



**HAL**  
open science

## The effect of a post-learning nap on motor memory consolidation in people with Parkinson's disease: a randomised controlled trial

Letizia Micca, Genevieve Albouy, Bradley R King, Nicholas D'cruz, Alice Nieuwboer, Wim Vandenberghe, Pascal Borzée, Bertien Buysse, Dries Testelmans, Judith Nicolas, et al.

### ► To cite this version:

Letizia Micca, Genevieve Albouy, Bradley R King, Nicholas D'cruz, Alice Nieuwboer, et al.. The effect of a post-learning nap on motor memory consolidation in people with Parkinson's disease: a randomised controlled trial. 2025. hal-04903456

**HAL Id: hal-04903456**

**<https://hal.science/hal-04903456v1>**

Preprint submitted on 21 Jan 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# The effect of a post-learning nap on motor memory consolidation in people with Parkinson's disease: a randomised controlled trial

Letizia Micca<sup>1</sup>; Genevieve Albouy<sup>2,3</sup>; Bradley R King<sup>3</sup>; Nicholas D'Cruz<sup>1</sup>; Alice Nieuwboer<sup>1</sup>; Wim Vandenberghe<sup>6,7</sup>; Pascal Borzée<sup>4</sup>; Bertien Buysse<sup>4,5</sup>; Dries Testelmans<sup>4,5</sup>; Judith Nicolas<sup>8\*</sup>; Moran Gilat<sup>1\*</sup>

\* Shared last authorship

1 – KU Leuven, Department of Rehabilitation Sciences, Neurorehabilitation Research Group (eNRGy), Leuven, Belgium

2 – KU Leuven, Movement Sciences Department, Leuven, Belgium

3 – University of Utah, Department of Health & Kinesiology, Salt Lake City, United States

4 – University Hospitals Leuven, Department of Pneumology, Leuven, Belgium

5 – KU Leuven, Department of Chronic Diseases and Metabolism, Laboratory of Respiratory Diseases and Thoracic Surgery (BREATHE), Leuven, Belgium

6 – University Hospitals Leuven, Department of Neurology, Leuven, Belgium

7 – KU Leuven, Department of Neurosciences, Leuven, Belgium

8 – Centre de Recherche en Neurosciences de Lyon - Inserm U1028 / CNRSUMR5292, Perception, Attention, Mémoire, BRON Cedex, France

**Keywords:** Healthy ageing; Rehabilitation; Retention; Napping; Motor Sequence Learning ; Dual-tasking; Automaticity; Electroencephalography

## Abstract

### *Study Objectives*

Motor memory consolidation is a process by which newly acquired skills become stable over time in the absence of practice. Sleep facilitates consolidation, yet it remains unknown whether sleep-dependent consolidation is intact in people with Parkinson's disease (PD). Here, we investigated whether a post-learning nap - as compared to wakefulness - improves motor memory consolidation in PD.

### *Methods*

Thirty-two people with PD and 32 healthy older adults (HOA) learned a finger-tapping sequence task before being randomized to a nap or wake intervention. Consolidation was measured as the change in performance between pre- and post-intervention and at 24-hours retention. Automaticity was measured with a dual-task assessed post-intervention and at retention. Sleep architecture and electrophysiological markers of plasticity were extracted from the experimental nap to assess their association with performance changes.

### *Results*

Behavioural results provided weak evidence for equivalent benefit of sleep-dependent consolidation over wakefulness in both PD and HOA, and no difference of intervention effects between groups. Napping did not affect dual-task costs in PD or HOA. Results suggested positive associations between performance improvements and slow wave density, amplitude, slope, and spindle amplitude in PD and not in HOA.

**NOTE:** This preprint reports new research that has not been certified by peer review and should not be used to guide clinical practice.

## Conclusions

A post-learning nap had similar effects in PD and HOA, yet the evidence remains inconclusive. Further, napping did not have a beneficial effect over wake in either group. In PD, sleep markers of plasticity were associated to performance improvements, suggesting that equivalent performance output between HOA and PD may be achieved using different consolidation mechanisms.

## Statement of significance

This is the first study to directly compare the effect of post-learning napping with wakefulness on motor memory consolidation in people with Parkinson's disease (PD), showing no beneficial effect of sleep as compared to wakefulness. Further, motor memory consolidation may be unaffected in PD as compared to healthy older adults. In PD, electrophysiological markers of plasticity during sleep were positively associated to motor performance improvement, indicating that HOA and PD may achieve equivalent performance outcomes through different consolidation mechanisms.

## Introduction

Parkinson's disease (PD) is the second most common neurodegenerative disorder worldwide, characterised primarily by the progressive degeneration of nigrostriatal dopaminergic neurons (Morrish et al., 1996). Eventually, the striatal dopamine depletion results in the cardinal motor symptoms of bradykinesia with resting tremor and/or muscle rigidity (Postuma et al., 2015). The progressive striatal dysfunction in PD likely impacts motor memory at different levels including learning during practice, consolidation, retention and automaticity (Nackaerts et al., 2020). Consolidation is a process that transforms recently acquired memory traces into robust and long-lasting memories in the absence of further practice (i.e., offline) (Born & Wilhelm, 2012). Practice and consolidation are needed to achieve retention and automaticity. Retention indicates that the learned skill has become robust against interposed activities and time, with performance usually re-assessed after a period of at least 24 hours. Automaticity indicates the ability to perform the motor task without focused attention, typically assessed with a dual-task (Bernstein, 1967). In PD, initial motor learning is relatively spared (Muslimović et al., 2007) but retention and ultimately automaticity are clearly impaired (Doyon et al., 2003, 2009; Nieuwboer, Rochester, Müncks, et al., 2009). Therefore, deficits in consolidation have been hypothesized and demonstrated already early in PD under certain task conditions (Marinelli et al., 2017). Hence, many neurorehabilitation strategies that depend on the acquisition or re-learning of motor skills and their retention (e.g., writing training or strategies for fall prevention) actually require continued practice and attentional resources to maintain sufficient performance levels in PD (Nieuwboer, Rochester, Müncks, et al., 2009; Wu, Hallett, et al., 2015).

In healthy young adults, non-rapid eye movement (NREM) sleep, particularly stages 2 (N2) and 3 (N3) (Born & Wilhelm, 2012), is known to enhance memory consolidation of tasks engaging the hippocampo-cortical network, such as the motor sequence learning (MSL) task (Backhaus & Junghanns, 2006; S. M. Fogel et al., 2014; Korman et al., 2007; Nishida & Walker, 2007). In healthy older adults (HOA) sleep-facilitated consolidation is diminished, but can appear under certain conditions (Fitzroy et al., 2021; S. M. Fogel et al., 2014; King et al., 2013). In people with PD, only three prior studies investigated the role of sleep on motor memory consolidation, all using MSL tasks. Interestingly, these three studies showed that sleep following practice showed similar effects on consolidation as in HOA (Dan et al., 2015; Lanir-Azaria et al., 2024; Terpening et al., 2013). Unfortunately, none of these studies directly compared sleep with an equivalent period of wake to determine whether these effects were specifically sleep-dependent.

Sleep-dependent motor memory consolidation reduction in HOA is likely due to age-related alterations of sleep macro-architecture, such as increased sleep fragmentation with greater amounts of wakefulness and percentage of stage 1 (N1) sleep, and reduced amounts of N3 sleep (Moraes et al., 2014). The sleep electrophysiological markers of plasticity, such as spindles, slow wave and their coupling, are also altered in HOA with decreased amplitude of spindles and slow waves, and a delayed coupling between the two (Carrier et al., 2001; S. Fogel et al., 2012; S. M. Fogel et al., 2014; King et al., 2013, 2017). Notably, people with PD experience even more severe sleep disruptions than HOA (Xu et al., 2021). Indeed, sleep disorders in PD, such as REM sleep behaviour disorder (RBD), sleep onset and maintenance, insomnia, as well as excessive daytime somnolence (Barone et al., 2009; Cochen et al., 2009; Lajoie et al., 2021), are known to have a disruptive impact on quality of life (Barone et al., 2009), and eventually affecting cognition (Latreille et al., 2015). Yet, the specific impact of sleep disorders on motor memory consolidation in PD remains unclear. Sleep spindles and slow waves exhibit reduced amplitudes in PD compared to HOA (Latreille et al., 2015), whereas a recent case-control study surprisingly found stronger coupling between spindles and slow waves in PD compared to HOA (Memon et al., 2023). Additionally, greater spindle density was associated to better overnight consolidation of a verbal pair-association cognitive task in people with PD (Lahlou et al., 2024).

Taken together, the current evidence suggests that sleep-facilitated consolidation in PD, although affected, may still occur. However, direct evidence comparing the effects of sleep and wakefulness on motor memory consolidation is still lacking. Furthermore, as sleep is altered to a greater extent in people with PD as compared to HOA, it is currently unknown how people with PD and HOA sometimes show similar consolidation levels. Hence, with this study we primarily aimed to determine whether a 2-hour post-learning nap would improve the consolidation of a MSL finger-tapping task, as compared to a similar period of post-learning wakefulness both in PD and HOA separately. Moreover, we set out to study the retention effects of napping on performance at a 24-hour test, and on task automaticity measured with a cognitive dual-task. We expected that napping would result in a greater offline performance improvement immediately after the intervention, at retention, and for task automaticity, as compared to wakefulness in both PD and HOA. We also expected that although these outcomes would possibly be diminished to some degree in PD due to their cortico-striatal deficits, that there would be no statistical group difference on consolidation of the MSL task. We also explored the relationship between performance changes (nap vs. wake) and electrophysiological sleep features to identify potential mechanisms occurring during PD sleep that may explain the expected similarity in sleep-facilitated consolidation despite poorer sleep quality.

## Methods

This study utilised a randomised-control open-label design (PD: N= 32, HOA: N = 32). The procedures and hypotheses were pre-registered on [clinicaltrials.gov](https://clinicaltrials.gov) (Experiment 1, [clinicaltrials.gov/study/NCT04144283](https://clinicaltrials.gov/study/NCT04144283)), and the reporting adheres to the Consolidated Standards of Reporting Trials (CONSORT) guidelines (see Appendix A) (Schulz et al., 2010). An independent researcher performed randomisation to either the nap or wake intervention group using a computerised blocked randomisation sequence ([app.studyrandomizer.com](http://app.studyrandomizer.com)). The researcher shared the concealed group assignments with the study assessors via secured email. Randomisation to the nap or wake group was performed 1:1 for PD and HOA separately with block size 4 and was stratified for age (under 65 years vs. 65 years or older) and self-reported biological sex (male vs. female at birth). The assessments were conducted at the Centre for Sleep Monitoring of the University Hospitals Leuven (UZ Leuven) in Belgium. The protocol was in accordance with the declaration of Helsinki and the World Medical Association, 2013 (“World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Subjects,” 2013) and was approved by the Medical Ethical Committee Research UZ / KU Leuven (S61792). All participants provided written informed consent prior to study related procedures [36].

## Participants

Potential participants were recruited between November 2019 and December 2023 through a contact database of the Parkinson's Disease Rehabilitation Research Group at the Department of Rehabilitation Sciences, KU Leuven, Belgium, or via a study flyer. Inclusion criteria comprised: (1) right-handedness, assessed with the Edinburgh Handedness Inventory (Oldfield, 1971); (2)  $\geq 40$  years of age (Quinn et al., 1987); (3) Mini Mental State Examination (MMSE) score  $\geq 24$  (Tombaugh & McIntyre, 1992); (4) no history of comorbidities that could interfere with the study protocol. In addition to these criteria, people with PD were considered eligible if: (5) they had a diagnosis of PD made by a neurologist, according to the latest Movement Disorder Society diagnostic criteria (Postuma et al., 2015) and (6) were in Hoehn & Yahr stage (H&Y) I-III ON medication (Hoehn & Yahr, 1967). Exclusion criteria for all participants were: (1) known diagnosis of insomnia; (2) severe apnoea (Apnoea Hypopnea Index (AHI)  $\geq 30$ ) as determined by an overnight screening PSG (Kirk et al., 2017). PD-specific additional exclusion criteria were: (3) deep brain stimulation; (4) left affected side for H&Y-I patients; (5) self-reported freezing of gait (FOG) with more than one freezing episode per month, according to the New Freezing of Gait Questionnaire (Nieuwboer, Rochester, Herman, et al., 2009).

At the time of the pre-registration there was no prior investigation of napping compared to wakefulness on sleep-dependent motor memory consolidation in PD. A power calculation was computed, but on hindsight the sample size calculation was deemed inaccurate. Therefore, this study should be regarded as a phase-two explorative trial. We maintained the hypotheses and design according to pre-registration, but we opted to deviate from the pre-registered analysis plan, to allow for the most direct interpretation of the intervention effect. This led to the successful enrolment of our target sample of 32 people with PD and 32 HOA, tested according to randomised allocation (16 in the nap group and 16 in the wake group, see Figure 1).

