The relationship between subjective sleep quality and cognitive performance in healthy young adults: Evidence from three empirical studies

Zsófia Zavecz[1,2,3], Nagy Tamás[2], Adrienn Galkó[2], Dezso Nemeth[2,3,4], Karolina Janacsek[2,3]

zavecz.zsofi@ppk.elte.hu, nagy.tamas@ppk.elte.hu, adri.galko@hotmail.com, nemeth@nemethlab.com, janacsek.karolina@ppk.elte.hu

[1]Doctoral School of Psychology, ELTE Eötvös Loránd University

[2]Institute of Psychology, ELTE Eötvös Loránd University, Budapest, Hungary

[3]Brain, Memory and Language Research Group, Institute of Cognitive Neuroscience and Psychology, Research Centre for Natural Sciences, Hungarian Academy of Sciences, Budapest, Hungary

[4]Lyon Neuroscience Research Center (CRNL), INSERM, CNRS, Université Claude Bernard Lyon 1, Lyon, France

Corresponding authors: Dezso Nemeth, PhD & Karolina Janacsek, PhD

Email: nemeth@nemethlab.com, janacsek.karolina@ppk.elte.hu

ORCID: https://orcid.org/0000-0002-9629-5856, https://orcid.org/0000-0001-7829-8220

Phone: +36 1 461-4500

Address: Eötvös Loránd University, Institute of Psychology, H-1064, Budapest, Izabella utca 46., Hungary

Abstract

Background: The role of sleep in cognitive performance has gained increasing attention in neuroscience and sleep research in the recent decades, however, the relationship between subjective (self-reported) sleep quality and cognitive performance has not yet been comprehensively characterized. In this paper, our aim was to test the relationship between subjective sleep quality and a wide range of cognitive functions in healthy young adults across three studies. Sleep quality was assessed by Pittsburgh Sleep Quality Index, Athens Insomnia Scale, and in a subgroup (Study 2), a sleep diary to capture general subjective sleep quality, and Groningen Sleep Quality Scale to capture prior night's sleep quality. Within cognitive functions, we tested several sub-processes of procedural learning, working memory and executive functions (assessed by the Alternating Serial Reaction Time, Counting Span and Wisconsin Card Sorting Test, respectively). Combined across the three studies, Pittsburgh Sleep Quality Index and Athens Insomnia Scale were aggregated using principal component analysis, and linear mixed-effects models were used to investigate the effect of poor sleep quality on cognitive performance metrics. Additionally, in Study 2, the associations between Sleep diary and Groningen Sleep Quality Scale and cognitive performance were tested. To test the *amount of evidence* either for associations or no associations between subjective sleep quality and cognitive performance, we calculated Bayes Factors along with frequentist analyses. **Results:** Unequivocally across all analyses, we showed that there is no association between subjective sleep quality and cognitive performance in the domain of procedural learning, working memory, and executive functions. **Conclusions:** Our paper can contribute to a deeper understanding of subjective sleep quality and its measures, and we discuss various factors that may affect whether associations can be observed between subjective sleep quality and cognitive performance.

Keywords: sleep, cognitive functioning, sequence learning, statistical learning, skill learning, self-reported sleep quality, Alternating Serial Reaction Time (ASRT), Pittsburgh Sleep Quality Index (PSQI), Athens Insomnia Scale (AIS)

Background

The role of sleep in cognitive performance has gained increasing attention in neuroscience and sleep research in the recent decades [1, 2]. Numerous experimental methods exist that can be employed for examining the association between sleep and cognitive performance. The most common approach is to compare cognitive performance of healthy participants (good sleepers) with that of patients with sleep disorders (e.g., for a recent meta-analysis on insomnia see É Fortier-Brochu, S Beaulieu-Bonneau, H Ivers and CM Morin [3]. Further insights can be gained from within-group investigations on the association between sleep parameters and cognitive performance. Sleep parameters can be evaluated based on actigraph or electroencephalograph measurements, which are time-consuming and require hardly accessible equipment. Hence, many studies tend to rely on questionnaires to assess sleep parameters and their relationship with cognitive performance [4-7].

Previous studies have shown that subjective and objective sleep parameters could differ [8-10]. Subjective sleep quality can vary from the objective sleep quality because it is estimated by a combination of parameters, including the initiation of sleep, sleep continuity (number of awakenings), and/or depth of sleep. For instance, extreme deviations can occur between objective and subjective measures in case of sleep disorders, such as insomnia, or sleep-state misperception. According to L Zhang and Z-X Zhao [11], in sleep disorders, the objective and the subjective measures together should determine the type of treatment and medication. E Stepanski, G Koshorek, F Zorick, M Glinn, T Roehrs and T Roth [12] showed that, within insomniac patients, the decisive factor whether a patient seeks medication is their

subjective evaluation of their sleep quality and daytime functioning. Furthermore, in a placebo sleep study, C Draganich and K Erdal [13] showed that assigned sleep quality predicted young adults' performance in attentional and executive function tasks. Namely, participants were randomly told they had below average or above average sleep quality based on their brainwaves and other psychophysiological measures, and their belief about their sleep quality affected their cognitive performance. Thus, alongside therapeutic importance, the subjective evaluation of sleep quality could deepen our understanding of the complex relationship between sleep and cognitive performance. The aim of the present paper is to clarify the relationship between subjective sleep quality and aspects of cognitive functioning in healthy young adults.

One of the most widely-used sleep questionnaires is the Pittsburgh Sleep Quality Index [PSQI, 14], a self-administered questionnaire, in which participants rate their subjective sleep quality based on several questions, including the average amount of sleep during night, the difficulty falling asleep, and other sleeping disturbances. Nevertheless, there are other popular measurements, such as the Athens Insomnia Scale [AIS, 15], which measures difficulties in falling asleep or maintaining sleep, and sleep diaries, which capture the sleeping habits of the participants from day to day, spanning a few days or weeks. Sleep questionnaires and sleep diaries are two different types of self-report measures: while a sleep questionnaire is retrospective, administered at a single point in time, and asks about various aspects of the sleep experience "in general", sleep diary is an ongoing, daily self-monitoring. E Libman, CS Fichten, S Bailes and R Amsel [16] showed that even though results of questionnaires and diaries are highly correlating, there are differences in the means of the sleep parameters depending on the type of self-report measurement. This suggests that the two measurement types are tapping the same domains but lead to somewhat different results due to

methodological differences: questionnaires can be susceptible to memory distortion while sleep diaries may be distorted by atypical sleep experiences during the monitored period.

