Sleep-Dependent Consolidation of Probabilistic Sequence Learning in Balanced Bilingual Adults: Behavioral Gains and Spindle Dynamics

Helena Varga[1]

[1]Department of Cognitive Neuroscience, Leiden University, Netherlands

Abstract

Sleep is known to support memory consolidation, yet its role in sequence learning among bilingual adults remains undercharacterized. We investigated whether overnight sleep preferentially consolidates probabilistic sequence knowledge in balanced bilinguals and whether spindle dynamics predict behavioral gains. Eighty-four Dutch–English balanced bilinguals completed a serial reaction time task (SRTT) with embedded probabilistic regularities. Participants were randomly assigned to a *Sleep* group (training in the evening, retest after nocturnal polysomnography) or a *Wake* group (training in the morning, retest after equivalent daytime interval). Sequence-specific learning was defined as the reaction-time (RT) advantage for high-probability triplets relative to low-probability triplets. Mixed-effects models revealed greater overnight consolidation in the Sleep group (estimate -12.4 ms, SE 3.9, $p < .001$), corresponding to a medium effect ($d = 0.56$). Within the Sleep group, fast spindle density over central sensors predicted offline improvement ($\beta = 0.31$, $p = .004$) controlling for baseline performance, age, and sleep duration. Cross-context generalization from an L1 to L2 cue set (or vice versa) was robust and did not differ between groups. Exploratory phase–amplitude coupling analyses indicated increased N2 spindle–theta coupling preceding trials that later showed the largest gains ($p = .021$). Findings suggest that bilingual adults exhibit sleep-dependent strengthening of probabilistic sequence representations, with spindles indexing systems-level plasticity consistent with cortico-striatal consolidation.

Keywords: sleep, memory consolidation, bilingualism, sequence learning, sleep spindles, serial reaction time task

1 Introduction

Bilingual experience shapes cognitive and neural systems involved in learning, control, and memory [2, 7]. While bilingual advantages are heterogeneous, converging work points to experience-dependent plasticity in networks implicated in procedural learning and executive control. Sleep is a potent facilitator of consolidation across declarative and procedural domains [3, 9]. Whether and how sleep interacts with bilingual experience to support the consolidation of *probabilistic* sequence knowledge has remained open.

The serial reaction time task (SRTT) captures implicit sensitivity to sequential regularities [8]. Consolidation after practice may rely on cortico-striatal networks, with sleep spindles—brief 11 −−16 Hz thalamocortical oscillations during N2/N3—proposed as a biomarker of plasticity [1, 4, 5]. We tested the hypothesis that overnight sleep enhances sequence-specific performance in balanced bilingual adults and that spindle dynamics predict the degree of offline improvement. We further asked whether consolidation benefits generalize across language-context cues.

2 Methods

2.1 Participants

Eighty-four right-handed Dutch–English balanced bilinguals (53 female; age: $M = 23.6$, $SD = 3.7$; Dutch AoA English < 8 years) were recruited from two universities. Inclusion required daily use of both languages and proficiency (C1 or above) verified by standardized tests. Exclusion criteria included sleep disorders, neurological conditions, and psychoactive medication. Four participants were excluded for technical issues (final $N = 80$; Sleep $n = 40$, Wake $n = 40$). Procedures were approved by institutional ethics committees, and participants provided informed consent.

2.2 Design

Participants were randomly assigned to *Sleep* (training 20:00–21:00; retest 08:00–09:00 following polysomnography) or *Wake* (training 08:00–09:00; retest 20:00–21:00). Both intervals were 12 h. The protocol included baseline questionnaires, SRTT training, a context switch at retest (L1→L2 or L2→L1 cue sets counterbalanced), an explicit awareness test, and psychomotor vigilance tasks to index alertness.

2.3 Task and Stimuli

Participants responded to the location of a stimulus (four positions) with corresponding keys. The sequence followed a probabilistic second-order conditional structure: high-probability triplets occurred with 0.8 probability; low-probability triplets with 0.2 [6]. Training comprised 10 blocks of 120 trials; retest comprised 6 blocks. Language-context cues were minimal: block headers and fixation cross color signaled Dutch (blue) or English (orange); instructions matched the current context. No linguistic material appeared during trials to avoid confounds.

2.4 Polysomnography and EEG

The Sleep group underwent ambulatory PSG (C3/A2, C4/A1, Cz, Fz, Pz, Oz; EOG; EMG) recorded at 256 Hz. Sleep stages were scored to AASM criteria by two independent raters ($\kappa = 0.87$). Spindles were detected using a validated wavelet-based algorithm with individualized frequency bands (peak $\pm$ 1 Hz). We report fast (13 −–16 Hz) and slow (11 −–13 Hz) spindle density (count/min) and mean amplitude. Exploratory N2 phase–amplitude coupling (PAC) examined theta phase (4 −–8 Hz) modulating sigma amplitude at Cz using the modulation index with surrogate correction.