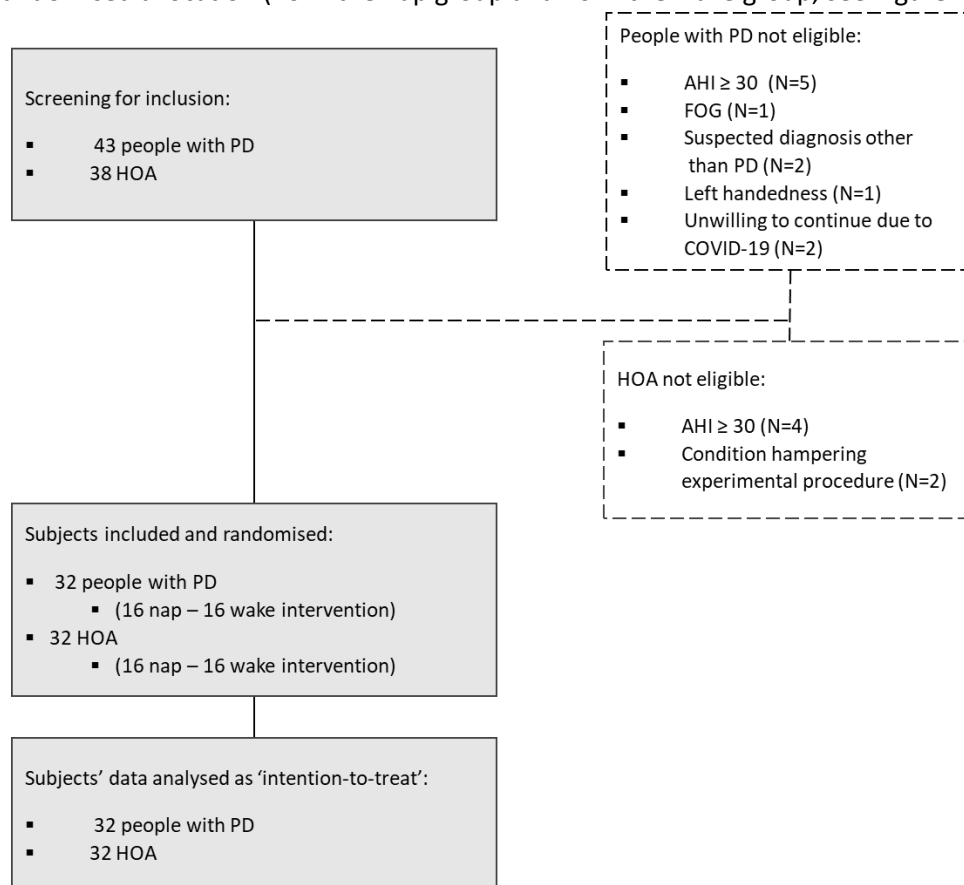


Figure 1. Study flow chart. A total of 43 people with Parkinson's disease (PD) and 38 healthy older adults (HOA) were screened to reach the planned sample size of 32 participants per population. Five PD participants were not considered eligible due to Apnoea Hypopnea Index (AHI) over 30 episodes per hour, 1 due to self-reported Freezing of Gait (FOG), 1 for left-handedness measured with the Edinburgh Handedness Inventory, 2 due to a presumed diagnosis other than PD (i.e., progressive supranuclear palsy, multiple systems atrophy), and 2 decided not to continue with the experiment after completion of screening due to health-related reasons unrelated to the study. Four HOA participants were not deemed eligible due to an AHI above 30, and 2 due to a comorbidity that could hamper the experimental procedures (essential tremor).

## General Experimental Design

Prior to inclusion, a separate screening visit was scheduled. During this assessment, demographic information was obtained and all participants underwent cognitive testing by means of the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005) and an overnight diagnostic polysomnography (PSG) to verify their AHI. The overnight PSG also served to familiarise participants to the experimental environment and EEG recording setup. People with PD were additionally tested on the Movement Disorders Society Unified Parkinson Disease Rating Scale (MDS-UPDRS) (Goetz et al., 2008), the Levodopa Equivalent Daily Dose (LEDD) (Tomlinson et al., 2010), the New Freezing of Gait Questionnaire (NFOGQ) (Nieuwboer, Rochester, Herman, et al., 2009) and Parkinson Disease Questionnaire 39 (PDQ-39) (Jenkinson et al., 1997). Disease duration information was also collected, with missing data from one person with PD in the wake group. Subjective sleep quality scales were also completed by all participants, comprising the Scales for Outcomes in Parkinson's Disease (SCOPA)-sleep (Marinus et al., 2003), Epworth Sleepiness Scale (ESS) (Johns, 1991), Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and the REM-sleep Behaviour Disorder Screening Questionnaire (RBDSQ) (Stiasny-Kolster et al., 2007). For all these sleep scales, we report missing data from one HOA and 2 PD in the wake group, and an additional missing value for the SCOPA-sleep Night and for the PSQI from one person with PD in the nap group. Following the screening night, participants' habitual sleep and motion levels were monitored for 7 days and nights with an actigraphy watch (Philips Respironics Actiwatch-II®) and a sleep diary. Eligible participants were then invited to return to the university hospital for the experiment, which took place at least one week after the screening visit. They were instructed to keep a regular sleep/wake schedule three days before and during the experiment, but this was not verified. They were additionally instructed to go to bed before midnight and refrain from caffeine and alcohol on the test days, though this latter information was not systematically recorded. People with PD continued taking their regular medications during the experiment. Medication intake was logged for all people with PD, but intake time was not systematically recorded (missing data for one patient post-intervention and one patient post-night). Notably, two people with PD were drug-naïve, thus not following any PD medication regimen.

The experiment consisted of three test sessions across two days (see Figure 2). At the beginning of each session, participants performed a Psychomotor Vigilance Test (PVT) to assess their level of vigilance (Dinges & Powell, 1985) (see Supplementary Material 1 for details). Prior to initial practice on the first session (pre-intervention, ~11 a.m. of Day 1), participants were tested on a motor execution task (MET, see section Motor Tasks below). This was followed by the testing of a unimanual self-initiated motor sequence learning (MSL) finger-tapping task in a dual-task configuration and by the training and testing of the same sequence but in a single-task configuration. After the pre-intervention session, participants were offered a standardised lunch, followed by a 2-hour opportunity to sleep or rest quietly in supine or sitting position for an equivalent time period, as determined by the randomization. Participants in the wake group were allowed to read and/or watch television, but they were not allowed to practice the MSL task or to do any form of physical activity. During the intervention period, all participants were monitored with low-density PSG, including those in the wake group, to monitor their wakeful state. Upon detection of N1 in the wake group, the assessor would enter the room to awaken the participant. The second session (post-intervention) started 30-40 minutes after the 2-hour nap/wake opportunity period to allow for possible sleep inertia effects to dissipate (Tassi & Muzet, 2000). During the post-intervention session, the training and testing of the same sequence in a single-task configuration were again performed, and served as immediate post-intervention assessment. The single task training and testing was followed by the dual-task testing. Lastly, a third session (post-night, on Day 2, 24 hours after the post-intervention session) comprised the training and testing of the sequence, first in a single-task configuration, then in dual-task. Notably, during the post-intervention and the post-night sessions, the single-task MSL (training and test) were performed first, followed by the dual-task MSL and MET in order to prevent interference of the dual-task practice in the offline consolidation assessment. Between Day 1 and Day 2,



## Experimental design

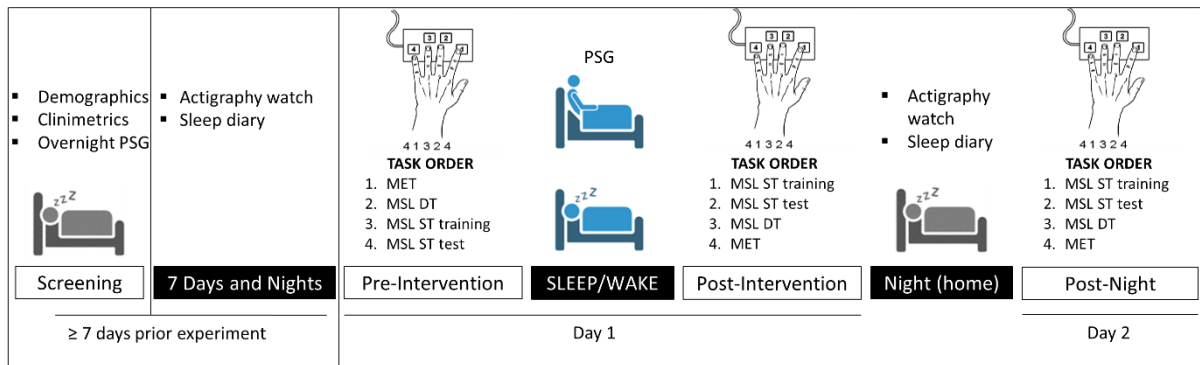


Figure 2. Experimental design with pre- and post-intervention assessments, as well as a 24-hour retention assessment (post-night). Note: MET = Motor Execution Test with four blocks of 48 key presses each sequence; DT = Dual-Task, with four blocks of 50 key presses sequence; ST, Single-Task training sequence, 14 blocks of 50 key presses sequence; ST test, four blocks of 50 key presses sequence; PSG = polysomnography

participants slept at home, and their sleep and motion were monitored with an actigraphy watch. They also completed a sleep diary including information on their sleep and daily physical activity during the two days of the experiment.

## Motor tasks

All the tasks were scripted in Matlab (Math Works Inc, Natick, MA, USA; version R2018a), using the Psychophysics Toolbox extensions (Brainard & Vision, 1997; Kleiner et al., 2007; Pelli & Vision, 1997). Participants were sitting comfortably in front of a laptop screen and used a left-handed Celeritas 5-Button Response Unit (Psychology Software Tools inc. Pittsburgh, USA) to practice the MET and the MSL with their left hand (non-dominant). The PVT was also performed in front of the laptop screen, but the spacebar of the keyboard was used as response button with the right (dominant) hand.

Both the MET and the MSL consisted of self-initiated unimanual finger-tapping tasks (Albouy et al., 2015; Albouy, Fogel, et al., 2013; Albouy, King, et al., 2013), during which the respective sequences were presented on the laptop screen for the whole duration of the practice blocks. During the MET and training and testing of the MSL, participants were instructed to perform the sequence displayed as quickly and as accurately as possible with their left, non-dominant hand positioned on their lap under the table, to avoid visual feedback. No feedback on performance was provided during or after the training and testing. During these tasks, the timing of each key press and the corresponding response were recorded for data processing.

The MET consisted of four blocks of 48 key presses (ideally 12 correctly typed sequences). During each block participants had to type continuously the sequence of numbers 4-3-2-1, with 4 and 1 corresponding to the little and index fingers, respectively. Each block was separated by a 20-second break, during which the sequence of numbers was concealed. This overtrained sequence served as a control condition to determine if any improvement observed on the MSL was due to sequence learning or to general improvement in motor execution.

The MSL training consisted of 14 blocks of 50 key presses (ideally 10 correct sequences, i.e., 'training') with a 20-second break between each block (King et al., 2016). During the 20-second rest period the sequence was concealed. After training all participants had a 2-minute break to allow fatigue dissipation (Pan & Rickard, 2015) and this was followed by another four blocks (i.e., 'test'). The sequence of numbers for the MSL task was 4-1-3-2-4, a motor sequence learning task (Albouy et al., 2015; Albouy, Fogel, et al., 2013; Albouy, King, et al.,

2013). Before training, participants were first allowed to type this sequence as slowly and correctly as possible while looking at their hand to ensure they understood the task instruction.

The dual-task version of the MSL task consisted of four blocks of 50 key presses of the same MSL sequence, but in addition participants were instructed to count the number of substitutions of a cross sign (“+”) visible in the centre of the screen, below the sequence, by a circle sign (“o”) occurring at pseudo-random moments during each block for 5 to 8 times. Participants were instructed to keep count in their mind while typing the sequence as fast and accurately as possible without using any strategy (e.g., count aloud, keep the count with the fingers of the other hand). At the end of each block, they verbally reported the count to the assessor to verify that they were actively engaged in the secondary task. Their responses were documented but not further analysed as they do not allow for an assessment of a dual-task cost of the secondary task.

### Preprocessing

Sequence duration was calculated as the average time between the first and last key press of each correctly typed sequences (MSL = 4-1-2-3-4; MET = 4-3-2-1) in each block, and accuracy consisted in the number of complete sequences typed correctly from the first to the last key within a block. The primary dependent variable was the performance index (PI), a joint measure of sequence duration and accuracy on the MSL and MET tasks, derived for each block separately (Dan et al., 2015; King et al., 2016) (see Equation 1).

$$PI(x) = e^{-(Sequence\ duration(x))} * e^{-\left(\frac{N\ Sequences\ per\ block - Correct\ sequences(x)}{N\ Sequences\ per\ block}\right)} * 100$$

*Equation 1. Performance Index (PI) calculated per block (x). The sequence duration (x) consists in the mean sequence duration for each block, calculated on the correct sequences. The accuracy component is expressed as the ratio of correctly typed sequences by the total number of sequences per block (N = 10).*

Sequence duration values above or below three standard deviations of the participant’s mean sequence duration of each block were considered outliers and subsequently excluded. This occurred only during the MET (MET PD = 0.93%; MET HOA = 0.87%), but not during the MSL blocks.

### Polysomnography

During the screening night and the experimental intervention (nap/wake period), participants were monitored with PSG using Medatec Brainnet system and Brainnet Software (Medatec, Brussels, Belgium), a device compliant with the AASM2019 recommendations.

For the screening night, EEG recordings comprised eight electrodes placed on the scalp (F3, F4, C3, C4, O1, O2, A1, A2), according to the international 10-20 system. A2 was used as recording reference. An electrode positioned in the centre of the forehead (Fpz), served as ground. Electrooculography (EOG) was recorded with two electrodes placed 1 cm from the external canthus of both eyes, below the left and above the right eye (Berry et al., 2018). Electromyography (EMG) was recorded with two electrodes, on the chin and on the sublingual muscle. Additionally, two electrodes were placed on the lower limbs to screen for restless limbs syndrome. Another two electrodes were used to capture heart rate. Finally, two breathing bands, one around the chest and one around the abdomen, a sensor for oro-nasal pressure, sound and oxygen saturation completed the PSG setup.

During the experimental intervention a simplified setup was used, comprising eight EEG (Fz, C3, Cz, C4, Pz, Oz, A1, A2), two EOG and two EMG (chin and sublingual muscle) electrodes, as well as the two breathing bands. Again, Fpz constituted the ground, and A2 was used as recording reference. Impedances for the electrodes were kept below 10 k $\Omega$  (Sinha et al., 2016). PSG data were collected with a sampling frequency of 500 Hz.



## Preprocessing

For offline scoring of the naps, the electroencephalography (EEG) recordings were band-pass filtered (0.16-70 Hz) with Brainnet software (Medatec, Brussels, Belgium). These were then manually scored by an experienced sleep researcher according to the AASM guidelines (Iber, 2007) on 30-second epochs using the fMRI Artefact rejection and Sleep scoring Toolbox (FASST) (Leclercq et al., 2011), implemented in MATLAB (Math Works Inc, Natick, MA, USA). We extracted percentage and duration of each sleep stage, total sleep time and sleep opportunity, and we calculated sleep efficiency as the percentage of time spent in sleep (e.g., N1, N2, N3 and REM) relative to the total time in bed.