Previous research on subjective sleep quality and cognitive performance has led to mixed findings both in healthy and sleep disordered populations. While some studies focusing on healthy participants have shown that poorer sleep quality (measured by the PSQI score) was associated with weaker working memory performance [5], executive functions [4] and decision-making [6], others have failed to find association between subjective sleep quality and cognitive performance [7, 12]. Focusing on sleep disorders, for instance, S Naismith, V Winter, H Gotsopoulos, I Hickie and P Cistulli [17] showed that greater subjective sleepiness was associated with weaker executive functions but not with IQ scores in patients with Obstructive Sleep Apnea. Importantly subjective sleepiness in this population was independent of polysomnographic sleep measures, which again suggests that even in sleep disorders subjective sleep quality may be an independent factor that underpins some aspects of cognitive functioning. CH Bastien, É Fortier-Brochu, I Rioux, M LeBlanc, M Daley and CM Morin [18] showed different associations between subjective sleep quality and cognitive performance in patients with insomnia with and without treatment and in elderly participants who reported good sleep quality. Interestingly, in good sleepers, greater subjective depth, quality and efficiency of sleep was associated with better performance on attention and concentration tasks but *poorer* memory performance [18], calling for further studies to test the complex relationship between subjective sleep quality and aspects of cognitive functioning.

Importantly, these previous studies focused on diverse populations, including adolescents, elderly and clinical groups, and relied on sample sizes ranging from around 20 to 100, with smaller sample sizes potentially limiting the robustness of the observed results. A recent powerful meta-analysis focused on one aspect of sleep quality, namely, on the effect of self-reported sleep duration on cognitive performance in elderly participants, and reported that

both short and long sleep increased the odds of poor cognitive performance [19]. Systematic investigations on the relationship between other aspects of subjective sleep quality and cognitive performance using larger sample sizes are, however, still lacking. Here we aimed to, at least partly, fill this gap by testing the associations between subjective sleep quality and cognitive performance using a more detailed examination of subjective sleep quality and a wide range of neuropsychological tests in a relatively large sample of healthy young adults.

In previous investigations focusing on the association between subjective sleep quality and various aspects of cognitive performance, the potential relationship with procedural learning/memory has largely been neglected. The procedural memory system underlies the learning, storage, and use of cognitive and perceptual-motor skills and habits [20]. Evidence suggests that the system is multifaceted in that it supports numerous functions that are performed automatically, including sequences, probabilistic categorization, and grammar, and perhaps aspects of social skills [21-25]. In light of the importance of this memory system, the clarification of its relationship with sleep would be indispensable. Although aspects of procedural learning have been previously tested in sleep disordered populations in relation to objective sleep parameters [26-29], systematic investigation of the relationship between subjective sleep quality and procedural learning is still missing.

In this paper, our aim was to provide an extensive investigation on the relationship between subjective sleep quality and cognitive performance, including procedural learning in healthy young adults. To increase the robustness of our analyses, we created a database of 235 participants' data by combining three separate datasets from our lab. Subjective sleep quality was assessed not only by PSQI but also by other, less frequently used sleep quality measures: namely, Athens Insomnia Scale (AIS, Study 1-3), Groningen Sleep Quality Scale (GSQS, Study 2), and a sleep diary (Study 2). These separate measures capture somewhat different aspects of self-reported sleep quality and thus provide a detailed picture. In all three studies

working memory, executive functions, and several sub-processes of procedural learning were probed. This approach enabled us to test – within the same participants and same experimental designs – whether procedural learning is differentially associated with subjective sleep quality as opposed to working memory and executive functions. To test the amount of evidence either for associations or no associations between subjective sleep and cognitive performance in the study population, we calculated Bayes Factors that offers a way of evaluating evidence against or in favor of the null hypothesis, respectively. To the best of our knowledge, this is the first extensive investigation on the relationship between subjective sleep quality and cognitive functions, covering such a wide range of assessments, in healthy young adults.

Methods

Participants

Participants were selected from a large pool of undergraduate students from Eötvös Loránd University in Budapest. The selection procedure was based on the completion of an online questionnaire assessing mental and physical health status. Respondents reporting current or prior chronic somatic, psychiatric or neurological disorders, or the regular consumption of drugs other than contraceptives were excluded. In addition, individuals reporting the occurrence of any kind of extreme life event (e.g., accident) during the last three months that might have had an impact on their mood, affect and daily rhythms were not included in the study.

The data was obtained from three different studies with slightly different focus. Importantly, the analyses presented in the current paper are completely novel, none of the separate studies focused on the relationship between subjective sleep quality and cognitive performance. Forty-seven participants took part in Study 1 [30], 103 participants took part in Study 2 [31], and 85 participants took part in Study 3 [32]. Descriptive characteristics of participants in the three studies are listed in Table 1. All participants provided written

informed consent and received course credits for taking part in one of the studies. The studies were approved by the research ethics committee of Eötvös Loránd University, Budapest, Hungary (201410, 2016/209). The study was conducted in accordance with the Declaration of Helsinki.

Table 1. Descriptive characteristics of participants

Study	n	Age *M (SD)*	Sex	Years in education *M (SD)*
Study 1	47	21.38 (1.79)	10M/37F	14.36 (1.58)
Study 2	103	21.62 (2.00)	30M/73F	14.50 (1.74)
Study 3	85	20.99 (1.59)	23M/62F	14.28 (1.60)

Note M - male, F - female

Procedure

Three separate studies on the association of subjective sleep quality (assessed by sleep questionnaires) and procedural learning (measured with ASRT) and other cognitive functions, such as working memory and executive functions was conducted. The tasks and questionnaires included in the studies and the timing of the ASRT task slightly differed. In Study 2, we included additional subjective sleep questionnaires: (1) a sleep diary to assess day-to-day general sleep quality and (2) Groningen Sleep Quality Scale (GSQS) to assess prior night's sleep quality.

In all three studies, PSQI and AIS sleep quality questionnaires were administered online, while the GSQS in Study 2 and the tasks assessing cognitive performance in all studies were administered in a single session in the lab. To ensure that participants do the tests in their preferred time of the day, the timing of the session was chosen by the participants themselves (between 7 am and 7 pm). The timing of the sessions was normally distributed in all three studies, with most participants performing the tasks during daytime between 11am

and 3 pm. The sleep diary in Study 2 was given to the participants 1 to 2 weeks prior to the cognitive assessment.

Questionnaires and tasks

All cognitive performance tasks and subjective sleep questionnaires are well-known and widely used in the field of psychology and neuroscience (for details about each task and questionnaire, see Supplementary methods, Additional file 1).

Subjective sleep quality questionnaires – To capture general sleep quality, we administered the *Athens Insomnia Scale* [Hungarian version: 33], the *Pittsburgh Sleep Quality Index* [Hungarian version: 34], and a *Sleep diary* [35]. Additionally, to capture the sleep quality of the night prior testing, we administered the *Groningen Sleep Quality Scale* [GSQS, 36, Hungarian version: 37].

