td>N2%</td>
<td>59.5%±1.9%</td>
<td>63.2%±1.5%</td>
<td>0.13</td>
</tr>
<tr>
<td>N3%</td>
<td>13.5%±2.6%</td>
<td>11.9%±1.8%</td>
<td>0.61</td>
</tr>
<tr>
<td>REM%</td>
<td>18.5%±1.6%</td>
<td>15.7%±1.6%</td>
<td>0.22</td>
</tr>
<tr>
<td>Oxygen nadir (%)</td>
<td>91.6±0.6%</td>
<td>86.1±1.0%</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>AHI (events/hr)</td>
<td>1.7±0.3</td>
<td>11.3±2.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Arousal index (events/hr)</td>
<td>18.7±1.5</td>
<td>23.8±2.4</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Definition of abbreviations: BMI = body mass index, TST = total sleep time,

AHI = apnea hypopnea index. Data are presented as mean ± SEM.

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Previous experience with keyboard typing varied among

participants. OSA subjects reported more hours spent typing per

week; however, this difference was not significant. (Table 1)

Psychomotor Vigilance Test (PVT)

PVT performance did not differ between groups in the evening

(mean RT: OSA = 396±29 ms, controls = 384±24 ms, p = 0.766;

lapses [RT>500 ms]: OSA = 8.2±2.5, controls = 7.0±2.4,

p = 0.73) or in the morning (mean RT = 429.9±36.7 ms

density (p = 0.0001) and age (p = 0.0001), but not for central spindle

density (p = 0.87) or AHI (p = 0.17).

Age, spindle density, AHI and arousal index were then entered

into a regression model as predictor variables for overnight MST

plateau improvement.

For the OSA group, the regression model (R² = 0.59) was

statistically significant for AHI (p = 0.01), arousal index

(p<0.0001) and age (p<0.0001), but not for central spindle

density.

In contrast, for the Non-OSA group, only arousal index

(p = 0.001) contributed significantly to overnight MST improve-

ment (R² = 0.34).

Discussion

Even healthy aging is associated with distinct changes in sleep

architecture and sleep efficiency [43,44]. Sleep changes include
reductions in slow wave activity (SWA) as well as an aging-related reduction in the number of sleep spindles along with K-complexes [45,46].

With regard to motor memory consolidation, a study testing older adults on a modified version of the serial reaction time task found that these individuals did not show any performance benefit for either explicit or implicit motor learning after post-training sleep [48]. On the other hand, a study by Tucker et al. using the same motor sequence task as in our study found that although elderly subjects perform generally at a slower pace, they still demonstrate sleep-related improvements in motor skill performance at levels similar to those seen in healthy young participants [49].

Few studies have examined the effect of aging on sleep-dependent memory consolidation. One study reported that aging-associated decline in sleep-dependent declarative memory was merely a function of the amount of slow wave sleep and that retention of declarative memories was the same for younger and older individuals when sleep periods contained equal amounts of SWS [47].

Table 2. Sleep Spindles.

<table>
<thead>
<tr>
<th></th>
<th>No OSA</th>
<th>OSA</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindles – C4 (#)</td>
<td>393.5 ± 21.8</td>
<td>316.5 ± 26.4</td>
<td>0.03</td>
</tr>
<tr>
<td>Spindles – C3 (#)</td>
<td>376.5 ± 21.4</td>
<td>320.0 ± 28.0</td>
<td>0.12</td>
</tr>
<tr>
<td>Spindle density C4</td>
<td>0.97 ± 0.0</td>
<td>0.77 ± 0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Spindle density C3</td>
<td>0.93 ± 0.0</td>
<td>0.78 ± 0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SEM.

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Figure 1. Overnight MST Improvement. Immediate improvement: comparison of first 3 MST trials in morning to final 3 from night (1A). Plateau improvement: measured by comparing final 6 MST trials in the morning with final 6 trials at night (1B). OSA subjects showed significantly less overnight improvement on the MST for both measures.

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In addition, there are few studies which have examined the effect of OSA in conjunction with aging-related changes [50,51]. These studies used attention and verbal encoding tasks, one study also in combination with functional imaging. They concluded that while younger patients with OSA are able to compensate the effects, older patients are exposed to what they termed a “double insult”, the combination of aging–related brain vulnerability and the long-term effects of OSA-induced intermittent hypoxia, resulting in diminished performance on these cognitive tasks, a finding which has also been reported in animal studies [52].

Our study is the first to evaluate the combined effects of aging and OSA on sleep-dependent memory consolidation.

Results for the Non-OSA group are consistent with previous research in young healthy college students, showing the same magnitude of sleep-dependent overnight improvement on the MST, an effect that was not mitigated by increasing age. While the number of arousals correlated with age, it was the arousal index and not age that predicted overnight MST improvement. That is, in healthy sleepers, sleep fragmentation at any age can have a detrimental effect on sleep-dependent memory processes.