As part of an exploratory analysis, we were interested in the sleep electrophysiological events occurring during the intervention. To do so, epochs of N2-N3 sleep were extracted and further processed with FieldTrip Toolbox (Oostenveld et al., 2011) in MATLAB. Raw data were resampled to 100 Hz and band-passed (0.5 – 30Hz) using Finite Impulse Response (FIR) filters. Data were subsequently manually screened for cleaning. Segments presenting abnormal muscular activity or eye movements were excluded. Next, Independent Component Analysis was performed, excluding components that presented cardiac artifacts. Sleep-related electrophysiological markers of plasticity were detected using YASA toolbox (Vallat & Walker, 2021) implemented in the Python environment. The YASA spindle detection algorithm was inspired by Lacourse and colleagues (Lacourse et al., 2019). Specifically, the relative power in the spindle frequency range (10–16Hz) was calculated as a ratio to the total power in the broad-band range (1–30Hz) using Short-Time Fourier Transforms, applied with 2-second windows and a 200ms overlap. Next, the algorithm employed a 300ms window with a 100ms step size to calculate the moving root mean squared (RMS) of the EEG data filtered in the sigma band. A moving correlation was then calculated between the broadband signal (1–30Hz) and the EEG signal filtered in the spindle frequency band. Sleep spindles were detected upon the simultaneous reaching of three thresholds: (1) a relative power in the sigma band (with respect to total power) above 0.2; (2) a moving RMS crossing the RMS mean + 1.5 RMS standard deviation threshold and (3) moving correlation above 0.65. Additionally, the detected spindles with duration below 0.3s or above 3s were discarded. Spindles occurring on different channels within 500ms of each other were merged, as they were considered to represent the same event.

Slow wave detection was performed based on previous reports (Carrier et al., 2011; Massimini et al., 2004). The signals were firstly bandpass filtered between 0.3–1.5Hz using a FIR filter. Negative peaks with an amplitude between  $-40$  and  $-200\mu\text{V}$  and positive peaks with an amplitude comprised between  $10$ – $150\mu\text{V}$  were detected in the filtered signal. Next, the slow wave was composed of the negative peak and the nearest following positive peaks a true slow wave was identified when the following criteria were met: (1) a duration of the negative deflection between 0.3–1.5 s, (2) and that of the positive deflection between 0.1–1.0s, (3) negative peak amplitude between  $40$ – $200\mu\text{V}$ , (4) positive peak amplitude between  $10$ – $150\mu\text{V}$  and (5) peak-to-peak amplitude between  $75$ – $350\mu\text{V}$ . Events were identified in all electrodes, but only spindles detected in C3 and slow waves detected in Fz were further analysed. We next extracted the amplitude and frequency of each detected spindle, and the amplitude and slope of each detected slow wave (Carrier et al., 2011; Latreille et al., 2011). We then computed the phase-amplitude coupling between the phase of slow waves (0.3–1.5 Hz) and the spindles-related sigma band amplitude (10–16 Hz). To do so, the normalised direct phase-amplitude coupling (ndPAC) was computed at the highest sigma peak amplitude within a 2 s epoch centred around the current slow-wave trough. The ndPAC allows to quantify the strength of the phase amplitude coupling (Canolty & Knight, 2010; Jensen & Colgin, 2007; Özkurt, 2012; Özkurt & Schnitzler, 2011).

We also extracted spindle and slow wave density. Spindle and slow wave density were defined as the number of these events occurring per minute. Features of spindles, slow waves and ndPAC above and below 3 standard deviations of each participant' mean were considered outliers (spindle amplitude: PD = 1.18%, HOA = 1.10%; spindle frequency: PD = 0.09%, HOA = 0.19%; slow wave amplitude: PD = 1.47%, HOA = 1.59%; slow wave

slope: PD = 1.00%, HOA = 1.10%; ndPAC: PD = 0.03%, HOA = 0.02%), and were therefore excluded from further analyses. We succeeded in the detection of spindles both in PD and in HOA (PD: mean = 345.1, range [45–877]; HOA: mean = 318.2, range [60–553]), as well as of slow waves (PD: mean = 191.3, range [6–1020]; HOA: mean = 141.2, range [20–411]). Notably, we did not detect slow waves in two HOA.

## Statistical analyses

Statistical analyses were performed for PI, sequence duration and accuracy. As the PI was our primary metric of interest, we report these results in the main text. Findings on sequence duration and accuracy are detailed in Supplementary Material 3 and 4.

Analyses were conducted with R open-source software (R Core Team, 2022). For this phase-two explorative study we adopted the use of Bayesian statistical tests, indicating the likelihood that the observed data supported the acceptance of the alternative hypothesis (e.g., the two conditions have different means) or the null hypothesis (e.g., the two conditions have similar means). Frequentist statistics are also provided in this manuscript to allow for comparison with previous studies. We calculated Bayes factors (BF) to provide a clearer interpretation to the statistical comparisons, using the BayesFactor package (Morey et al., 2022). Specifically, we present  $BF_{10}$  as a relative measure of evidence in favour of a difference for a statistical test, in comparison to the null test. To assess the strength of evidence against the null hypothesis, we classified BFs according to the guidelines provided by Lee and Wagenmakers (Lee & Wagenmakers, 2014), where values above 1 indicate evidence in favour of the alternative hypothesis and values below 1 suggest evidence in favour of the null hypothesis. Evidence was reported in different degrees ( $1 < BF \leq 3$  as weak evidence,  $3 < BF \leq 10$  as moderate evidence,  $10 < BF \leq 100$  as strong evidence,  $BF > 100$  as decisive evidence). In contrast, BFs below one indicated evidence in favour of the null hypothesis in different degrees ( $0.33 \leq BF < 1$  as weak evidence,  $0.01 \leq BF < 0.33$  as moderate evidence,  $0.001 \leq BF < 0.01$  as strong evidence and  $BF < 0.001$  as decisive evidence) (Lee & Wagenmakers, 2014). Evidence defined as weak ( $0.33 \leq BF < 3$ ) should be regarded as inconclusive. For the analyses using Bayesian statistics, (i) we assigned a noninformative Jeffreys prior for the variance and a Cauchy prior for the standardised effect size with value  $\sqrt{2}/2$ , (ii) implemented 10.000 Markov Chain Monte Carlo iterations, and (iii) we excluded the non-available values. Post-hoc comparisons were performed when BFs were above 3 (i.e., moderate evidence in favour of an effect).

Bayesian analyses of variance (ANOVA) or general Bayesian tests were used to obtain BFs using the functions “anovaBF” and “generalTestBF” from the R package BayesFactor (Morey et al., 2022). For the Bayesian ANOVA’s, the null model included only the random effect, while for the general Bayesian tests the null model comprised the intercept. We set the parameter “whichModels” to “all” in order to extract the appropriate BFs. We kept the default values for the prior probability of the fixed and random effects. For reference, these analyses were also performed with frequentist statistics, using linear mixed effects models with random effects implemented with lme4 package in R (Fisher’s F statistics and p-values are reported) (Bates et al., 2014).

For the Bayesian t-tests, the null model held the assumption that the difference between the means is zero, and we calculated BFs using the function “ttestBF” (Morey et al., 2022). We complemented these Bayesian statistical analyses with frequentist Student’s t-tests or Mann-Whitney U tests and we report the confidence interval for the mean difference. For Bayesian correlation analyses, we reported the BFs output by the function “correlationBF” from the package BayesFactor (Morey et al., 2022). Frequentist correlation analyses were performed with Pearson’s r tests or Spearman S tests (r and p-values are reported).

Additionally, effect sizes were reported as partial eta squared ( $\eta^2$ ), Cohen’s d (for frequentist parametric tests) or rank-biserial correlation ( $r_{rb}$ ) for frequentist non-parametric tests. The  $r_{rb}$  was computed as the Spearman correlation coefficient between a dichotomous variable (e.g., group, intervention) and the outcome of interest. Negative values for the effect sizes favour the PD group in comparisons between PD and HOA. When comparing

interventions, positive values suggest an effect favouring the nap over the wake intervention. Values of  $r_{rb}$  should be interpreted according to the values reported by Cohen, 1992, and are complemented with the p-value of the correlation, to indicate their significance (Cohen, 1992).

## Behaviour

### *Pre-requisites*

MSL performance was tested against that of the MET, to verify whether the differences observed over the three sessions were related to actual learning or to general motor execution improvement. As the MET sequence consisted of four key presses, in contrast with the five of the MSL sequence, only relative performance changes were compared. Specifically, the relative difference between the MET four blocks pre-intervention and post-night, was compared to the relative difference between the MSL first four blocks of single-task training pre-nap and the last four blocks single-task test post-night. For this analysis, a Bayesian ANOVA was used, including group, intervention and task (MSL/MET) as fixed effects, and subject as random effect, against the null model including only the random intercept (subject). Overall, these results suggest that the performance change was not related to general motor execution improvement only, but to actual learning, irrespective of group and intervention (results in Supplementary Material 2).

To ensure that the necessary plateau of performance was reached before the intervention, we explored the differences in PI among the four blocks of test pre-intervention (results in Supplementary Material 2). Here, a first block effect was found, therefore we excluded this first block of test pre-intervention in the calculation of offline performance changes post-intervention, both in PD and in HOA. The same analysis was performed on the four blocks of test post-intervention, where we again found evidence for differences between the first block and the following three. Hence, we opted for excluding the first block of the test post-intervention also in the computation of post-night offline changes (i.e., retention) (Supplementary Material 2).

To verify that medication did not influence learning and memory consolidation in our study, we performed a control exploratory analysis where we correlated the post-intervention and post-night offline changes, as well as dual-task costs (see below) post-intervention and post-night, with the levodopa equivalent daily dose (LEDD) for the nap and wake group separately. We found weak evidence in favour of no correlation between the two variables (see Supplementary Material 5). LEDD was thus not included as a confounder in the analyses of offline changes.

### *Main analyses*

We tested for differences between nap and wake interventions for the PD and HOA groups separately using Bayesian t-tests. Our primary interest was the relative offline performance change in PI between the mean of the last three blocks of test pre-intervention and that of the first three blocks of single-task training post-intervention.

The secondary interest were offline overnight changes, measured as the performance change between the last three blocks of test post-intervention and the first three blocks of single-task training post-night. Again, we compared the two interventions separately in the PD and HOA group, using Bayesian t-tests.

Automaticity was assessed as the dual-task cost computed as the relative difference between dual-task performance and single-task performance at post-training test, both at post-intervention and at post-night separately. Values of dual-task cost of the people with PD allocated to nap and to wakefulness were compared with Bayesian t-tests and similarly in the HOA group. For this analysis we did not exclude the first block of test single-task or of dual-task MSL, since the reaching of a performance plateau was not a requirement for the computation of dual-task cost (Bachar Kirshenboim et al., 2023; Milnik et al., 2013).

We further explored differences between people with PD and HOA for the nap and wake interventions separately. Here we compared the two populations on post-intervention and post-night offline changes, and dual-task costs post-intervention and post-night using Bayesian t-tests.

In agreement with current evidence suggesting that sleep not only impact offline consolidation, but may also have a beneficial effect on extended practice (King et al., 2016; Terpening et al., 2013), we also tested whether napping had an effect on performance changes between the beginning and the end of the training (extended practice) post-intervention and post-night. For this analysis we employed Bayesian t-tests. For each session (post-intervention and post-night) the relative difference of the mean of the first four blocks (start) and that of the last four blocks (end) of MSL training was calculated. These values were compared between nap and wake intervention, within the PD and HOA groups separately. The two populations were also compared according to the intervention allocation with two Bayesian t-tests (i.e., one for the people with PD and HOA in the nap group, and one for those in the wake group).

Finally, we explored the change in performance across sessions taking into account the aggregated effects of consolidation and extended practice. To do so, we compared the mean performance of the first four single-task training blocks of each session (pre-intervention, post-intervention, retention) with a Bayesian ANOVA, including group, intervention and session as fixed effects and subject as random effect. BFs were reported in relation to the null model including only the random factor (subject).

### Electroencephalography

The electrophysiological sleep parameters obtained during the experimental nap were compared between people with PD and HOA using general Bayesian general tests (“generalTestBF”). For completeness, in these analyses we included gender, age, and AHI, as they are known to influence sleep micro-architecture (Purcell et al., 2017) (results in Supplementary Material 6). These covariates were added together with their interactions with the group factor, and their effects compared to the null model (including only the intercept). The model with highest BF was then reported.

Additionally, we tested the correlation between characteristics of spindles (amplitude, frequency, density) and slow waves (amplitude, slope, density) as well as their coupling (ndPAC), and the relative offline change in MSL performance post-intervention using Bayesian correlations.

## Results

The demographic characteristics of the included participants can be found in Table 1. According to the reported BFs, we found overall weak evidence supporting similarity between nap/wake intervention groups for age, gender, AHI, cognition (measured with MMSE and MoCA), sustained attention (measured with PVT) and subjective sleep scales, within each population group (PD/HOA). Also, moderate to weak evidence was found for differences in sustained attention between pre- and post-intervention (PD-nap:  $BF_{10} = 1.29$ ; PD-wake:  $BF_{10} = 0.35$ ; HOA-nap:  $BF_{10} = 0.26$ ; HOA-wake:  $BF_{10} = 0.27$ ), and post-intervention and retention (PD-nap:  $BF_{10} = 1.07$ ; PD-wake:  $BF_{10} = 0.47$ ; HOA-nap:  $BF_{10} = 2.35$ ; HOA-wake:  $BF_{10} = 0.82$ ).