Cognitive performance tasks – *Working memory* was measured by the Counting Span task [38-40, Hungarian version: 41] and *executive functions* were assessed by The Wisconsin Card Sorting Test [WCST, 42, 43, on a Hungarian sample: 44]. The outcome measure of this task was the number of *perseverative errors*, which shows the inability/difficulty to change the behavior despite feedback. *Procedural learning* was measured by the explicit version of the Alternating Serial Reaction Time (ASRT) task (Figure S1, [45]). There are several learning indices that can be acquired from this task. *Higher-order sequence learning* refers to the acquisition of the sequence order of the stimuli. *Statistical learning* refers to the acquisition of frequency information embedded in the task. However, previous ASRT studies often assessed *Triplet learning*, which is a mixed measure of acquiring frequency and sequential information (for details, see Supplementary methods, Additional file 1). In addition to these learning indices, we measured the average reaction times (RTs) and accuracy (ACC), and changes in RT and ACC performance from the

beginning to the end of the task, that indicate g*eneral skill learning*, such as more efficient visuo-motor and motor-motor coordination as the task progresses [46].

Data analysis

Statistical analyses were conducted in R 3.5.2 [47] with the lme4 [48] and robustlmm [49] packages, and in JASP Version 0.8.2.0 (JASP Team, 2017).

Analysis of the ASRT data - Performance in the ASRT task was analyzed by repeated measures analyses of variance (ANOVA) in each study (for details of these analyses, see Supplementary methods, Additional file 1). Based on these ANOVAs, *Triplet learning*, *Higher-order sequence learning* and *Statistical learning* occurred in all three studies, both in ACC and RT (all *p*s < .001, for details see Supplementary results, and Figure S2, Additional file 1).

Analysis of the relationship between subjective sleep quality and cognitive performance - Subjective sleep quality scales (PSQI and AIS) were combined into a single metric, using principal component analysis. Then separate linear mixed-effect models were created for each outcome measure (i.e., performance metric), where the aggregated sleep quality metric (hereinafter referred to as sleep disturbance) was used as a predictor, and 'Study' (1, 2 or 3) was added as random intercept. This way we could estimate an aggregated effect while accounting for the potential differences between studies. As residuals did not show normal distribution, we used robust estimation of model parameters using the robustlmm package [49]. Bayes Factors (BF_{01}) were calculated by using the exponential of the Bayesian Information Criterion (BIC) of the fitted models minus the BIC of the null models – that contained no predictor, but a random intercept by study [50]. The BF is a statistical technique that helps conclude whether the collected data favors the null-hypothesis (H_0) or the alternative hypothesis (H_1); thus, the BF could be considered as a weight of evidence provided by the data [51]. It is an effective mathematical approach to show if there's

no association between two measures. In Bayesian correlation analyses, H_0 is the lack of associations between the two measures, and H_1 states that association exists between the two measures. Here we report BF_{01} values. According to Wagenmakers et al. [51], BF_{01} values between 1 and 3 indicate anecdotal evidence for H_0, while values between 3 and 10 indicate substantial evidence for H_0. Conversely, while values between 1/3 and 1 indicate anecdotal evidence for H_1, values between 1/10 and 1/3 indicate substantial evidence for H_1. If the BF is below 1/10, 1/30, or 1/100, it indicates strong, very strong, or extreme evidence for H_1, respectively. Values around one do not support either H_0 or H_1. Thus, Bayes Factor is a valuable tool to provide evidence for no associations between constructs as opposed to frequentists analyses, where no such evidence can be obtained based on non-significant results.

In Study 2, to test the association between the additional subjective sleep quality measures and cognitive performance, we used a similar robust linear regression, this time without random effects. Bayes factors were calculated in the previously described way. Normality of data distribution was violated in sleep questionnaire scores, thus we only used robust methods.

Results

Combining sleep quality metrics

Principal component analysis was used to combine PSQI and AIS into a single ‘sleep disturbance’ metric. The Bartlett’s test of sphericity indicated that the correlation between the scales were adequately large for a PCA, $\chi^2(235) = 84.88$, $p < .0001$. One principal factor with an eigenvalue of 1.55 was extracted to represent sleep disturbance. The component explained 83.7% of the variance, and it was named ‘sleep disturbance’, as higher values of this metric show more disturbed sleep.

Associations between subjective sleep quality and cognitive performance

As described above, to study the associations between subjective sleep quality and cognitive performance, separate linear mixed-effect models were created for each outcome measure (i.e., cognitive performance metric), where sleep disturbance was used as a fixed predictor, and 'Study' was added as random intercept. Sleep disturbance did not show an association with any of the cognitive performance metrics (see Table 2 and Figure 1). Bayes Factors ranged from 3.49 to 14.65, thus, there is a *substantial* evidence for *no* association between subjective sleep quality and the measured cognitive processes [51].

Table 2. The association of sleep disturbance with cognitive performance metrics

Outcome	*β*	Std.error	*t*	df	*p*	BF_{01}
ACC learning indices						
ACC Triplet learning	-0.061	0.053	-1.14	230	0.2552	5.09
ACC Higher-order sequence learning	-0.072	0.055	-1.31	230	0.1904	7.00
ACC Statistical learning	-0.026	0.059	-0.43	230	0.6657	13.12
RT learning indices						
RT Triplet learning	-0.006	0.036	-0.17	230	0.8620	10.86
RT Higher-order sequence learning	0.011	0.028	0.38	230	0.7070	14.28
RT Statistical learning	-0.036	0.064	-0.55	230	0.5812	13.28
General skill indices						
Average ACC	0.039	0.034	1.15	230	0.2529	3.49
ACC general skill learning	0.068	0.035	1.93	230	0.0543	3.68
RT average	-0.066	0.066	-1.00	230	0.3192	11.47
RT general skill learning	-0.059	0.060	-0.98	230	0.3278	6.61
WM and EF indices						
Counting Span	-0.047	0.064	-0.73	230	0.4641	14.65
WCST – perseverative error	0.035	0.051	0.67	224	0.5007	8.92

Note: The table shows standardized regression coefficients for sleep disturbance, where the 'Study' random intercept was included in separate linear mixed-effect models for each cognitive performance metrics. BF_{01} was derived from BIC (see text for details). ACC = accuracy. RT = reaction time. WM = working memory. EF = executive function. WCST = Wisconsin Card Sorting Test.