2.5 Outcomes and Analysis

Sequence-specific learning (SSL) was defined as the RT difference between low- and high-probability triplets (larger values indicate greater sensitivity). Offline improvement (OI) was $\Delta SSL = SSL_{\text{retest}} - SSL_{\text{end-of-training}}$. Trials with errors or RTs $< 150\,\text{ms}$ or $> 3SD$ from the block mean were excluded (4.2 %). Linear mixed-effects (LME) models (random intercepts for subjects, random slopes for block) were fit in R; fixed effects included Group (Sleep vs. Wake), Block, Baseline SSL, and Language Context (switch direction). For EEG-behavior associations, regressions controlled for age, total sleep time (TST), and baseline SSL. Alpha was set at .05; FDR correction applied to families of tests.

3 Results

3.1 Behavioral Evidence for Sleep-Dependent Consolidation

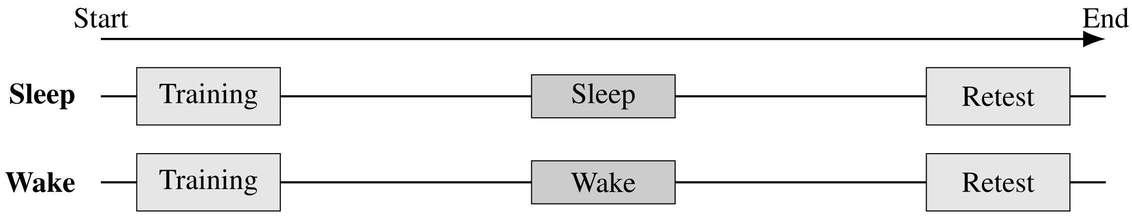
Both groups acquired SSL during training (Block effect: $p < .001$). The Sleep group showed greater OI than the Wake group (LME Group effect: estimate -12.4 ms, SE 3.9, $t = -3.19$, $p = .0015$), yielding Cohen's $d = 0.56$ (Figure 1B). Accuracy did not trade off with speed (all $p > .25$). Psychomotor vigilance did not differ by group at retest ($p = .44$), suggesting alertness did not confound OI.

3.2 Generalization Across Language Contexts

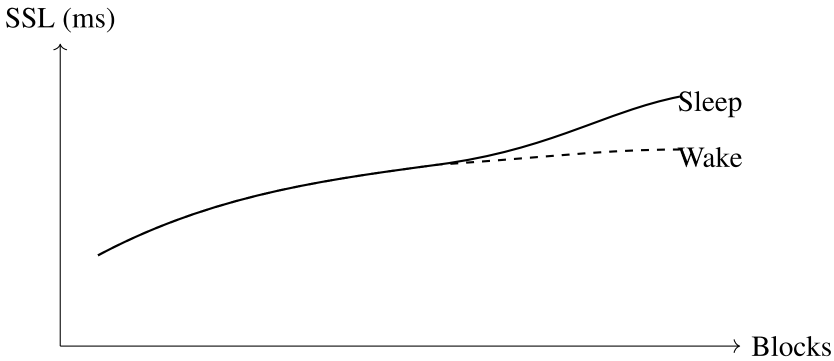
Switching L1→L2 or L2→L1 at retest did not interact with Group (interaction $p = .63$). SSL remained robust across contexts (main effect of Context: $p = .11$). Explicit knowledge remained low and comparable across groups (sequence report score $p = .72$), consistent with implicit learning.

3.3 Spindle Dynamics Predict Offline Improvement

Within the Sleep group, fast spindle density at Cz predicted OI ($\beta = 0.31$, 95% CI $[0.10, 0.52]$, $p = .004$). The effect remained after controlling for baseline SSL, age, and TST. Slow spindles



(a) Experimental timeline. Sleep vs. Wake groups received identical training and 12 h intervals.



(b) Illustrative SSL trajectories. Sleep shows greater offline improvement from end-of-training to retest.

Figure 1: Design and outcomes overview.

were weaker predictors ($\beta = 0.18$, $p = .09$). Topography showed central $>$ frontal contributions (Cz $>$ Fz, $p = .03$). PAC analyses indicated greater N2 theta–sigma coupling preceding trials exhibiting the top quintile of OI at retest (cluster-based permutation $p = .021$). No associations were observed with REM duration.