When comparing the two population groups, irrespective of the intervention, weak evidence for a higher AHI for HOA than for PD was found ( $BF_{10} = 2.84$ ,  $W = 333$ ,  $p = 0.01$ ,  $r_{fb} = 0.30$ ,  $p = 0.02$ ). Decisive evidence in favour of a true difference was found for the RBDSQ, which was higher in PD ( $BF_{10} = 601.69$ ,  $W = 684.5$ ,  $p < 0.01$ ,  $r_{fb} = -0.50$ ,  $p < 0.01$ ). Decisive to strong evidence was found for daytime sleepiness, measured with the SCOPA-Sleep Day ( $BF_{10} > 1000$ ,  $W = 752$ ,  $p < 0.01$ ,  $r_{fb} = -0.54$ ,  $p < 0.01$ ) and the ESS ( $BF_{10} = 97.79$ ,  $W = 708$ ,  $p < 0.01$ ,  $r_{fb} = -0.45$ ,  $p < 0.01$ ). For night-time sleep quality, strong evidence in favour of a difference was found for the PSQI

( $BF_{10} = 26.59$ ,  $W = 658.5$ ,  $p < 0.01$ ,  $r_{rb} = -0.41$ ,  $p < 0.01$ ), but this was only weakly in favour of a difference between the two groups for the SCOPA-Sleep night ( $BF_{10} = 2.50$ ,  $W = 617$ ,  $p = 0.01$ ,  $r_{rb} = -0.32$ ,  $p = 0.01$ ). Taken together, these findings suggest that the two populations were similar, except for subjective sleep scales where people with PD reported worse sleep quality as compared to HOA (see Table 1).

Table 1. General demographic characteristics.

	PD Nap (=16)	PD Wake (=16)	Test result (PD nap – wake)	HOA Nap (=16)	HOA Wake (=16)	Test result (HOA nap – wake)	Test result (PD – HOA)
<b>Demographic statistics</b>							
<b>Age (years) mean [range]</b>	66.9 [53–78]	65.7 [47–80]	BF <sub>10</sub> = 0.37 t <sub>(30)</sub> = 0.47 p = 0.64	65.56 [48–75]	68 [51–78]	BF <sub>10</sub> = 0.49 t <sub>(30)</sub> = -0.99 p = 0.33	BF <sub>10</sub> = 0.26 t <sub>(62)</sub> = -0.26 p = 0.80
<b>Gender (M/F)</b>	9/7	11/5		11/5	11/5		χ <sup>2</sup> <sub>(3)</sub> = 0.44 p = 0.93
<b>AHI (n./hour)</b>	9.1 [5.0–13.1]	6.15 [2.9–9.4]	BF <sub>10</sub> = 0.58 W = 164.5 p = 0.17	11.2 [6.8–15.6]	13.3 [8.6–18.0]	BF <sub>10</sub> = 0.40 W = 115 p = 0.64	BF <sub>10</sub> = 2.84 W = 333 p = 0.01
<b>MMSE (0 – 30)</b>	29.1 [28.6–29.7]	29.3 [28.6–30.0]	BF <sub>10</sub> = 0.36 W = 100 p = 0.24	29 [28.4–29.7]	28.9 [28.2–29.5]	BF <sub>10</sub> = 0.35 W = 135.5 p = 0.78	BF <sub>10</sub> = 0.37 W = 597 p = 0.22
<b>MoCA (0 – 30)</b>	26.26 [25.1–27.4]	27.13 [25.7–28.6]	BF <sub>10</sub> = 0.49 W = 89 p = 0.14	26.56 [25.5–27.6]	27.31 [26.2–28.5]	BF <sub>10</sub> = 0.51 t <sub>(30)</sub> = -1.03 p = 0.31	BF <sub>10</sub> = 0.28 W = 506 p = 0.94
<b>PVT pre-intervention</b>	0.36 [0.31–0.40]	0.36 [0.30–0.41]	BF <sub>10</sub> = 0.34 W = 130 p = 0.96	0.35 [0.33–0.37]	0.37 [0.34–0.39]	BF <sub>10</sub> = 0.52 W = 108.5 p = 0.47	BF <sub>10</sub> = 0.26 W = 583 p = 0.34
<b>PVT post-intervention</b>	0.34 [0.31–0.38]	0.38 [0.33–0.43]	BF <sub>10</sub> = 0.55 W = 126 p = 0.96	0.35 [0.32–0.37]	0.37 [0.35–0.39]	BF <sub>10</sub> = 0.63 W = 88.5 p = 0.14	BF <sub>10</sub> = 0.26 W = 528 p = 0.84
<b>PVT post-night</b>	0.39 [0.35–0.44]	0.36 [0.33–0.40]	BF <sub>10</sub> = 0.48 W = 160 p = 0.24	0.34 [0.32–0.36]	0.36 [0.34–0.38]	BF <sub>10</sub> = 0.84 W = 90.5 p = 0.16	BF <sub>10</sub> = 1.48 W = 604 p = 0.22
<b>PD-specific measures</b>							
<b>Disease duration (years)</b>	4.7 [2.5–6.89]	5.2 [3.0–7.5]	BF <sub>10</sub> = 0.34 W = 131 p = 0.68	-	-	-	-
<b>MDS-UPDRS III (0 – 132)</b>	29.2 [23.6–34.8]	31.6 [25.8–37.4]	BF <sub>10</sub> = 0.39 W = 109 p = 0.48	-	-	-	-
<b>LEDD (mg/24h)</b>	450.7 [323.4– 578.0]	656.4 [404.2– 908.7]	BF <sub>10</sub> = 0.83 W = 94.5 p = 0.21	-	-	-	-
<b>Dominant symptom side<sup>§</sup> (R/L)</b>	9/7	9/7		-	-	-	-
<b>Subjective sleep measures</b>							
<b>PSQI (0 – 21)</b>	7.2 [4.6–9.8]	7.4 [5.3–9.5]	BF <sub>10</sub> = 0.35 W = 99.5 p = 0.83	3.4 [2.1–4.7]	4.9 [3.5–6.3]	BF <sub>10</sub> = 1.00 W = 72 p = 0.06	BF <sub>10</sub> = 26.59 W = 658.5 p < 0.01*
<b>SCOPA-sleep night (0 – 21)</b>	5.3 [3.7–7.4]	6.3 [4.1–8.5]	BF <sub>10</sub> = 0.39 t <sub>(27)</sub> = -0.53 p = 0.60	4.4 [2.5–6.3]	3.0 [1.2–4.8]	BF <sub>10</sub> = 0.54 W = 151 p = 0.22	BF <sub>10</sub> = 2.50 W = 617 p = 0.01*
<b>SCOPA-sleep day (0 – 18)</b>	5.8 [3.9–7.6]	7.5 [5.1–9.9]	BF <sub>10</sub> = 0.60 t <sub>(28)</sub> = -1.21 p = 0.24	2.75 [1.77–3.73]	2.7 [1.4–3.9]	BF <sub>10</sub> = 0.34 t <sub>(29)</sub> = 0.11 p = 0.91	BF <sub>10</sub> = 1287.79 W = 752 p < 0.01*
<b>ESS (0 – 24)</b>	10.0 [7.6–12.4]	10.6 [8.1–13.1]	BF <sub>10</sub> = 0.36 t <sub>(28)</sub> = -0.34 p = 0.74	4.9 [3.0–6.8]	6.8 [4.2–9.4]	BF <sub>10</sub> = 0.59 W = 92 p = 0.27	BF <sub>10</sub> = 97.79 W = 708 p < 0.01*
<b>RBDSQ (0 – 13)</b>	4.6 [3.0–6.1]	5.7 [4.2–7.2]	BF <sub>10</sub> = 0.54 W = 83 p = 0.23	2.9 [1.3–4.5]	2.5 [0.8–4.3]	BF <sub>10</sub> = 0.39 W = 142 p = 0.38	BF <sub>10</sub> = 601.69 W = 731.5 p < 0.01*

AHI, Apnea Hypopnea Index; MMSE, Mini-Mental State Examination; MoCA, Montreal Cognitive Assessment; PVT, Psychomotor Vigilance Test; LEDD, Levodopa Equivalent Daily Dose; MDS-UPDRS, Movement Disorders Society – Unified Parkinson’s Disease Rating Scale; PSQI, Pittsburgh Sleepiness Questionnaire, International; ESS, Epworth Sleepiness Scale; SCOPA-Sleep, Scales for Outcomes in Parkinson’s Disease – Sleep; RBDSQ, REM sleep Behaviour Disorder Screening Questionnaire; HADS, Hospital Anxiety and Depression Scale.

§ The dominant symptom side was determined as the side with the higher sum of scores from the left-side and right-side items on the Movement Disorders Society – Unified Parkinson’s Disease Rating Scale part III (Seuthe et al., 2024).

Variables are presented as the mean (±95% confidence interval), unless otherwise specified

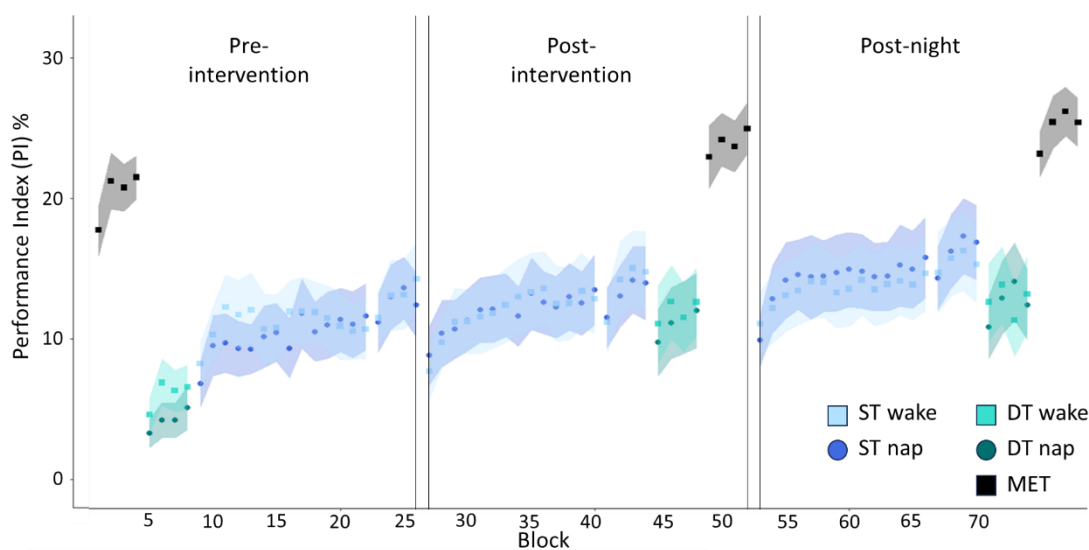


## Behavioural data

Figure 3 shows overall performance of the PD (Figure 3A) and HOA group (Figure 3B) across the three sessions, measured with PI. Results reporting analyses on sequence duration and accuracy are presented in Supplementary Material 3 and 4.

### Behavioural results: Performance Index

#### A. Performance PD group across sessions



#### B. Performance HOA group across sessions

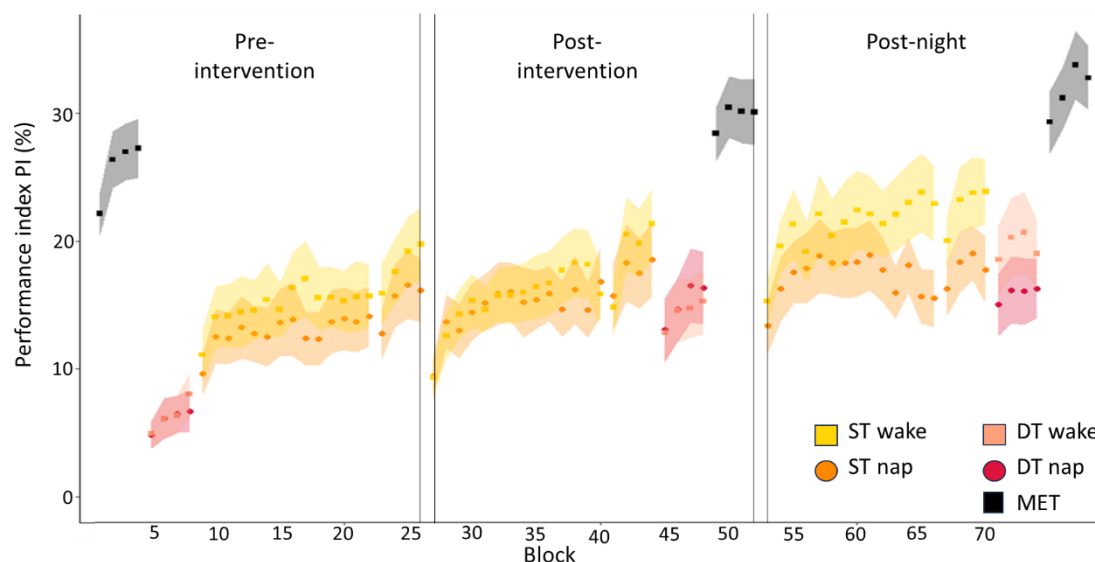


Figure 3. Representation of the of performance index (PI) over the three sessions, expressed as mean and standard error (A) for the PD group (in cold colours) and (B) for the HOA (in warm colours). MET: motor execution test; ST: single task; DT: dual-task.

## Main analyses

### Offline MSL changes post-intervention

Our primary interest was the offline consolidation post-intervention of the MSL single-task. We found weak evidence for no effect of nap versus wakefulness, both in PD ( $BF_{10} = 0.35$ ,  $t_{(30)} = 0.29$ , 95% CI [-14.00–18.60],  $p = 0.78$ , Cohen's  $d = 0.10$ ; Figure 4A, in cold colours) and in HOA ( $BF_{10} = 0.98$ ,  $t_{(30)} = 1.69$ , 95% CI [-2.95–31.42],  $p = 0.10$ , Cohen's  $d = 0.60$ ; Figure 4A, in warm colours).

When comparing post-intervention offline changes between PD and HOA allocated to the nap group, we found weak evidence for a similar effect between groups ( $BF_{10} = 0.88$ ,  $t_{(30)} = -1.60$ , 95% CI [-29.76–3.64],  $p = 0.12$ , Cohen's  $d = 0.56$ ; Figure 4A), and similar results were found for the comparison between wake PD and HOA on offline changes post-intervention ( $BF_{10} = 0.34$ ,  $t_{(30)} = -0.14$ , 95% CI [-17.93 – 15.68],  $p = 0.89$ , Cohen's  $d = 0.05$ ; Figure 4A).