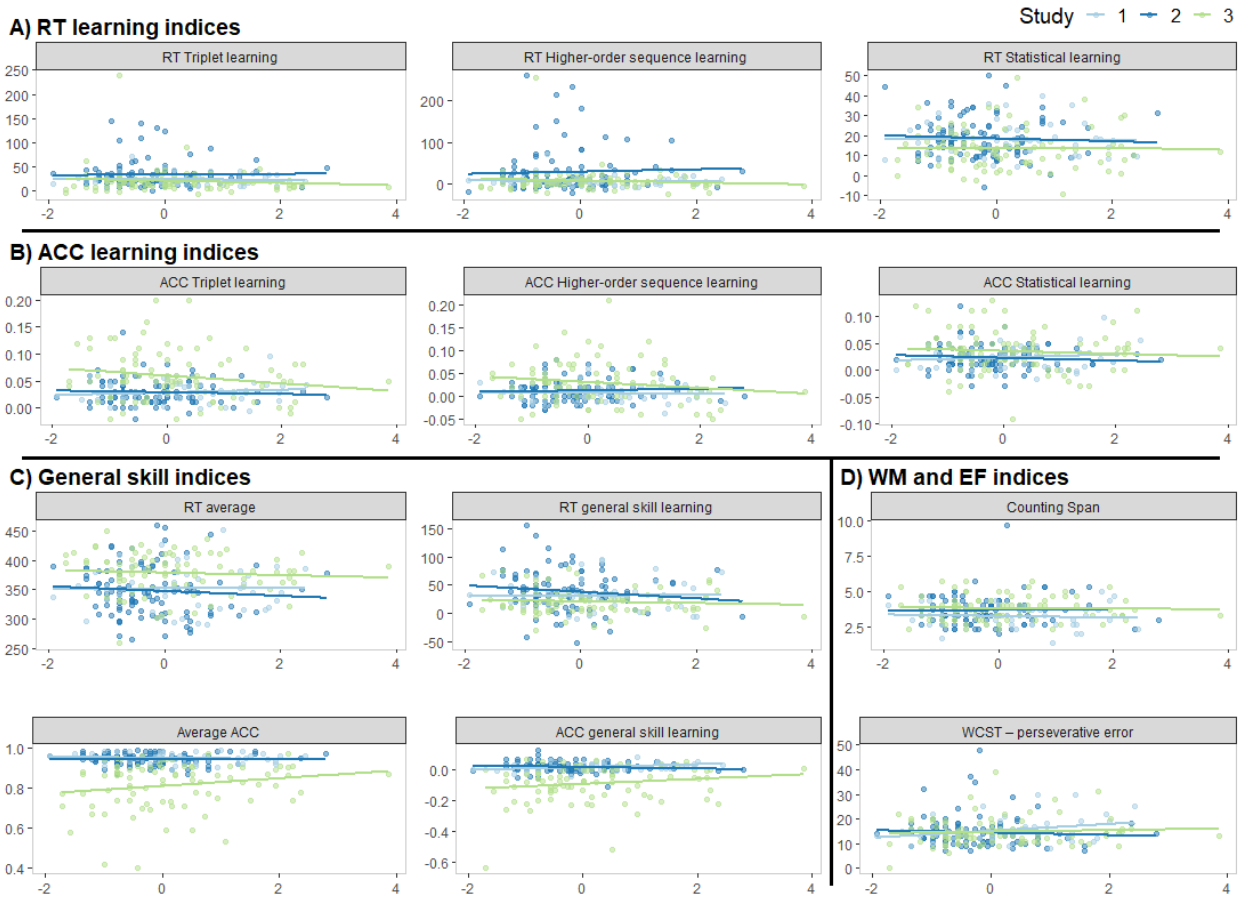

Figure 1. Association between sleep disturbance and cognitive performance metrics by study. The scatterplots and the linear regression trendlines show no association between subjective sleep quality and procedural learning indices in terms of reaction time (RT, A), or accuracy (ACC, B), general skill indices in terms of RT or ACC (C), and working memory and executive function indices (D).

In **Study 2,** to study the associations between further subjective sleep quality questionnaires and cognitive performance, we created a separate linear mixed-effect models for each outcome measure (i.e., cognitive performance metric), and each additional sleep

questionnaire (e.g. sleep diary and GSQS). Sleep diary scores did not show association with any of the cognitive performance metrics (all *p*s > .10, see Table 3 and Figure 2). Bayes Factors ranged from 2.41 to 12.58, thus, there is evidence for *no* association between subjective sleep quality and the measured cognitive processes [51].

Table 3. The association of sleep diary with cognitive performance metrics

Outcome	*β*	Std.error	*t*	df	*p*	BF_{01}
ACC learning indices						
ACC Triplet learning	-0.061	0.093	-0.65	97	0.5159	7.00
ACC Higher-order sequence learning	-0.065	0.091	-0.72	97	0.4763	8.60
ACC Statistical learning	0.013	0.095	0.14	97	0.8916	10.40
RT learning indices						
RT Triplet learning	-0.044	0.060	-0.73	97	0.4673	7.36
RT Higher-order sequence learning	0.005	0.049	0.10	97	0.9176	10.32
RT Statistical learning	-0.158	0.096	-1.65	97	0.1027	7.01
General skill indices						
Average ACC	0.042	0.104	0.40	97	0.6879	8.70
ACC general skill learning	-0.141	0.080	-1.76	97	0.0823	2.41
RT average	-0.105	0.103	-1.02	97	0.3102	12.58
RT general skill learning	-0.052	0.093	-0.56	97	0.5777	7.63
WM and EF indices						
Counting Span	-0.053	0.089	-0.59	97	0.5549	6.73
WCST – perseverative error	-0.055	0.064	-0.86	97	0.3911	6.62

Note: The table shows standardized regression coefficients for sleep diary scores in separate linear mixed-effect models for each cognitive performance metrics. BF_{01} was derived from BIC (see text for details). ACC = accuracy. RT = reaction time. WM = working memory. EF = executive function. WCST = Wisconsin Card Sorting Test.