On the other hand, in the presence of obstructive sleep apnea we found a decline in sleep-dependent memory consolidation with increasing age. Based on our regression models, not only higher age, but also a higher arousal index and more severe sleep-disordered breathing (higher AHI), all seemed to be independently associated with a decline in sleep-dependent memory consolidation.

Although we did not find an association between overnight improvement and oxygen nadir, the AHI, which did correlate, can be considered an indirect marker of recurrent oxidative stress from hypoxia. In fact, intermittent hypoxia rather than continuous hypoxemia has previously been associated with higher oxidative stress and more adverse outcomes [53]. Given that the arousal

**Figure 2. Correlation Overnight MST Improvement by Age.** There was a significant negative correlation between overnight MST improvement and age for the OSA group (2A: $r^2 = 0.3; p = 0.01$), an effect that was not observed in the Non-OSA group (2B: $r^2 = 0.08; p = 0.23$).

doi:10.1371/journal.pone.0085918.g002
index was also a predictor of overnight improvement, this finding could suggest that the combination of hypoxia and sleep fragmentation may well have an additive effect over time and modulate aging processes in the brain.

Lastly, previous research has pointed to sleep spindles reflecting the cortical aspect of hippocampal–neocortical dialogue involved in the consolidation of new learning, thus being an index of intellectual abilities and the capacity for learning [54]. Based on animal experiments, we assume that these off-line processes during sleep involve experience-dependent activation patterns of hippocampal and cortical brain regions, which then facilitate synaptic plasticity [55].

Earlier studies have shown an association between motor sequence learning and sleep spindles [56,57]. Studies have also found an age-related decline in number and density of sleep spindles [58], but thus far these two components have not been linked.

Our results show that subjects without obstructive sleep apnea preserve the ability to produce sleep spindles with increasing age, whereas OSA subjects demonstrate and age-related decline in sleep spindle production. This may be interpreted as a marker of alterations of the thalamo-cortical regulatory mechanisms. It would have been interesting to also evaluate the change in spindle number (density) from a baseline night to the MST test night. However, no baseline night recording was obtained.

Based on our findings, we could speculate that the function of these sleep spindles in OSA patients remains preserved and that the positive correlation between central sleep spindle density and immediate overnight improvement supports the proposed relationship between sleep-spindle activity and the ability to process newly learned information successfully [41,59].

Sleep and cognition are linked by sharing biological regulatory mechanisms. As it stands, the parallel age-related decline in both sleep and cognitive function may either reflect possible interrelationships or alternatively, sleep and cognitive function could be viewed as independent by-products of structural gray and white matter degenerative changes [60].

Whether sleep disturbances directly inhibit sleep-dependent memory consolidation, or whether the neuroanatomical or neurochemistry changes that result from aging and recurrent hypoxemia lead to atrophy, synaptic degeneration, which then leads to poorer performance, remains open [61].

Sleep disorders are frequently undiagnosed and untreated, particularly in the [32] elderly [62,63,64]. This study emphasizes the importance of efforts that should be invested in understanding and improving the wellbeing of healthy older adults by preserving good sleep quality. Targeting younger patients with preventative strategies may also warrant further study. Our data advocate for future research studies to investigate whether treating sleep disorders can reestablish sleep’s naturally occurring restorative process, and enhance cognition and performance in older adults.

Despite these limitations, we are confident that our new findings are a useful addition to the literature and will help to inform further mechanistic research such as examining if the decline of sleep-dependent memory consolidation is tied to the onset of neurodegenerative disease.

**Supporting Information**

File S1 Figure S1, Evening MST training. MST performance for each of the 12 training trials in the evening. Subjects were asked to type either 4-2-3-1-4 (sequence A) or 2-4-1-3-2 (sequence B) as fast and accurate as possible. Displayed is the average number of correctly typed sequences (bars represents SEMs) for each 30 second trial for the OSA and Non-OSA group. NON-OSA subjects performed slightly better. Figure S2, Comparison PM and AM training on the MST. Subjects trained on the motor sequence task in the evening. They were randomized to one of two sequences in the evening: 4-2-3-1-4 (sequence A) or 2-4-1-3-2 (sequence B). The following morning, subjects were tested on the MST sequence that they learned in the evening. After a 10-minute break, they then learned a new MST sequence. Learning the MST is sequence specific, with no transfer of learning to new sequences. Both, OSA patients and NON-OSA subjects showed similar performances during their initial training session in the evening compared to training of a new sequence in the morning. (DOCX)

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**Author Contributions**

Conceived and designed the experiments: ID RS AM. Performed the experiments: ID PM AC MG. Analyzed the data: ID PM MG AC RS AM. Contributed reagents/materials/analysis tools: ID AM RS. Wrote the paper: ID PM MG AC RS AM.

**References**