These findings suggest no evidence for a differential effect of a period of sleep compared to an equivalent time awake, on motor memory consolidation, neither in PD nor in HOA.

### Offline MSL changes post-night

Our secondary interest was the post-night performance change of the MSL sequence. Weak evidence in favour of no difference between interventions was found for both PD ( $BF_{10} = 0.40$ ,  $W = 146$ ,  $p = 0.51$ ,  $r_{rb} = -0.12$ ,  $p = 0.51$ ; Figure 4B, in cold colours) and HOA ( $BF_{10} = 0.34$ ,  $W = 127$ ,  $p = 0.99$ ,  $r_{rb} = 0.01$ ,  $p = 0.97$ ; Figure 4B, in warm colours). The change in performance at post-night also showed weak evidence in favour of no difference between PD and HOA both in the nap ( $BF_{10} = 0.46$ ,  $W = 147$ ,  $p = 0.49$ ,  $r_{rb} = 0.13$ ,  $p = 0.48$ ; Figure 4B) and in the wake ( $BF_{10} = 0.34$ ,  $W = 131$ ,  $p = 0.93$ ,  $r_{rb} = 0.02$ ,  $p = 0.91$ ; Figure 4B) groups. These results suggest that the sleep intervention did not generate protracted benefits after 24-hours, and offline changes at post-night were similar between PD and HOA.

## Offline memory consolidation: Performance Index

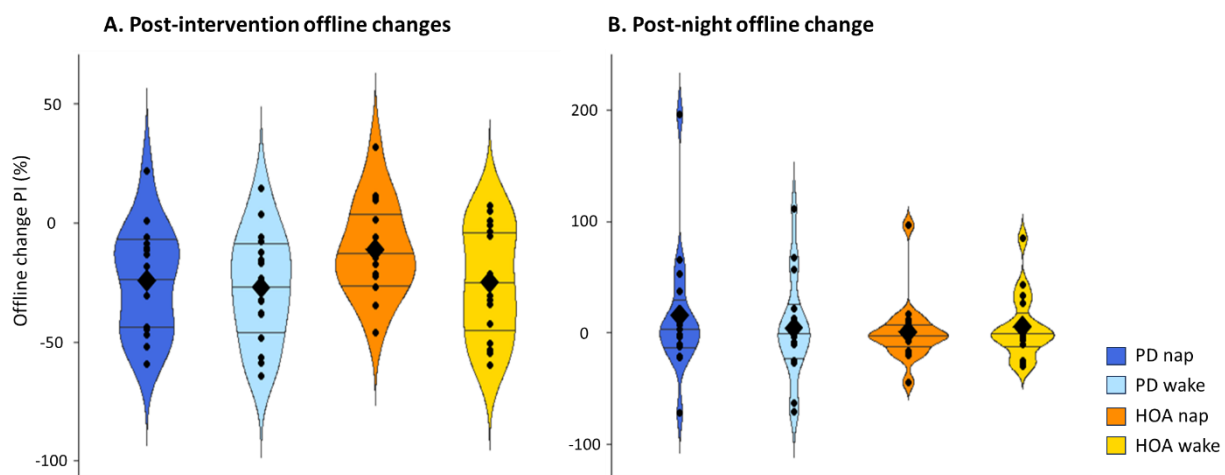


Figure 4. (A) Post-intervention offline changes of single-task MSL performance in the PD and HOA groups. (B) Post-night offline changes of single-task MSL performance in the PD and HOA groups.

Violin plot: mean (diamond), median (central horizontal bar), and 25<sup>th</sup> (lower bar) and 75<sup>th</sup> (higher bar) percentiles.

### Dual-task costs

Automaticity of the MSL task was tested with the dual-task cost, whereby higher values indicate larger cost of the secondary task. In PD, this analysis revealed weak evidence in favour of similar dual-task cost between nap and wake at post-intervention ( $BF_{10} = 0.34$ ,  $t_{(30)} = -0.01$ , 95% CI [-21.14 – 20.97],  $p = 0.99$ , Cohen's  $d = -0.01$ ;

Figure 5A, in warm colours) and retention ( $BF_{10} = 0.46$ ,  $t_{(30)} = -0.90$ , 95% CI [-28.59 – 11.04],  $p = 0.37$ , Cohen's  $d = -0.32$ ; Figure 5B, in cold colours). Weak evidence favouring the nap group was found in HOA ( $BF_{10} = 1.14$ ,  $t_{(30)} = 1.81$ , 95% CI [-1.99 – 33.05],  $p = 0.08$ , Cohen's  $d = 0.64$ ; Figure 5A, in warm colours) post-intervention, whereas it was weakly favouring no difference between interventions at retention ( $BF_{10} = 0.39$ ,  $W = 143$ ,  $p = 0.59$ ,  $r_{rb} = -0.10$ ,  $p = 0.59$ ; Figure 5B, in warm colours).

Comparisons of the dual-task costs post-intervention between people with PD and HOA revealed weak evidence for similar effect between groups allocated to the nap intervention ( $BF_{10} = 0.56$ ,  $t_{(30)} = -1.16$ , 95% CI [-30.35 – 8.31],  $p = 0.25$ , Cohen's  $d = 0.41$ ; Figure 5A), and to the wake intervention groups ( $BF_{10} = 0.37$ ,  $t_{(30)} = 0.48$ , 95% CI [-14.81–24.00],  $p = 0.63$ , Cohen's  $d = 0.10$ ; Figure 5A). At retention, dual-task costs showed weak evidence for a difference between people with PD and HOA allocated to the nap intervention ( $BF_{10} = 1.71$ ,  $t_{(30)} = -2.10$ , 95% CI [-33.86 – -0.45],  $p = 0.04$ , Cohen's  $d = 0.74$ ; Figure 5B), whereas evidence was weakly in favour of no difference in the wake intervention ( $BF_{10} = 0.35$ ,  $W = 111$ ,  $p = 0.54$ ,  $r_{rb} = -0.12$ ,  $p = 0.53$ ; Figure 5B).

These findings suggest that automaticity was not affected by the nap intervention in PD and in the HOA groups, neither in the short- nor in the long-term.

### Dual-task cost: Performance Index

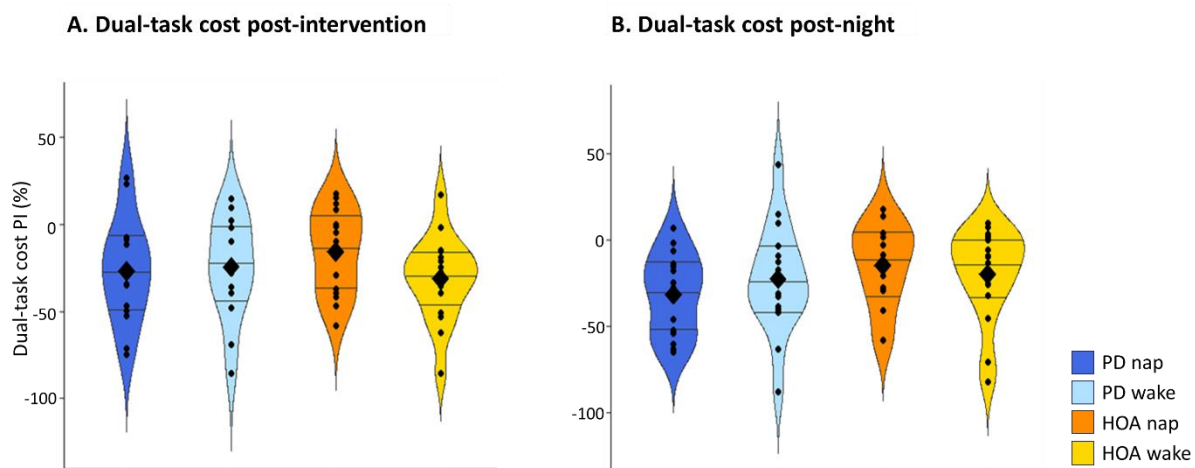


Figure 5. Dual-task costs. (A) Post-intervention dual-task cost of performance of the MSL sequence in the PD and HOA groups. (B) Post-night dual-task cost of performance of the MSL sequence in the PD and HOA groups. Violin plot: mean (diamond), median (central horizontal bar), and 25<sup>th</sup> (lower bar) and 75<sup>th</sup> (higher bar) percentiles.

#### Extended practice post-intervention and post-night

At post-intervention, weak evidence for an effect of nap over wakefulness on extended practice was found both in PD and HOA (PD:  $BF_{10} = 0.34$ ,  $t_{(30)} = 0.0009$ , 95% CI [-6.96 – 6.96],  $p = 0.99$ , Cohen's  $d = 0.0003$ ; HOA:  $BF_{10} = 0.38$ ,  $t_{(30)} = -0.57$ , 95% CI [-8.89 – 5.04],  $p = 0.58$ , Cohen's  $d = -0.20$ ). Similarly, when comparing PD with HOA, weak evidence for no difference was found in the nap ( $BF_{10} = 0.43$ ,  $t_{(30)} = 0.82$ , 95% CI [-4.00 – 9.35],  $p = 0.42$ , Cohen's  $d = 0.29$ ), and in the wake groups ( $BF_{10} = 0.64$ ,  $t_{(30)} = 1.30$ , 95% CI [-2.63 – 11.84],  $p = 0.20$ , Cohen's  $d = 0.46$ ).

At post-night, weak evidence for no difference between nap and wake intervention was found in PD ( $BF_{10} = 0.34$ ,  $t_{(30)} = 0.26$ , 95% CI [-6.61 – 8.55],  $p = 0.80$ , Cohen's  $d = 0.09$ ). For HOA, results showed weak evidence for a difference between interventions ( $BF_{10} = 1.22$ ,  $t_{(30)} = -1.86$ , 95% CI [-13.86–0.65],  $p = 0.07$ , Cohen's  $d = -0.66$ ). Only weak evidence for no difference between PD and HOA was found in the nap groups ( $BF_{10} = 0.35$ ,  $t_{(30)} = 0.34$ , 95% CI [-5.78 – 8.06],  $p = 0.74$ , Cohen's  $d = 0.12$ ), but this was weakly in favour of a difference for the wake groups ( $BF_{10} = 2.19$ ,  $t_{(30)} = 2.26$ , 95% CI [0.84–16.60],  $p = 0.03$ , Cohen's  $d = 0.80$ ) whereby HOA participants performed better than PD.

Hence, the rate of performance change during training was not different between people with PD and HOA at post-intervention, but our results suggest a protracted impact of the wake intervention on extended practice that differed between PD and HOA. Notably, when comparing the two interventions no evidence for a difference was found neither in PD nor in HOA.

### Aggregated effect across sessions

To investigate the aggregated effect of consolidation and extended practice across sessions, we compared the means of performance at the beginning of each training session. We found decisive evidence for an effect of session ( $BF_{10} > 1000$ ,  $F_{(2,120)} = 27.30$ ,  $p < 0.01$ , partial  $\eta^2 = 0.31$ ), but weak evidence for an effect of group ( $BF_{10} = 1.16$ ,  $F_{(1,60)} = 3.03$ ,  $p = 0.09$ , partial  $\eta^2 = 0.05$ ), and weak evidence for no effect of intervention ( $BF_{10} = 0.45$ ,  $F_{(1,60)} = 0.20$ ,  $p = 0.66$ , partial  $\eta^2 < 0.01$ ) or interaction of group by intervention ( $BF_{10} = 0.51$ ,  $F_{(1,60)} = 0.07$ ,  $p = 0.79$ , partial  $\eta^2 < 0.01$ ). We report moderate evidence for no interaction of group and session ( $BF_{10} = 0.28$ ,  $F_{(2,120)} = 1.93$ ,  $p = 0.15$ , partial  $\eta^2 = 0.03$ ), intervention by session: ( $BF_{10} = 0.17$ ,  $F_{(2,120)} = 1.04$ ,  $p = 0.36$ , partial  $\eta^2 = 0.02$ ) and group by intervention by session ( $BF_{10} = 0.26$ ,  $F_{(2,120)} = 1.03$ ,  $p = 0.36$ , partial  $\eta^2 = 0.02$ ). Post-hoc analyses on the main effect of session suggested weak evidence favouring no difference between pre-intervention and post-intervention ( $BF_{10} = 0.16$ ,  $V = 826$ ,  $p = 0.29$ ,  $r_{rb} = 0.01$ ,  $p = 0.90$ ), whereas decisive evidence was found for a difference between post-intervention and post-night ( $BF_{10} > 1000$ ,  $V = 199$ ,  $p < 0.01$ ,  $r_{rb} = 0.19$ ,  $p = 0.03$ ), and between pre-intervention and post-night ( $BF_{10} > 1000$ ,  $V = 224$ ,  $p < 0.01$ ,  $r_{rb} = 0.20$ ,  $p = 0.03$ ). These findings indicate that performance at the beginning of the same-day pre-intervention and post-intervention training sessions were similar, whereas it was greater at the beginning of the post-night training session, regardless of the group or of the intervention.

### EEG analyses

Bayesian t-tests revealed weak evidence for no difference between people with PD and HOA on overall sleep efficiency, percentages of N1, N2, N3, and REM (see Table 2). All participants presented at least 14 minutes of N2 sleep. Moreover, twelve HOA presented N3 sleep, and 8 also showed REM sleep. In the PD group, 10 of the 16 participants allocated to the nap intervention showed N3 sleep and three reached REM sleep.

Table 2. Sleep macro-architecture metrics from the nap in PD and HOA.