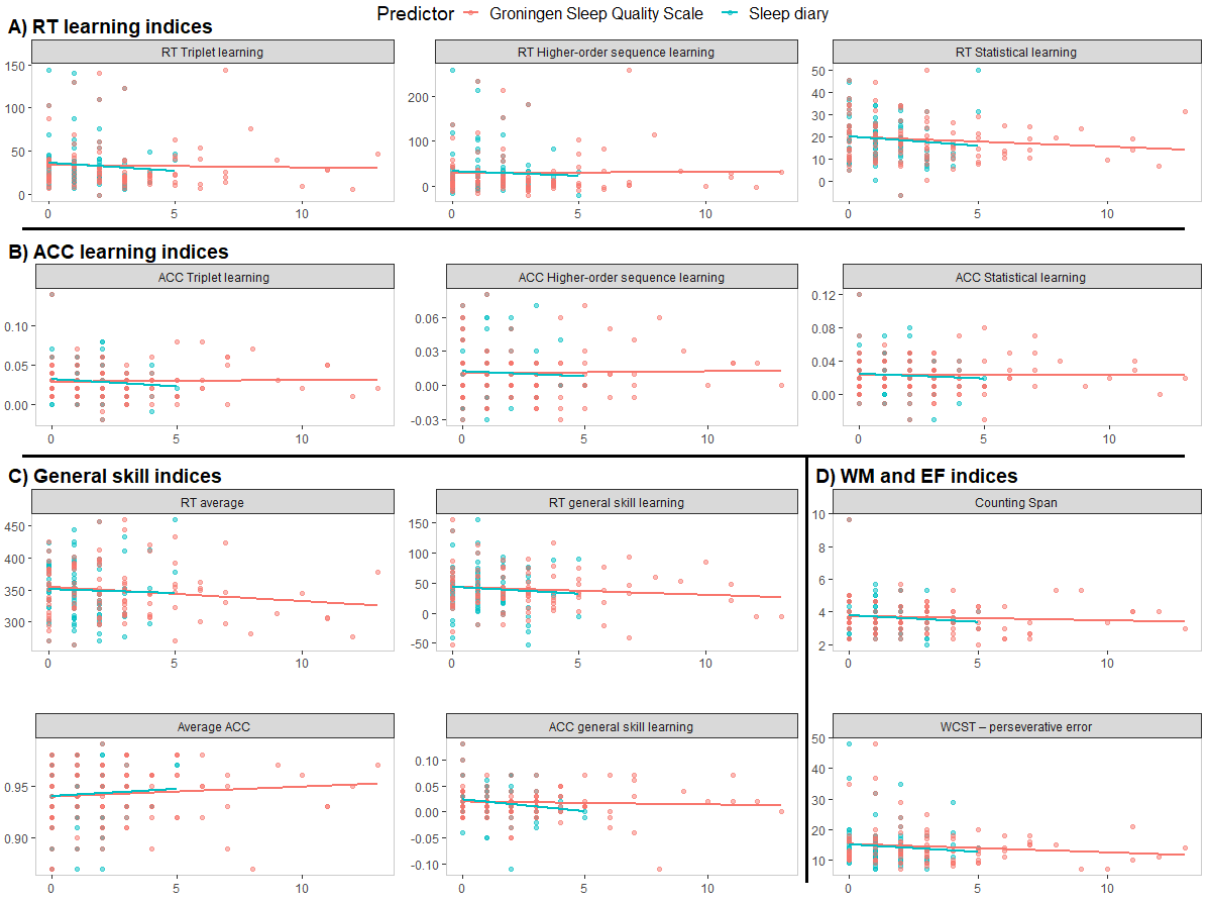

Figure 2. Association between sleep diary and GSQS scores and cognitive performance metrics. The scatterplots and the linear regression trendlines show no association between subjective sleep quality (measured with a sleep diary (blue) or the GSQS (red)) and procedural learning indices in terms of reaction time (RT, A), or accuracy (ACC, B), general skill indices in terms of RT or ACC (C), and working memory and executive function indices (D).

Similarly, GSQS scores did not show association with any of the cognitive performance metrics (all *ps* > .25, see Table 4 and Figure 2). Bayes Factors ranged from 3.30 to 11.85, thus, there is *substantial* evidence for *no* association between subjective sleep quality and the measured cognitive processes [51].

Table 4. The association of GSQS with cognitive performance metrics

Outcome	*β*	Std.error	*t*	df	*p*	BF_{01}
ACC learning indices						
ACC Triplet learning	0.042	0.088	0.48	102	0.6311	9.98
ACC Higher-order sequence learning	0.050	0.093	0.55	102	0.5841	10.35
ACC Statistical learning	0.030	0.092	0.33	102	0.7437	9.98
RT learning indices						
RT Triplet learning	-0.031	0.057	-0.54	102	0.5923	9.62
RT Higher-order sequence learning	0.0003	0.047	0.01	102	0.9952	10.05
RT Statistical learning	-0.111	0.096	-1.16	102	0.2470	4.40
General skill indices						
Average ACC	0.106	0.097	1.09	102	0.2796	5.43
ACC general skill learning	0.024	0.081	0.30	102	0.7630	11.85
RT average	-0.178	0.097	-1.84	102	0.0690	3.30
RT general skill learning	-0.096	0.089	-1.07	102	0.2882	5.61
WM and EF indices						
Counting Span	-0.048	0.088	-0.54	102	0.5888	7.87
WCST – perseverative error	-0.048	0.066	-0.72	101	0.4708	7.31

Note: The table shows standardized regression coefficients for GSQS scores in separate linear mixed-effect models for each cognitive performance metrics. BF_{01} was derived from BIC (see text for details). ACC = accuracy. RT = reaction time. WM = working memory. EF = executive function. WCST = Wisconsin Card Sorting Test.

Discussion

Our aim was to investigate, in healthy young adults, the relationship between subjective sleep quality (assessed by self-report measures) and performance in various cognitive functions, such as working memory, executive functions, and procedural learning – which has mainly been neglected in studies of subjective sleep quality before – and to show whether procedural learning is differentially associated with subjective sleep quality as opposed to working memory and executive functions. To provide more reliable results, we combined data

obtained from three different studies and included robust frequentists and Bayesian statistical analysis as well. We did not find associations between subjective sleep quality and cognitive performance. Moreover, the Bayes factors provided substantial evidence for no associations between subjective sleep quality and most measures of procedural learning, or other cognitive performance measure included in our investigation.

None of the procedural learning indices showed associations with subjective sleep quality (supported by Bayes Factors). Higher-order sequence learning, Statistical learning, Triplet learning and general skill learning (both in terms of ACC and RT) thus seem to be independent of self-reported sleep quality. In procedural learning, its relationship with objective sleep quality is still debated [27, 52-54]. The results so far have been controversial, as some studies have showed associations between various aspects of sleep, such as time spent in REM sleep [52] or time spent in NREM 2 sleep [53] and procedural learning, while others, focusing primarily on patients with sleep disorders, or examining sleep effects in an AM-PM vs. PM-AM design have not found such associations [26, 27, 54-56]. Here we focused on subjective sleep quality and showed evidence for no association with procedural learning in healthy young adults, which is consistent with previous studies showing no relationship between procedural learning performance and objective sleep measures [26, 27, 54-56]. Importantly, there is a great variability across studies in using different tasks or testing different sleep parameters, as well as in other study settings (e.g., population characteristics, or time of the day of testing). Our results suggest that procedural learning is not related to subjective sleep quality in healthy young adults. Nevertheless, further investigations with similar settings (e.g., with the same tasks and/or same sleep parameters) across studies are needed to clarify the specific circumstances under which subjective and/or objective sleep quality may be associated with aspects of procedural learning.

Contrary to our expectations, working memory and executive functions also did not show association with subjective sleep quality. As presented in the introduction, some studies reported associations between subjective sleep quality and working memory performance [5], executive functions [4] and decision making [6], although other studies also exist that failed to find such associations [7, 12]. These studies focused primarily on healthy/disordered elderly or adolescent populations. To the best of our knowledge, our study is the first that investigates cognitive performance in association with subjective sleep quality in a relatively large sample of healthy young adults. A possible explanation for the diverse results is that when cognitive performance peaks in young adulthood, subjective sleep quality may not have a substantial impact on it, while in other populations, such as in adolescents, older adults, or in various clinical disorders, where cognitive performance has not yet peaked or have declined, subjective sleep quality can have a bigger impact on performance. In line with this explanation, IB Saksvik, B Bjorvatn, H Hetland, GM Sandal and S Pallesen [57] found in their meta-analysis that young adults are not as prone to the negative consequences of shift work as the elderly. Also in support of this view, JC Lo, JA Groeger, GH Cheng, D-J Dijk and MW Chee [19] showed that sleep duration extremities (both very short or very long sleep) in elderly populations are associated with poorer cognitive functions in the domains of verbal and working memory and executive functions.