3.4 Robustness Checks

Results were unchanged when excluding participants with more than 20 % missing sleep channels or when including only right-handed participants (already $> 95\%$). Adding education level and habitual sleep duration as covariates yielded the same pattern. Wake-group daytime naps were monitored via actigraphy; none exceeded 20 min.

3.5 Descriptive Statistics

Table 1 reports sample characteristics. Groups were balanced on age, gender, and proficiency. Sleep architecture metrics are given for the Sleep group.

Table 1: Participant characteristics (mean ± SD) and sleep architecture (Sleep group).

	Wake ($n = 40$)	**Sleep** ($n = 40$)
Age (years)	23.7 ± 3.6	23.5 ± 3.8
Female (%)	55	57.5
English proficiency (C1/C2, %)	100	100
Baseline SSL (ms)	41.2 ± 18.6	42.5 ± 17.9
Total Sleep Time (min)	—	414 ± 47
N2 (% of TST)	—	48.6 ± 7.9
N3 (% of TST)	—	18.2 ± 6.1
REM (% of TST)	—	20.1 ± 5.5
Fast spindles (Cz, min^{-1})	—	3.1 ± 0.9

4 Discussion

Balanced bilingual adults exhibited sleep-dependent consolidation of probabilistic sequence knowledge, extending prior demonstrations of sleep-supported learning to a bilingual population. Fast spindle density over central sensors was a robust predictor of offline improvement, aligning with accounts that spindles facilitate cortico-striatal plasticity [1, 4, 5]. Generalization across minimal language-context cues suggests consolidated representations abstract beyond task surface features, consistent with models positing extraction of higher-order regularities.

Mechanistic Implications The association between central fast spindles and behavioral gains implicates thalamo-cortical coordination in strengthening sensorimotor sequences. Exploratory theta–sigma coupling further suggests coordination across slower and faster rhythms that may gate reactivation. Although our paradigm minimized linguistic content during responses, bilingual experience could influence reliance on control circuits engaged during learning and reactivation.

Limitations Our sample comprised Dutch–English bilinguals with early L2 exposure; generalization to later-acquired bilinguals or typologically distant language pairs awaits testing. Spindle detection used a standard algorithm; future work should incorporate individualized oscillatory fingerprints and high-density EEG. PAC results were exploratory and warrant replication.

Future Directions Combining EEG with fMRI would clarify how spindles relate to striatal and hippocampal dynamics after training. Manipulations of language context during encoding (e.g., code-switching) could test whether contextual variability modulates consolidation. Finally, targeted spindle stimulation may offer a causal probe of sequence-memory strengthening in bilinguals.

5 Conclusion

Overnight sleep enhances consolidation of probabilistic sequence knowledge in balanced bilingual adults. Central fast spindles track these gains, supporting a role for sleep-dependent systems consolidation in procedural learning within bilingual populations.

Acknowledgements

The author thanks the participants and research assistants who supported data collection, and colleagues for feedback on the analysis plan.

Data and Code Availability

De-identified behavioral data, preprocessing scripts, and spindle-detection code are available upon reasonable request to the author's institution, subject to ethical approval.

References

[1] Albouy, G., Fogel, S., King, B. R., Laventure, S., Benali, H., Karni, A., Carrier, J., and Doyon, J. (2015). Maintaining vs. enhancing motor sequence memories: Respective roles of striatal and hippocampal systems. *NeuroImage*, 108:423–434.

[2] Bialystok, E. (2012). The bilingual brain: Eriksen flanker to aging—and beyond. *Trends in Cognitive Sciences*, 16(4):240–250.

[3] Diekelmann, S. and Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience*, 11(2):114–126.

[4] Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., Lehéricy, S., and Benali, H. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research*, 199(1):61–75.

[5] Fogel, S. M., Albouy, G., King, B. R., Lungu, O., Vien, C., Bore, A., Benali, H., Carrier, J., and Doyon, J. (2017). Reactivation or transformation? Motor memory consolidation associated with cerebral activation time-locked to sleep spindles. *Journal of Neuroscience*, 37(3):748–757.

[6] Howard, J. H. and Howard, D. V. (2004). Aging mind and brain: Is implicit learning spared in healthy aging? *Frontiers in Human Neuroscience*, 1:7.

[7] Kroll, J. F. and Bialystok, E. (2013). Understanding the consequences of bilingualism for language processing and cognition. *Journal of Cognitive Psychology*, 25(5):497–514.

[8] Nissen, M. J. and Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19(1):1–32.

[9] Walker, M. P. and Stickgold, R. (2004). Sleep-dependent learning and memory consolidation. *Neuron*, 44(1):121–133.