	PD (= 16)	HOA (= 16)	Test result (PD – HOA)
Overall sleep efficiency (%)	54.8 [42.0 – 67.5]	48.8 [37.2 – 60.4]	$BF_{10} = 0.40$ $t_{(30)} = 0.68$ , $p = 0.50$
N1 (%)	11.8 [8.7 – 14.8]	14.2 [8.8 – 19.6]	$BF_{10} = 0.42$ $W = 125$ , $p = 0.93$
N2 (%)	41.6 [33.0 – 50.2]	34.5 [27.6 – 41.5]	$BF_{10} = 0.61$ $t_{(30)} = 1.25$ , $p = 0.22$
N3 (%)	11.3 [3.4 – 19.2]	11.9 [5.5 – 18.3]	$BF_{10} = 0.34$ $W = 117$ , $p = 0.69$
REM (%)	1.8 [-0.5 – 4.1]	2.4 [0.9 – 3.9]	$BF_{10} = 0.36$ $W = 92$ , $p = 0.11$

Sleep efficiency: percentage of total sleep time/total time in bed. The values are reported as mean [ $\pm$  95% confidence interval]

Comparisons between PD and HOA on electrophysiological markers of plasticity during sleep revealed overall weak evidence for a group difference (spindle amplitude:  $BF_{10} = 0.89$ , spindle frequency:  $BF_{10} = 0.34$ , spindle density:  $BF_{10} = 0.34$ ; slow wave amplitude:  $BF_{10} = 0.35$ ; slow wave slope:  $BF_{10} = 0.37$ ; slow wave density:  $BF_{10} = 0.39$ ; ndPAC:  $BF_{10} = 0.38$ ) (see Figure 6). Further results on the effects of gender, age and AHI on these metrics are reported in Supplementary Material 6.

### Sleep micro-architecture metrics: people with Parkinson's disease and healthy older adults

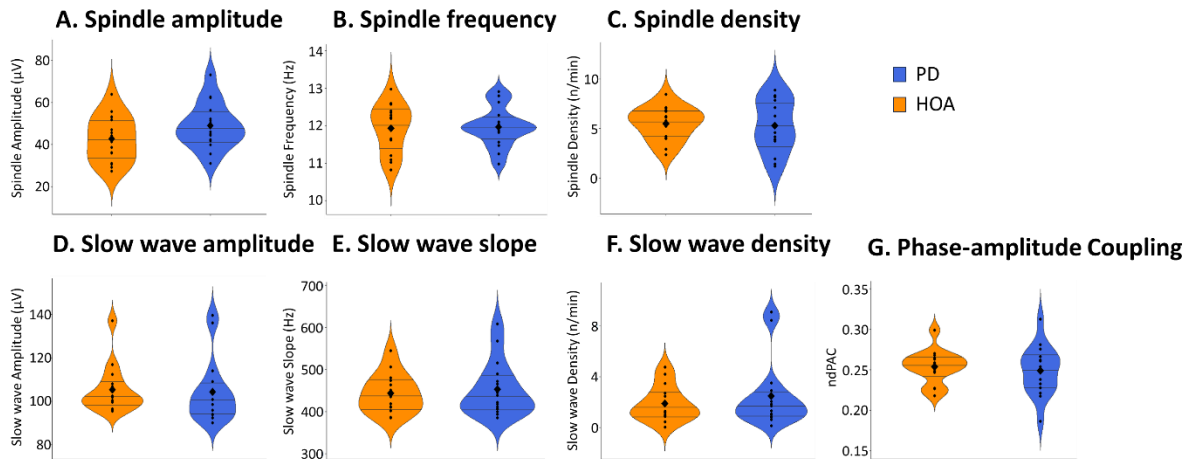


Figure 6. Overview of sleep micro-architecture metrics of people with PD (blue) and HOA (orange) allocated to the nap intervention. (A) Spindle amplitude, (B) spindle frequency, (C) spindle density, (D) slow wave amplitude, (E) slow wave slope and (F) slow wave density; (G) phase-amplitude coupling, measured as normalised direct phase-amplitude coupling (ndPAC). Violin plot: mean (diamond), median (central horizontal bar), and 25<sup>th</sup> (lower bar) and 75<sup>th</sup> (higher bar) percentiles.

Lastly, correlations between post-intervention offline changes in PI and sleep micro-architecture metrics obtained from the experimental nap were explored. In PD, strong evidence for a correlation was found between PI and slow wave amplitude ( $BF_{10} = 11.82$ ,  $S = 270$ ,  $r = 0.60$ ,  $p = 0.02$ , Figure 7D, in blue) and slow wave slope ( $BF_{10} = 14.31$ ,  $S = 314$ ,  $r = 0.54$ ,  $p = 0.03$ , Figure 7E, in blue). Moderate evidence was found for a correlation with spindle amplitude in PD ( $BF_{10} = 3.96$ , Pearson  $t_{(14)} = 2.64$ ,  $r = 0.58$ ,  $p = 0.02$ , Figure 7A, in blue).

### Correlations between sleep metrics and PI offline change post-intervention

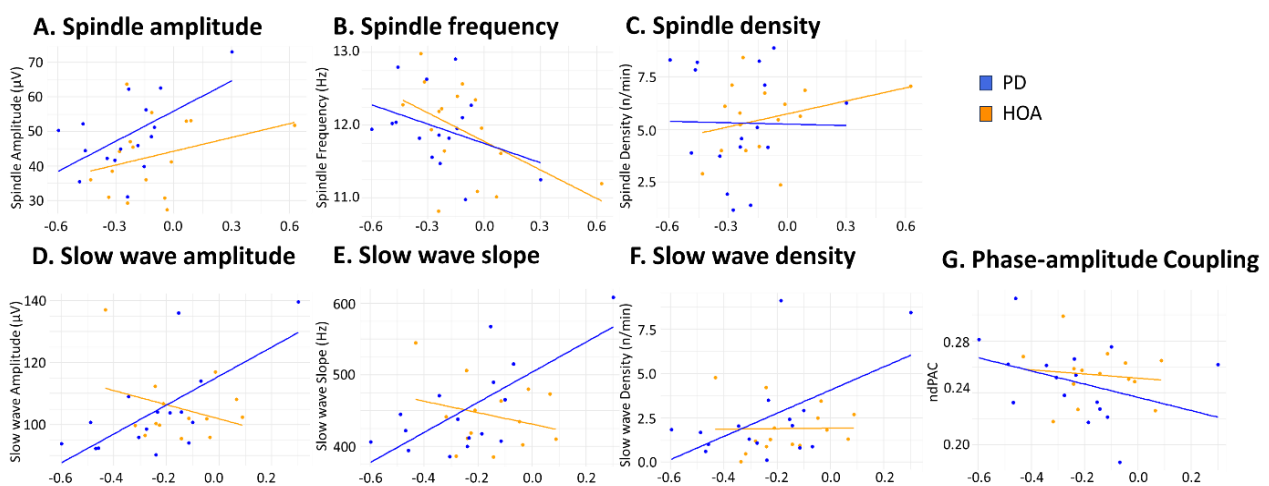


Figure 7. Correlations between sleep micro-architecture metrics and PI offline relative change post-intervention of people with PD (blue) and HOA (orange) allocated to the nap intervention. (A) Spindle amplitude, (B) spindle frequency, (C) spindle density, (D) slow wave amplitude, (E) slow wave slope and (F) slow wave density; (G) phase-amplitude coupling, measured as normalised direct phase-amplitude coupling (ndPAC).

Weak evidence for a correlation was found between PI relative change at post-intervention slow wave density ( $BF_{10} = 2.83$ ,  $S = 464$ ,  $r = 0.32$ ,  $p = 0.23$ , Figure 7F, in blue), and for spindle frequency ( $BF_{10} = 1.06$ , Pearson  $t_{(14)} = -1.45$ ,  $r = -0.36$ ,  $p = 0.17$ , Figure 7B, in blue). In HOA, weak evidence was found for no correlation between PI and slow wave amplitude ( $BF_{10} = 0.84$ ,  $S = 418$ ,  $r = 0.08$ ,  $p = 0.78$ , Figure 7D, in orange), slow wave slope ( $BF_{10} = 0.73$ ,  $S = 518$ ,  $r = -0.14$ ,  $p = 0.64$ , Figure 7E, in orange), slow wave density ( $BF_{10} = 0.53$ ,  $S = 410$ ,  $r = 0.27$ ,  $p = 0.33$ , Figure 7F, in orange), spindle amplitude ( $BF_{10} = 0.85$ ,  $S = 496$ ,  $r = 0.27$ ,  $p = 0.31$ , Figure 7A, in orange) and spindle frequency ( $BF_{10} = 2.31$ ,  $S = 1014$ ,  $r = -0.49$ ,  $p = 0.06$ , Figure 7B, in orange).

Weak evidence in both groups was found for correlations between PI and percentage of time spent in N2 and N3 (PD:  $BF_{10} = 1.41$ , Pearson  $t_{(14)} = -1.75$ ,  $r = -0.42$ ,  $p = 0.10$ ; HOA:  $BF_{10} = 0.59$ ,  $S = 414$ ,  $r = 0.26$ ,  $p = 0.35$ ), spindle density (PD:  $BF_{10} = 0.52$ ,  $t_{(14)} = -0.07$ ,  $r = -0.02$ ,  $p = 0.95$ ; HOA:  $BF_{10} = 0.86$ ,  $S = 490$ ,  $r = 0.28$ ,  $p = 0.29$ , Figure 7C), and phase-amplitude coupling (PD:  $BF_{10} = 1.07$ , Pearson  $t_{(14)} = -1.46$ ,  $r = -0.36$ ,  $p = 0.17$ ; HOA:  $BF_{10} = 0.58$ , Spearman  $S = 490$ ,  $r = -0.08$ ,  $p = 0.80$ , Figure 7G).

These results suggest that an association between behavioural performance change measured with PI and slow wave density, amplitude and slope could exist in PD, but it remains unclear in HOA.

## Discussion

In this study, we investigated the effect of a 2-hour post-learning nap compared to wakefulness on the consolidation and retention of a unimanual self-initiated motor sequence learning task in people with Parkinson's disease and healthy older adults. Our findings showed that people with PD and HOA exhibit similar levels of consolidation. Further, no impact of napping was observed on immediate offline consolidation, nor on 24-hour retention or automaticity, both in PD and HOA. Although PD had worse subjective sleep, both groups achieved similar sleep efficiency during the experimental nap and similar consolidation levels as expected. Interestingly, associations between sleep markers of plasticity and performance were only observed in the PD group.

The present study indicates that consolidation does not differ between PD and HOA, suggesting that such processes are similarly impaired in both populations as compared to younger adults (Backhaus & Junghanns, 2006; S. M. Fogel et al., 2014; Korman et al., 2007; Nishida & Walker, 2007). Further, we found that a 2-hour nap did not improve offline behavioural performance compared to wakefulness, neither in PD nor in HOA. This finding is in contrast with our initial hypothesis, where we expected similar improvement in PD and HOA after a diurnal napping intervention. This expectation was based on the relative preservation of sleep-facilitated consolidation in HOA (Fitzroy et al., 2021; King et al., 2016) and in PD (Dan et al., 2015; Lanir-Azaria et al., 2024; Terpening et al., 2013). Our results also showed that motor performance did not deteriorate immediately after a period of wakefulness in PD, contradicting our initial hypothesis that wakefulness would exacerbate the memory consolidation issues, given that the striatum is implicated in time-dependent consolidation in PD, possibly because the tests in the current experiment were performed ON dopaminergic medication and the duration of the consolidation period was limited to two hours (Albouy, King, et al., 2013; Morrish et al., 1996).

PD and HOA also performed similarly at retention following both nap and wakefulness when measured with the performance index, taking into account speed and accuracy. Yet, people with PD improved more on accuracy than HOA (Supplementary Material 4) at retention. This result is in line with Lanir-Azaria and colleagues (Lanir-Azaria et al., 2024), who investigated whether memory of a practiced motor sequence would transfer to another similarly trained sequence, following overnight sleep. Their results showed an improvement in accuracy at post-night retention on all the different initially trained motor sequences, both in PD and HOA. It is thus possible that to achieve similar performance people with PD used a different strategy, favouring accuracy over speed, than HOA. Such preference for accuracy over speed is frequently observed in



PD, and likely related to the core symptom of bradykinesia and an implicit decision not to move faster because of an already higher than normal energy expenditure to move at a normal speed (Mazzoni et al., 2007).

Delving in the effects of sleep on automaticity, we found that dual-task performance was similar between PD and HOA. This result is not in line with our expectation given that motor automaticity relies on the posterior striatum (Poldrack et al., 2005), which becomes progressively dysfunctional in PD (Poldrack et al., 2005; Wu, Hallett, et al., 2015; Wu, Liu, et al., 2015). It is also not in line with the literature as several studies suggested that automaticity is impaired in PD (Doyon et al., 1998; Hirata et al., 2020; Nieuwhof et al., 2017; Wu et al., 2010; Wu, Liu, et al., 2015). Yet, in our study, automaticity was assessed after a period of consolidation. It is thus possible that this period of rest ultimately improved automaticity levels in PD and restored them to HOA levels. Another possibility is that, to achieve seemingly similar automaticity levels at the behavioural level, people with PD actually used attentional compensatory networks compared to HOA (Gilat et al., 2021; Nieuwhof et al., 2017), though this could not be verified in the present study. The intervention, however, similarly impacted automaticity regardless the condition (nap or wake) in both groups. One can speculate that automaticity emerges after practice and non-sleep specific consolidation (Fang et al., 2021; S. M. Fogel et al., 2014; Gui et al., 2017; King et al., 2013; Spencer et al., 2007).

Importantly, all participants exhibited motor learning. This is in line with current literature suggesting that learning of a motor task is not necessarily impaired in the early to mid-stages of PD (Nackaerts et al., 2020), likely due to the activation of compensatory neural circuits in this population (Carbon & Eidelberg, 2006; Wu & Hallett, 2005). However, when investigating the performance level at the beginning of each session, we found no difference between the initial training session and the post-intervention session in both groups and regardless the intervention. The preservation to perform at the initial level, rather than to improve on performance after the intervention may reflect insufficient encoding that could have in turn prevented triggering offline sleep- or wake-dependent memory consolidation processes. Indeed, it has been suggested that the success of initial encoding of a motor sequence is central to induce sleep-dependent memory consolidation processes in healthy ageing (King et al., 2016). This speculation is further supported by the difference between the beginning of the post-intervention session and the beginning of the post-night session suggesting that two training sessions were necessary to trigger offline consolidation. Yet, the specificity of sleep cannot be assessed in the current study as the post-intervention and the post-night session were separated by a night of sleep at home in both intervention arms. Therefore, future studies should consider extending initial practice to ensure successful initial encoding.