It is also worth noting that sleep quality disturbance is more prevalent in adolescent or elderly populations and in clinical disorders. Consequently, variance and extremities in subjective sleep quality could be greater in these populations, while it can remain relatively low in healthy young adults. However, the variance of the cognitive performance tasks and the subjective sleep questionnaires scores in this paper were sufficient to test associations between subjective sleep quality and cognitive performance (for details, see Supplementary results, Additional file 1). Thus, we believe that finding no association between subjective

sleep quality and cognitive performance in the current study is not due to methodological issues (such as low variance of the used measures). Another possibility that may affect the relationship between subjective sleep quality and cognitive performance is whether a poorer sleep quality is relatively transient or persists for years or even for decades. It is plausible and would worth to test *systematically* whether, and in which cases, such long-term poor sleep quality has a more detrimental effect on cognitive performance compared to a relatively more recent decline is sleep quality.

Associations between objective sleep quality (measured by actigraph or electroencephalograph) and various aspects of memory or executive functions have been frequently reported before [1, 2]. Here we showed that subjective sleep quality is not associated with working memory and executive functions. As already mentioned in the Introduction, this dissociation suggests that subjective and objective sleep quality, although measuring the same domains, do not necessarily measure the same aspects of sleep quality and sleep disturbances. GJ Landry, JR Best and T Liu-Ambrose [8] compared a sleep questionnaire (namely, PSQI) and a sleep diary with actigraphy data. According to their results, while the sleep questionnaire and the sleep diary scores moderately correlated, actigraphy data had only weak correlation with both self-reported measures. LG Guedes, GdA Abreu, DF Rodrigues, LR Teixeira, RR Luiz and KV Bloch [9] showed that the discrepancy of sleep duration quantified by actigraphy or self-reported measures can even be 1-2 hours on average. Objective and subjective assessments of sleep quality, despite the fact that they often carry labels that imply direct relationship or equivalence, may relate to different parameters [10], such as impressions of sleep quality, restedness, or sleep depth do not appear to be strongly correlated with sleep architecture. Furthermore, subjective sleep quality might be represented by a combination of more than one objective sleep parameter.

It is also possible that the important parameters of sleep that contribute to memory or executive function performance cannot be captured with self-reported instruments. For example, it is often reported (see also above), that spindle activity or time spent in slow wave sleep (SWS), or in REM sleep is essential for memory consolidation [58-60]. These sleep parameters could not be evaluated subjectively. Also, in laboratory sleep examinations, the general subjective sleep quality together with the sleep quality of preceding days of the examination is usually carefully controlled. Thus, potentially, the parameters showed to be important in the associations of objective sleep parameters and cognitive performance during a given night can only be measured in these carefully controlled conditions (i.e., when sleep quality in general and in preceding days are good). Hence it is possible that while results with objective sleep quality show how healthy sleep is related to cognitive functioning, results with subjective sleep quality may reflect aspects of sleep disturbances and their potential relationship with cognitive functioning.

Importantly, we found no associations with cognitive performance both for general sleep quality (assessed for a one-month period) and for the previous night's subjective sleep quality. The Bayes Factors showed evidence for no associations between previous night's sleep quality and procedural learning, working memory or executive function, in the case of the GSQS questionnaire. These results suggest that in healthy young adults neither persistent nor transient subjective sleep quality contribute to cognitive performance.

Considering the dissociation between objective and subjective sleep quality, the use of self-reported tools to measure sleep quality should be treated carefully in generalizing results to all aspects of sleep quality. Usage of these questionnaires should also be avoided for diagnostic purposes, as also suggested by G West, MA Vadillo, DR Shanks and C Hulme [61], who attempted to validate sleep questionnaires with PSG in insomniac patients. Comparative studies have also shown significant discrepancies between subjective and

objective measures of sleep pathology [11, 62]. Subjective sleep quality, rather than used interchangeably with objective sleep quality, should be assessed to gain further information of participants' or patients' sleep, as it may have different explanatory and predictive value to cognitive performance, and treatment seeking or outcome [12, 13]. Subjective sleep quality can be especially informative in populations with extremities in subjective sleep experience that are more susceptible to sleep disturbance. For instance, D Gavriloff, B Sheaves, A Juss, CA Espie, CB Miller and SD Kyle [63] in a recent paper showed that providing sham feedback to patients with insomnia influenced their daytime symptoms and cognitive performance such as attention and vigilance.

Our paper has some limitations. Even though we included a wide range of cognitive performance measure in our study, it remains to be tested whether self-reported sleep quality is associated with performance in other cognitive tests, such as attentional or other executive function tasks. It is also possible (as mentioned above), that investigating populations more susceptible to sleep disturbances could yield different results, and the lack of associations could be specific to healthy young adults. Furthermore, it could also be tested if individual differences in other factors (for example, interoceptive ability, i.e., how accurately one perceives their own body sensations) influence the relationship between subjective sleep quality and cognitive performance.

Conclusions

In conclusion, we showed that self-reported sleep quality is not associated with various aspects of procedural learning, working memory, and executive function in a relatively large sample of healthy young adults. These findings were supported not only by classical (frequentist) statistical analyses, but also by Bayes factors (that provided *evidence for no associations* between these functions). Importantly, however, our findings do not imply that sleep *per se* has no relationship with these cognitive functions; instead, it emphasizes the difference between self-reported and objective sleep quality. Together with previous research

on dissociations between subjective and objective sleep quality, here we outlined various situations where subjective sleep questionnaires may provide valuable information besides or instead of assessing objective sleep parameters. Nevertheless, careful consideration should be taken in all cases in order to select the best subjective/objective sleep measures depending on the research question. We believe that our approach of systematically testing the relationship between self-reported sleep questionnaires and a relatively wide range of cognitive functions can inspire future systematic studies on the relationship between subjective/objective sleep parameters and cognition.

List of abbreviations

ASRT - Alternating Serial Reaction Time

PSQI - Pittsburgh Sleep Quality Index

AIS - Athens Insomnia Scale

WCST - Wisconsin Card Sorting Task

BF - Bayes Factor

RT - Reaction Time

ACC - Accuracy

GSQS - Groningen Sleep Quality Scale

BF - Bayes Factor

FDR - False Discovery Rate

WM - Working Memory

EF - Executive Functions

REM - Rapid Eye Movement

NREM - Non-Rapid Eye Movement

Declarations

Ethics approval and consent to participate

All healthy young adult participants provided written informed consent for taking part in one of the studies. The studies were approved by the research ethics committee of Eötvös Loránd University, Budapest, Hungary (reference numbers: 201410, 2016/209). The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

Not applicable

Availability of data and materials

The datasets generated and/or analysed during the current study are available in the Open Science Framework repository, https://osf.io/hcnsx/.

Competing interests

The authors declare that they have no competing interests.