We also found that the improvement rate, namely the difference between the beginning and the end of practice at post-intervention, was similar between nap and wakefulness in both populations. This result does not align with our expectations that a period of sleep could still enhance performance gains during extended practice, especially in HOA (Terpening et al., 2013) although at retention, our analyses did show that after wake, HOA may have a bigger improvement rate than people with PD. This result could suggest that wakefulness followed by a night of sleep improves performance gains during practice in HOA but not in PD. This impairment in people with PD could be attributed to the striatal dysfunction hampering consolidation over longer time periods if not preceded by an additional period of post-learning sleep.

Interestingly, PD and HOA showed similar sleep quality and similar amounts of consolidation-related electrophysiological markers of sleep during the experimental nap, which is striking in light of the substantial differences on subjective sleep quality between the groups. It must be noted, however, that in our study we measured a short diurnal sleep period with limited REM sleep, so there was less opportunity for the common sleep disorders of PD to impact on sleep efficiency and consolidation. (Stefani & Högl, 2020). This might explain the lack of differences between the electrophysiological markers of sleep (spindle density and amplitude, slow

wave amplitude, and phase-amplitude coupling) between PD and HOA as found by others assessing nocturnal sleep (Latreille et al., 2015; Memon et al., 2023). An interesting finding was that consolidation, as assessed by the offline performance change, was associated with higher slow wave density, amplitude, and slope, as well as with higher spindle amplitude in PD only, which is in line with the study by Lahlou et al. who found similar correlations in the declarative memory domain (Lahlou et al., 2024). Taken these findings together, one can speculate that diurnal sleep might allow people with PD to compensate for nocturnal sleep debts and achieve similar consolidation levels as HOA. Surprisingly, better learning was not associated with cross-frequency coupling between spindles and slow waves, particularly important for memory consolidation (Helfrich et al., 2018; Muehlroth et al., 2019). This lack of association was apparent in both groups. Overall, it appears that improvements of accuracy are particularly associated to slow wave quality in people with PD. Future research is indicated to determine whether sleep interventions (e.g., targeted memory reactivation) can leverage these specific sleep waves and enhance their quality to improve memory consolidation in these patients. Such non-invasive interventions have already proved their efficacy in young adults (Antony et al., 2012; Nicolas et al., 2022), and they are feasible also in older adults (Johnson et al., 2020; Nicolas et al., 2024).

This study presents several limitations. Firstly, the sample size was limited and findings are still to be interpreted with caution. Despite the fact that the protocol was based on prior work in HOA (King et al., 2016), the training provided before the intervention may not have been sufficient for the required encoding of the motor sequencing in our cohorts. Although we intentionally opted for a napping paradigm to allow for a wake-control group and to minimise possible confounding circadian and homeostatic effects, it is possible that a 2-hour opportunity to sleep was too short to sufficiently consolidate the memory traces of the motor task in our cohort of older adults with and without PD. Moreover, EEG did not allow for the specific investigation of the key brain areas involved in motor memory consolidation. Future studies using additional imaging techniques (e.g., fMRI) could aid the interpretation of behavioural effects. Most importantly, the present study shows that conducting napping protocols to study memory processes in PD is feasible, as there was good sleep efficiency and no adverse events related to the interventions were noted.

To conclude, this study compared for the first time the effects of a 2-hour sleep opportunity with an equivalent time of wakefulness on motor memory consolidation in people with Parkinson's disease and in healthy older adults. Overall, these findings suggest similar consolidation levels between people with PD and HOA. Results also showed that a single post-learning nap did not further enhance motor memory consolidation as compared to wakefulness. However, the association between sleep and behaviour in PD, and not in HOA, may indicate that equivalent performance output between HOA and PD may be achieved using different consolidation mechanisms.

## Disclosure statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Acknowledgements

Funding for this study was provided by the Funds Malou Malou & Perano, managed by the King Baudouin Foundation (2019-J4121350-212854) and Internal Funds KU Leuven (STG/21/035). Moran Gilat was supported by a Marie-Skłodowska-Curie Action Postdoctoral Fellowship (TARGET-SLEEP, 838576). Letizia Micca is supported by a FWO PhD Fellowship (SLEEP ON IT, 11PQB24N). Judith Nicolas was funded by The Fondation Pour la Recherche Médicale (ARF202309017485). The authors would like to sincerely thank all the participants for their efforts. We also like to thank the staff at the Centre for Sleep Monitoring of UZ Leuven, Tine Wouters,

Charlotte Moris, Evi Van de Velde and the master thesis students of Rehabilitation Sciences at KU Leuven for their assistance with data collection.

## References

- Albouy, G., Fogel, S., King, B. R., Laventure, S., Benali, H., Karni, A., Carrier, J., Robertson, E. M., & Doyon, J. (2015). Maintaining vs. enhancing motor sequence memories: Respective roles of striatal and hippocampal systems. *NeuroImage*, *108*, 423–434.  
<https://doi.org/10.1016/j.neuroimage.2014.12.049>
- Albouy, G., Fogel, S., Pottiez, H., Nguyen, V. A., Ray, L., Lungu, O., Carrier, J., Robertson, E., & Doyon, J. (2013). Daytime sleep enhances consolidation of the spatial but not motoric representation of motor sequence memory. *PLoS One*, *8*(1), e52805.
- Albouy, G., King, B. R., Maquet, P., & Doyon, J. (2013). Hippocampus and striatum: Dynamics and interaction during acquisition and sleep-related motor sequence memory consolidation. *Hippocampus*, *23*(11), 985–1004.
- Antony, J. W., Gobel, E. W., O’Hare, J. K., Reber, P. J., & Paller, K. A. (2012). Cued memory reactivation during sleep influences skill learning. *Nature Neuroscience*, *15*(8), 1114–1116.  
<https://doi.org/10.1038/nn.3152>
- Bachar Kirshenboim, Y., Weitzer, T., & Rand, D. (2023). Assessing upper extremity-cognitive dual-task ability in neurological populations: A systematic review. *NeuroRehabilitation, Preprint*, 1–13.
- Backhaus, J., & Junghanns, K. (2006). Daytime naps improve procedural motor memory. *Sleep Medicine*, *7*(6), 508–512.
- Barone, P., Antonini, A., Colosimo, C., Marconi, R., Morgante, L., Avarello, T. P., Bottacchi, E., Cannas, A., Ceravolo, G., Ceravolo, R., & others. (2009). The PRIAMO study: a multicenter assessment of nonmotor symptoms and their impact on quality of life in Parkinson’s disease. *Movement Disorders: Official Journal of the Movement Disorder Society*, *24*(11), 1641–1649.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *arXiv. ArXiv Preprint ArXiv:1406.5823*, 23.
- Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Pergamon Press.
- Berry, R., Albertario, C., & Harding, S. (2018). Medicine for the aa of S. the AASM manual for the scoring of sleep and associated events: rules, terminology and technical Specifications., version 2.5, version 2.5. *Darien, IL: American Academy of Sleep Medicine*.
- Born, J., & Wilhelm, I. (2012). System consolidation of memory during sleep. *Psychological Research*, *76*, 192–203.
- Brainard, D. H., & Vision, S. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436.
- Buysee, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). Pittsburgh sleep quality index. *Journal of Clinical Psychology in Medical Settings*.
- Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences*, *14*(11), 506–515.
- Carbon, M., & Eidelberg, D. (2006). Functional imaging of sequence learning in Parkinson’s disease. *Journal of the Neurological Sciences*, *248*(1–2), 72–77.

- Carrier, J., Land, S., Buysse, D. J., Kupfer, D. J., & Monk, T. H. (2001). The effects of age and gender on sleep EEG power spectral density in the middle years of life (ages 20–60 years old). *Psychophysiology*, *38*(2), 232–242.
- Carrier, J., Viens, I., Poirier, G., Robillard, R., Lafortune, M., Vandewalle, G., Martin, N., Barakat, M., Paquet, J., & Filipini, D. (2011). Sleep slow wave changes during the middle years of life. *European Journal of Neuroscience*, *33*(4), 758–766.
- Cochén, V., Arbus, C., Soto, M. E., Villars, H., Tiberge, M., Montemayor, T., Hein, C., Veccherini, M. F., Onen, S.-H., & Ghorayeb, I. (2009). Sleep disorders and their impacts on healthy, dependent, and frail older adults. *The Journal of Nutrition, Health and Aging*, *13*(4), 322–329.
- Cohen, J. (1992). *QUANTITATIVE METHODS IN PSYCHOLOGY A Power Primer*.
- Dan, X., King, B. R., Doyon, J., & Chan, P. (2015). Motor sequence learning and consolidation in unilateral de novo patients with Parkinson’s disease. *PLoS One*, *10*(7), e0134291.
- Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, *17*(6), 652–655.
- Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., Lehericy, S., & Benali, H. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research*, *199*(1), 61–75.
- Doyon, J., Laforce Jr, R., Bouchard, G., Gaudreau, D., Roy, J., Poirier, M., Bédard, P. J., Bédard, F., & Bouchard, J.-P. (1998). Role of the striatum, cerebellum and frontal lobes in the automatization of a repeated visuomotor sequence of movements. *Neuropsychologia*, *36*(7), 625–641.
- Doyon, J., Penhune, V., & Ungerleider, L. G. (2003). Distinct contribution of the cortico-striatal and cortico-cerebellar systems to motor skill learning. *Neuropsychologia*, *41*(3), 252–262.
- Fang, Z., Smith, D. M., Albouy, G., King, B. R., Vien, C., Benali, H., Carrier, J., Doyon, J., & Fogel, S. (2021). Differential Effects of a Nap on Motor Sequence Learning-Related Functional Connectivity Between Young and Older Adults. *Frontiers in Aging Neuroscience*, *13*.  
<https://doi.org/10.3389/fnagi.2021.747358>
- Fitzroy, A. B., Kainec, K. A., Seo, J., & Spencer, R. M. C. (2021). Encoding and consolidation of motor sequence learning in young and older adults. *Neurobiology of Learning and Memory*, *185*, 107508.
- Fogel, S., Albouy, G., Vien, C., King, B., Hoge, R., Jbabdi, S., Benali, H., Karni, A., Maquet, P., Carrier, J., & others. (2012). *Age-related differences in cerebral activation for motor sequence learning are correlated with sleep spindles*.
- Fogel, S. M., Albouy, G., Vien, C., Popovici, R., King, B. R., Hoge, R., Jbabdi, S., Benali, H., Karni, A., Maquet, P., & others. (2014). fMRI and sleep correlates of the age-related impairment in motor memory consolidation. *Human Brain Mapping*, *35*(8), 3625–3645.
- Gilat, M., Ginis, P., Zoetewij, D., De Vleeschhauer, J., Hulzinga, F., D’Cruz, N., & Nieuwboer, A. (2021). A systematic review on exercise and training-based interventions for freezing of gait in Parkinson’s disease. In *npj Parkinson’s Disease* (Vol. 7, Issue 1). Nature Research.  
<https://doi.org/10.1038/s41531-021-00224-4>

- Goetz, C. G., Tilley, B. C., Shaftman, S. R., Stebbins, G. T., Fahn, S., Martinez-Martin, P., Poewe, W., Sampaio, C., Stern, M. B., & Dodel, R. (2008). Movement Disorder Society-sponsored revision of the Unified Parkinson's Disease Rating Scale (MDS-UPDRS): scale presentation and clinimetric testing results. *Movement Disorders: Official Journal of the Movement Disorder Society*, *23*(15), 2129–2170.
- Gui, W. J., Li, H. J., Guo, Y. H., Peng, P., Lei, X., & Yu, J. (2017). Age-related differences in sleep-based memory consolidation: A meta-analysis. *Neuropsychologia*, *97*, 46–55.  
<https://doi.org/10.1016/j.neuropsychologia.2017.02.001>
- Helfrich, R. F., Mander, B. A., Jagust, W. J., Knight, R. T., & Walker, M. P. (2018). Old brains come uncoupled in sleep: slow wave-spindle synchrony, brain atrophy, and forgetting. *Neuron*, *97*(1), 221–230.
- Hirata, K., Hattori, T., Kina, S., Chen, Q., Ohara, M., & Yokota, T. (2020). Striatal dopamine denervation impairs gait automaticity in drug-Naïve Parkinson's disease patients. *Movement Disorders*, *35*(6), 1037–1045.
- Hoehn, M. M., & Yahr, M. D. (1967). Parkinsonism: onset, progression, and mortality. *Neurology*, *17*(5), 427–442.
- Iber, C. (2007). The AASM manual for the scoring of sleep and associated events: rules, terminology, and technical specification. (*No Title*).
- Jenkinson, C., Fitzpatrick, R. A. Y., Peto, V. I. V, Greenhall, R., & Hyman, N. (1997). The Parkinson's Disease Questionnaire (PDQ-39): development and validation of a Parkinson's disease summary index score. *Age and Ageing*, *26*(5), 353–357.
- Jensen, O., & Colgin, L. L. (2007). Cross-frequency coupling between neuronal oscillations. *Trends in Cognitive Sciences*, *11*(7), 267–269.
- Johns, M. W. (1991). A new method for measuring daytime sleepiness: the Epworth sleepiness scale. *Sleep*, *14*(6), 540–545.
- Johnson, B. P., Scharf, S. M., Verceles, A. C., & Westlake, K. P. (2020). Sensorimotor performance is improved by targeted memory reactivation during a daytime nap in healthy older adults. *Neuroscience Letters*, *731*, 134973.
- King, B. R., Fogel, S. M., Albouy, G., & Doyon, J. (2013). Neural correlates of the age-related changes in motor sequence learning and motor adaptation in older adults. *Frontiers in Human Neuroscience*, *7*, 142.
- King, B. R., Hoedlmoser, K., Hirschauer, F., Dolfen, N., & Albouy, G. (2017). Sleeping on the motor engram: the multifaceted nature of sleep-related motor memory consolidation. *Neuroscience & Biobehavioral Reviews*, *80*, 1–22.
- King, B. R., Saucier, P., Albouy, G., Fogel, S. M., Rumpf, J.-J., Klann, J., Buccino, G., Binkofski, F., Classen, J., Karni, A., & others. (2016). Cerebral activation during initial motor learning forecasts subsequent sleep-facilitated memory consolidation in older adults. *Cerebral Cortex*, bhv347.
- Kirk, V., Baughn, J., D'Andrea, L., Friedman, N., Galion, A., Garetz, S., Hassan, F., Wrede, J., Harrod, C. G., & Malhotra, R. K. (2017). American Academy of Sleep Medicine position paper for the use of a home sleep apnea test for the diagnosis of OSA in children. *Journal of Clinical Sleep Medicine*, *13*(10), 1199–1203.



- Kleiner, M., Brainard, D. H., & Pelli, D. G. (2007). *What's new in Psychtoolbox-3? Perception, 36 (ECPV Abstract Supplement), 1–16.*
- Korman, M., Doyon, J., Doljansky, J., Carrier, J., Dagan, Y., & Karni, A. (2007). Daytime sleep condenses the time course of motor memory consolidation. *Nature Neuroscience, 10(9), 1206–1213.*
- Lacourse, K., Delfrate, J., Beaudry, J., Peppard, P., & Warby, S. C. (2019). A sleep spindle detection algorithm that emulates human expert spindle scoring. *Journal of Neuroscience Methods, 316, 3–11.*
- Lahlou, S., Kaminska, M., Doyon, J., Carrier, J., & Sharp, M. (2024). Sleep spindle density and temporal clustering are associated with sleep-dependent memory consolidation in Parkinson's disease. *Journal of Clinical Sleep Medicine, jcs-11080.*
- Lajoie, A. C., Lafontaine, A.-L., & Kaminska, M. (2021). The spectrum of sleep disorders in Parkinson disease: a review. *Chest, 159(2), 818–827.*
- Lanir-Azaria, S., Chishinski, R., Tauman, R., Nir, Y., & Giladi, N. (2024). Sleep improves accuracy, but not speed, of generalized motor learning in young and older adults and in individuals with Parkinson's disease. *Frontiers in Behavioral Neuroscience, 18.*  
<https://doi.org/10.3389/fnbeh.2024.1466696>
- Latreille, V., Carrier, J., Lafortune, M., Postuma, R. B., Bertrand, J.-A., Panisset, M., Chouinard, S., & Gagnon, J.-F. (2015). Sleep spindles in Parkinson's disease may predict the development of dementia. *Neurobiology of Aging, 36(2), 1083–1090.*
- Latreille, V., Carrier, J., Montplaisir, J., Lafortune, M., & Gagnon, J.-F. (2011). Non-rapid eye movement sleep characteristics in idiopathic REM sleep behavior disorder. *Journal of the Neurological Sciences, 310(1–2), 159–162.*
- Leclercq, Y., Schrouff, J., Noirhomme, Q., Maquet, P., Phillips, C., & others. (2011). fMRI artefact rejection and sleep scoring toolbox. *Computational Intelligence and Neuroscience, 2011.*
- Lee, M. D., & Wagenmakers, E.-J. (2014). *Bayesian cognitive modeling: A practical course.* Cambridge university press.
- Marinelli, L., Quartarone, A., Hallett, M., Frazzitta, G., & Ghilardi, M. F. (2017). The many facets of motor learning and their relevance for Parkinson's disease. *Clinical Neurophysiology, 128(7), 1127–1141.*
- Marinus, J., Visser, M., van Hilten, J. J., Lammers, G. J., & Stiggelbout, A. M. (2003). Assessment of sleep and sleepiness in Parkinson disease. *Sleep, 26(8), 1049–1054.*
- Massimini, M., Huber, R., Ferrarelli, F., Hill, S., & Tononi, G. (2004). The sleep slow oscillation as a traveling wave. *Journal of Neuroscience, 24(31), 6862–6870.*
- Mazzoni, P., Hristova, A., & Krakauer, J. W. (2007). Why don't we move faster? Parkinson's disease, movement vigor, and implicit motivation. *Journal of Neuroscience, 27(27), 7105–7116.*
- Memon, A. A., Catiul, C., Irwin, Z., Pilkington, J., Memon, R. A., Joop, A., Wood, K. H., Cutter, G., Miocinovic, S., & Amara, A. W. (2023). Quantitative Sleep Electroencephalogram in Parkinson's Disease: A Case-Control Study. *Journal of Parkinson's Disease, Preprint, 1–15.*
- Milnik, A., Nowak, I., & Müller, N. G. (2013). Attention-dependent modulation of neural activity in primary sensorimotor cortex. *Brain and Behavior, 3(2), 54–66.*

- Moraes, W., Piovezan, R., Poyares, D., Bittencourt, L. R., Santos-Silva, R., & Tufik, S. (2014). Effects of aging on sleep structure throughout adulthood: a population-based study. *Sleep Medicine, 15*(4), 401–409.
- Morey, R. D., Rouder, J. N., Jamil, T., Urbanek, S., Forner, K., & Ly, A. (2022). BayesFactor: Computation of Bayes Factors for Common Designs (2024). *R Package Version 0.9*, 12–14.
- Morrish, P. K., Sawle, G. V., & Brooks, D. J. (1996). Regional changes in [18F] dopa metabolism in the striatum in Parkinson's disease. *Brain, 119*(6), 2097–2103.
- Muehlroth, B. E., Sander, M. C., Fandakova, Y., Grandy, T. H., Rasch, B., Shing, Y. L., & Werkle-Bergner, M. (2019). Precise Slow Oscillation–Spindle Coupling Promotes Memory Consolidation in Younger and Older Adults. *Scientific Reports, 9*(1). <https://doi.org/10.1038/s41598-018-36557-z>
- Nackaerts, E., Ginis, P., Heremans, E., Swinnen, S. P., Vandenberghe, W., & Nieuwboer, A. (2020). Retention of touchscreen skills is compromised in Parkinson's disease. *Behavioural Brain Research, 378*, 112265.
- Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695–699.
- Nicolas, J., Carrier, J., Swinnen, S. P., Doyon, J., Albouy, G., & King, B. R. (2024). Targeted memory reactivation during post-learning sleep does not enhance motor memory consolidation in older adults. *Journal of Sleep Research, 33*(1). <https://doi.org/10.1111/jsr.14027>
- Nicolas, J., King, B. R., Levesque, D., Lazzouni, L., Coffey, E., Swinnen, S., Doyon, J., Carrier, J., & Albouy, G. (2022). Sigma oscillations protect or reinstate motor memory depending on their temporal coordination with slow waves. *eLife, 11*. <https://doi.org/10.7554/eLife.73930>
- Nieuwboer, A., Rochester, L., Herman, T., Vandenberghe, W., Emil, G. E., Thomaes, T., & Giladi, N. (2009). Reliability of the new freezing of gait questionnaire: agreement between patients with Parkinson's disease and their carers. *Gait & Posture, 30*(4), 459–463.
- Nieuwboer, A., Rochester, L., Müncks, L., & Swinnen, S. P. (2009). Motor learning in Parkinson's disease: limitations and potential for rehabilitation. *Parkinsonism & Related Disorders, 15*, S53–S58.
- Nieuwhof, F., Bloem, B. R., Reelick, M. F., Aarts, E., Maidan, I., Mirelman, A., Hausdorff, J. M., Toni, I., & Helmich, R. C. (2017). Impaired dual tasking in Parkinson's disease is associated with reduced focusing of cortico-striatal activity. *Brain, 140*(5), 1384–1398.
- Nishida, M., & Walker, M. P. (2007). Daytime naps, motor memory consolidation and regionally specific sleep spindles. *PLoS One, 2*(4), e341.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113.
- Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, 2011*, 1–9.
- Özkurt, T. E. (2012). Statistically reliable and fast direct estimation of phase-amplitude cross-frequency coupling. *IEEE Transactions on Biomedical Engineering, 59*(7), 1943–1950.

- Özkurt, T. E., & Schnitzler, A. (2011). A critical note on the definition of phase–amplitude cross-frequency coupling. *Journal of Neuroscience Methods*, *201*(2), 438–443.
- Pan, S. C., & Rickard, T. C. (2015). Sleep and motor learning: Is there room for consolidation? *Psychological Bulletin*, *141*(4), 812–834. <https://doi.org/10.1037/bul0000009>
- Pelli, D. G., & Vision, S. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.
- Poldrack, R. A., Sabb, F. W., Foerde, K., Tom, S. M., Asarnow, R. F., Bookheimer, S. Y., & Knowlton, B. J. (2005). The neural correlates of motor skill automaticity. *Journal of Neuroscience*, *25*(22), 5356–5364. <https://doi.org/10.1523/JNEUROSCI.3880-04.2005>
- Postuma, R. B., Berg, D., Stern, M., Poewe, W., Olanow, C. W., Oertel, W., Obeso, J., Marek, K., Litvan, I., Lang, A. E., & others. (2015). MDS clinical diagnostic criteria for Parkinson’s disease. *Movement Disorders*, *30*(12), 1591–1601.
- Purcell, S. M., Manoach, D. S., Demanuele, C., Cade, B. E., Mariani, S., Cox, R., Panagiotaropoulou, G., Saxena, R., Pan, J. Q., Smoller, J. W., Redline, S., & Stickgold, R. (2017). Characterizing sleep spindles in 11,630 individuals from the National Sleep Research Resource. *Nature Communications*, *8*. <https://doi.org/10.1038/ncomms15930>
- Quinn, N., Critchley, P., & Marsden, C. D. (1987). Young onset Parkinson’s disease. *Movement Disorders: Official Journal of the Movement Disorder Society*, *2*(2), 73–91.
- R Core Team. (2022). *R: A Language and Environment for Statistical Computing*. <https://www.R-project.org/>
- Schulz, K. F., Altman, D. G., & Moher, D. (2010). CONSORT 2010 statement: updated guidelines for reporting parallel group randomised trials. *Journal of Pharmacology and Pharmacotherapeutics*, *1*(2), 100–107.
- Seuthe, J., Hermanns, H., Hulzinga, F., D’Cruz, N., Deuschl, G., Ginis, P., Nieuwboer, A., & Schlenstedt, C. (2024). Gait asymmetry and symptom laterality in Parkinson’s disease: two of a kind? *Journal of Neurology*, 1–10.
- Sinha, S. R., Sullivan, L., Sabau, D., San-Juan, D., Dombrowski, K. E., Halford, J. J., Hani, A. J., Drislane, F. W., & Stecker, M. M. (2016). American clinical neurophysiology society guideline 1: minimum technical requirements for performing clinical electroencephalography. *Journal of Clinical Neurophysiology*, *33*(4), 303–307.
- Spencer, R. M. C., Gouw, A. M., & Ivry, R. B. (2007). Age-related decline of sleep-dependent consolidation. *Learning and Memory*, *14*(7), 480–484. <https://doi.org/10.1101/lm.569407>
- Stefani, A., & Högl, B. (2020). Sleep in Parkinson’s disease. *Neuropsychopharmacology*, *45*(1), 121–128.
- Stiasny-Kolster, K., Mayer, G., Schäfer, S., Möller, J. C., Heinzel-Gutenbrunner, M., & Oertel, W. H. (2007). The REM sleep behavior disorder screening questionnaire—a new diagnostic instrument. *Movement Disorders*, *22*(16), 2386–2393.
- Tassi, P., & Muzet, A. (2000). Sleep inertia. *Sleep Medicine Reviews*, *4*(4), 341–353.

- Terpening, Z., Naismith, S., Melehan, K., Gittins, C., Bolitho, S., & Lewis, S. J. G. (2013). The contribution of nocturnal sleep to the consolidation of motor skill learning in healthy ageing and Parkinson's disease. *Journal of Sleep Research, 22*(4), 398–405.
- Tombaugh, T. N., & McIntyre, N. J. (1992). The mini-mental state examination: a comprehensive review. *Journal of the American Geriatrics Society, 40*(9), 922–935.
- Tomlinson, C. L., Stowe, R., Patel, S., Rick, C., Gray, R., & Clarke, C. E. (2010). Systematic review of levodopa dose equivalency reporting in Parkinson's disease. *Movement Disorders, 25*(15), 2649–2653.
- Vallat, R., & Walker, M. P. (2021). An open-source, high-performance tool for automated sleep staging. *Elife, 10*, e70092.
- World Medical Association declaration of Helsinki: Ethical principles for medical research involving human subjects. (2013). In *JAMA* (Vol. 310, Issue 20, pp. 2191–2194). American Medical Association. <https://doi.org/10.1001/jama.2013.281053>
- Wu, T., & Hallett, M. (2005). A functional MRI study of automatic movements in patients with Parkinson's disease. *Brain, 128*(10), 2250–2259.
- Wu, T., Hallett, M., & Chan, P. (2015). Motor automaticity in Parkinson's disease. *Neurobiology of Disease, 82*, 226–234.
- Wu, T., Liu, J., Zhang, H., Hallett, M., Zheng, Z., & Chan, P. (2015). Attention to automatic movements in Parkinson's disease: modified automatic mode in the striatum. *Cerebral Cortex, 25*(10), 3330–3342.
- Wu, T., Wang, L., Hallett, M., Li, K., & Chan, P. (2010). Neural correlates of bimanual anti-phase and in-phase movements in Parkinson's disease. *Brain, 133*(8), 2394–2409. <https://doi.org/10.1093/brain/awq151>
- Xu, Z., Anderson, K. N., Saffari, S. E., Lawson, R. A., Chaudhuri, K. R., Brooks, D., & Pavese, N. (2021). Progression of sleep disturbances in Parkinson's disease: a 5-year longitudinal study. *Journal of Neurology, 268*(1), 312–320. <https://doi.org/10.1007/s00415-020-10140-x>