Funding

This research was supported by the Research and Technology Innovation Fund, Hungarian Brain Research Program (National Brain Research Program, project 2017-1.2.1-NKP-2017-00002); Hungarian Scientific Research Fund (NKFIH-OTKA PD 124148, PI: KJ; NKFIH-OTKA K 128016, to DN); and Janos Bolyai Research Fellowship of the Hungarian Academy of Sciences (to KJ). They had no role in study design, collection, analysis and interpretation of data, in the writing of the manuscript, and in the decision to submit the manuscript for publication.

Authors' contributions

ZZ, JK and ND designed the present study and wrote the manuscript. GA, and ZZ collected the data. GA, ZZ, JK and TN analyzed the data. ZZ, JK, TN and ND contributed to the interpretation of data and helped revising the manuscript critically for important intellectual content. All authors read and approved the final manuscript.

Acknowledgements

Authors are thankful to Csenge Török, Kata Horváth, Eszter Tóth-Fáber, Orsolya Pesthy, Noémi Éltető, Andrea Kóbor, and Ádám Takács for their help in data collection.

References

1. Diekelmann S, Born J: The memory function of sleep. *Nature Reviews Neuroscience* 2010, 11(2):114-126.
2. Jones K, Harrison Y: Frontal lobe function, sleep loss and fragmented sleep. *Sleep Med Rev* 2001, 5(6):463-475.
3. Fortier-Brochu É, Beaulieu-Bonneau S, Ivers H, Morin CM: Insomnia and daytime cognitive performance: a meta-analysis. *Sleep Med Rev* 2012, 16(1):83-94.
4. Nebes RD, Buysse DJ, Halligan EM, Houck PR, Monk TH: Self-reported sleep quality predicts poor cognitive performance in healthy older adults. *The Journals of Gerontology: Series B* 2009, 64(2):180-187.
5. van den Noort M, Struys E, Perriard B, Staudte H, Yeo S, Lim S, Bosch P: Schizophrenia and depression: The relation between sleep quality and working memory. *Asian J Psychiatr* 2016, 24:73-78.
6. Telzer EH, Fuligni AJ, Lieberman MD, Galván A: The effects of poor quality sleep on brain function and risk taking in adolescence. *Neuroimage* 2013, 71:275-283.
7. Miyata S, Noda A, Iwamoto K, Kawano N, Okuda M, Ozaki N: Poor sleep quality impairs cognitive performance in older adults. *J Sleep Res* 2013, 22(5):535-541.
8. Landry GJ, Best JR, Liu-Ambrose T: Measuring sleep quality in older adults: a comparison using subjective and objective methods. *Frontiers in aging neuroscience* 2015, 7.
9. Guedes LG, Abreu GdA, Rodrigues DF, Teixeira LR, Luiz RR, Bloch KV: Comparison between self-reported sleep duration and actigraphy among adolescents: gender differences. *Revista Brasileira de Epidemiologia* 2016, 19(2):339-347.

10. Armitage R, Trivedi M, Hoffmann R, Rush AJ: Relationship between objective and subjective sleep measures in depressed patients and healthy controls. *Depression and anxiety* 1997, 5(2):97-102.

11. Zhang L, Zhao Z-X: Objective and subjective measures for sleep disorders. *Neuroscience Bulletin* 2007, 23(4):236-240.

12. Stepanski E, Koshorek G, Zorick F, Glinn M, Roehrs T, Roth T: Characteristics of individuals who do or do not seek treatment for chronic insomnia. *Psychosomatics* 1989, 30(4):421-427.

13. Draganich C, Erdal K: Placebo sleep affects cognitive functioning. *J Exp Psychol Learn Mem Cogn* 2014, 40(3):857.

14. Buysse DJ, Reynolds III CF, Monk TH, Berman SR, Kupfer DJ: The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. *Psychiatry Res* 1989, 28(2):193-213.

15. Soldatos CR, Dikeos DG, Paparrigopoulos TJ: Athens Insomnia Scale: validation of an instrument based on ICD-10 criteria. *J Psychosom Res* 2000, 48(6):555-560.

16. Libman E, Fichten CS, Bailes S, Amsel R: Sleep questionnaire versus sleep diary: which measure is better? *International Journal of Rehabilitation and Health* 2000, 5(3):205-209.

17. Naismith S, Winter V, Gotsopoulos H, Hickie I, Cistulli P: Neurobehavioral functioning in obstructive sleep apnea: differential effects of sleep quality, hypoxemia and subjective sleepiness. *J Clin Exp Neuropsychol* 2004, 26(1):43-54.

18. Bastien CH, Fortier-Brochu É, Rioux I, LeBlanc M, Daley M, Morin CM: Cognitive performance and sleep quality in the elderly suffering from chronic insomnia: relationship between objective and subjective measures. *J Psychosom Res* 2003, 54(1):39-49.

19. Lo JC, Groeger JA, Cheng GH, Dijk D-J, Chee MW: Self-reported sleep duration and cognitive performance in older adults: a systematic review and meta-analysis. *Sleep Med* 2016, 17:87-98.

20. Poldrack RA, Clark J, Pare-Blagoev EJ, Shohamy D, Creso Moyano J, Myers C, Gluck MA: Interactive memory systems in the human brain. *Nature* 2001, 414(6863):546-550.

21. Fiser J, Aslin RN: Unsupervised statistical learning of higher-order spatial structures from visual scenes. *Psychol Sci* 2001, 12(6):499-504.

22. Howard JH, Jr., Howard DV: Age differences in implicit learning of higher-order dependencies in serial patterns. *Psychol Aging* 1997, 12(4):634-656.

23. Lieberman MD: Intuition: a social cognitive neuroscience approach. *Psychol Bull* 2000, 126(1):109-137.

24. Poldrack RA, Foerde K: Category learning and the memory systems debate. *Neurosci Biobehav Rev* 2008, 32(2):197-205.

25. Pothos EM: Theories of artificial grammar learning. *Psychol Bull* 2007, 133(2):227-244.

26. Csabi E, Benedek P, Janacsek K, Zavecz Z, Katona G, Nemeth D: Declarative and Non-declarative Memory Consolidation in Children with Sleep Disorder. *Front Hum Neurosci* 2015, 9:709.

27. Nemeth D, Csábi E, Janacsek K, Varszegi M, Mari Z: Intact implicit probabilistic sequence learning in obstructive sleep apnea. *J Sleep Res* 2012, 21(4):396-401.

28. Backhaus J, Junghanns K, Born J, Hohaus K, Faasch F, Hohagen F: Impaired declarative memory consolidation during sleep in patients with primary insomnia: influence of sleep architecture and nocturnal cortisol release. *Biol Psychiatry* 2006, 60(12):1324-1330.

29. Nissen C, Kloepfer C, Nofzinger EA, Feige B, Voderholzer U, Riemann D: Impaired sleep-related memory consolidation in primary insomnia-a pilot study. *SLEEP-NEW YORK THEN WESTCHESTER-* 2006, 29(8):1068.

30. Török CJ, Karolina; Nemeth Dezso: How to boost consolidation of implicit probabilistic learning by manipulation of reconsolidation. In: *INTERNATIONAL CONFERENCE ON MEMORY* Budapest, Hungary; 2016.

31. Simor P, Zavecz Z, Horvath K, Elteto N, Török C, Pesthy O, Gombos F, Janacsek K, Nemeth D: Deconstructing procedural memory: Different learning trajectories and consolidation of sequence and statistical learning. *Front Psychol* 2019, 9:2708.

32. Takács ÁK, Andrea.; Janacsek, Karolina.; Honbolygó, Ferenc.; Kardos, Zsófia.; & Nemeth, Dezso. : Controlled and automatic functions in risk-taking behavior. In: *3rd Conference of the European Society for Cognitive and Affective Neuroscience*. Porto, Portugal; 2016.

33. Novak M, Mucsi I, Shapiro CM, Rethelyi J, Kopp MS: Increased utilization of health services by insomniacs—an epidemiological perspective. *J Psychosom Res* 2004, 56(5):527-536.

34. Takács J, Bódizs R, Ujma PP, Horváth K, Rajna P, Harmat L: Reliability and validity of the Hungarian version of the Pittsburgh Sleep Quality Index (PSQI-HUN): comparing psychiatric patients with control subjects. *Sleep and Breathing* 2016, 20(3):1045-1051.

35. Gilson M, Deliens G, Leproult R, Bodart A, Nonclercq A, Ercek R, Peigneux P: REM-enriched naps are associated with memory consolidation for sad stories and enhance mood-related reactivity. *Brain sciences* 2015, 6(1):1.

36. Meijman T, de Vries-Griever A, De Vries G, Kampman R: The evaluation of the Groningen sleep quality scale. *Groningen: Heymans Bulletin (HB 88-13-EX)* 1988, 2006.

37. Simor P, Köteles F, Bódizs R, Bárdos G: A questionnaire based study of subjective sleep quality: the psychometric evaluation of the Hungarian version of the Groningen Sleep Quality Scale. *Mentálhigiéné és Pszichoszomatika* 2009, 10(3):249-261.

38. Case R, Kurland DM, Goldberg J: Operational efficiency and the growth of short-term memory span. *J Exp Child Psychol* 1982, 33(3):386-404.

39. Engle RW, Tuholski SW, Laughlin JE, Conway ARA: Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *J Exp Psychol* 1999, 128(3):309-331.

40. Conway AR, Kane MJ, Bunting M, Hambrick DZ, Wilhelm O, Engle RW: Working memory span tasks: A methodological review and user's guide. *Psychonomic Bulletin & Review* 2005, 12(5):769-786.

41. Virag M, Janacsek K, Horvath A, Bujdoso Z, Fabo D, Nemeth D: Competition between frontal lobe functions and implicit sequence learning: evidence from the long-term effects of alcohol. *Exp Brain Res* 2015, 233(7):2081-2089.

42. Berg EA: A simple objective treatment for measuring flexibility in thinking. *J Gen Psychol* 1948, 39:15-22.

43. Piper BJ, Mueller ST, Geerken AR, Dixon KL, Kroliczak G, Olsen RH, Miller JK: Reliability and validity of neurobehavioral function on the Psychology Experimental Building Language test battery in young adults. *PeerJ* 2015, 3:e1460.

44. Nemeth D, Janacsek K, Polner B, Kovacs ZA: Boosting Human Learning by Hypnosis. *Cereb Cortex* 2013, 23(4):801-805.

45. Nemeth D, Janacsek K, Fiser J: Age-dependent and coordinated shift in performance between implicit and explicit skill learning. *Front Comput Neurosci* 2013, 7.

46. Hallgato E, Győri-Dani D, Pekár J, Janacsek K, Nemeth D: The differential consolidation of perceptual and motor learning in skill acquisition. *Cortex* 2013, 49(4):1073-1081.

47. Team RC: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Austria, 2015. In.: ISBN 3-900051-07-0: URL http://www. R-project. org; 2018.

48. Bates D, Mächler M, Bolker B, Walker S: Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* 2015, 67(1):1-48.

49. Koller M: robustlmm: an R package for robust estimation of linear mixed-effects models. *Journal of statistical software* 2016, 75(6):1-24.

50. Wagenmakers EJ: A practical solution to the pervasive problems of p values. *Psychon Bull Rev* 2007, 14(5):779-804.

51. Wagenmakers EJ, Wetzels R, Borsboom D, van der Maas HL: Why psychologists must change the way they analyze their data: the case of psi: comment on Bem (2011). *J Pers Soc Psychol* 2011, 100(3):426-432.

52. Fischer S, Hallschmid M, Elsner AL, Born J: Sleep forms memory for finger skills. *PNAS* 2002, 99(18):11987-11991.

53. Walker MP, Brakefield T, Morgan A, Hobson JA, Stickgold R: Practice with sleep makes perfect: sleep-dependent motor skill learning. *Neuron* 2002, 35(1):205-211.

54. Wilhelm I, Diekelmann S, Born J: Sleep in children improves memory performance on declarative but not procedural tasks. *Learn Mem* 2008, 15(5):373-377.

55. Csabi E, Varszegi-Schulz M, Janacsek K, Malecek N, Nemeth D: The consolidation of implicit sequence memory in obstructive sleep apnea. *PLoS One* 2014, 9(10):e109010.

56. Simor P, Zavecz Z, Csábi E, Benedek P, Janacsek K, Gombos F, Németh D: Delta and theta activity during slow-wave sleep are associated with declarative but not with non-declarative learning in children with sleep-disordered breathing. *Sleep Spindles & Cortical Up States* 2017, 1(1):55-66.

57. Saksvik IB, Bjorvatn B, Hetland H, Sandal GM, Pallesen S: Individual differences in tolerance to shift work–a systematic review. *Sleep Med Rev* 2011, 15(4):221-235.

58. Walker MP: The Role of Slow Wave Sleep in Memory Processing. *J Clin Sleep Med* 2009, 5(2 Suppl):S20-S26.

59. Siegel DJ: Memory: an overview, with emphasis on developmental, interpersonal, and neurobiological aspects. *J Am Acad Child Adolesc Psychiatry* 2001, 40(9):997-1011.

60. Clemens Z, Fabo D, Halasz P: Overnight verbal memory retention correlates with the number of sleep spindles. *Neuroscience* 2005, 132(2):529-535.

61. West G, Vadillo MA, Shanks DR, Hulme C: The procedural learning deficit hypothesis of language learning disorders: we see some problems. *Developmental science* 2017.

62. Tang NK, Harvey AG: Correcting distorted perception of sleep in insomnia: a novel behavioural experiment? *Behav Res Ther* 2004, 42(1):27-39.

63. Gavriloff D, Sheaves B, Juss A, Espie CA, Miller CB, Kyle SD: Sham sleep feedback delivered via actigraphy biases daytime symptom reports in people with insomnia: Implications for insomnia disorder and wearable devices. *J Sleep Res* 2018:e12726.