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RESEARCH ARTICLE

The impact of sleep on factual memory retention over 24 hr

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Summary

Although a period of sleep seems to benefit the retention of declarative memories, recent studies have challenged both the size of this effect and its active influence on memory consolidation. This study aimed to further investigate the effect of sleep and its time dependency on the consolidation of factual information. In a within-subjects design, 48 participants (M_{age} = 24.37 ± 4.18 years, 31F) were asked to learn several facts in a multi-sensory "flashcard-like" memory task at 21:00 hours (sleep first condition) or at 09:00 hours (wake first condition). Then, in each condition, participants performed an immediate recall test (T0), and two delayed tests 12 hr (T1) and 24 hr (T2) later. Participants' sleep was recorded at their homes with a portable device. Results revealed that memory retention was better after a night of sleep compared with wakefulness, regardless of the delay from encoding (a few hr versus 12+ hr), but the sleep effect was modest. The decline in memory during the wake period following sleep was smaller compared with the decline observed during the 12 hr of wakefulness after encoding. However, after 24 hr from the encoding, when all participants experienced a period of both sleep and wakefulness, memory performance in the two conditions was similar. Overall, our data suggest that sleep exerts a small, yet beneficial, influence on memory retention by likely reducing interference and actively stabilizing memory traces.

KEYWORDS
factual memory consolidation, sleep, time-dependency, wakefulness

1 | INTRODUCTION

In 1924, Jenkins and Dallenbach published a seminal work in which they described for the first time the so-called "sleep effect", that is, the beneficial effect of sleep against declarative memory decline compared with an equal period spent in wakefulness (Jenkins & Dallenbach, 1924). According to their hypothesis, sleep plays a passive role in memory by shielding acquired information from interference as interactions with the external environment are considerably reduced during these periods. Furthermore, a large amount of new material is encoded during wakefulness, with higher interference levels compared with a sleep period, leading to a major memory detriment.

This idea was challenged by Benson and Feinberg (1977), who showed that a period of sleep that occurs just after the encoding of declarative information (i.e. word pairs) reduces memory forgetting 24 hr after learning compared with a delayed sleep (16+ hr) after the encoding. The authors suggested that sleeping shortly after encoding some information could either minimize interference in a very sensitive window for consolidation, or accelerate memory consolidation processes.

Since Benson and Feinberg (1977), several studies have been conducted to investigate whether there is an optimal time window following learning during which sleep best supports memory consolidation. According to many of these studies, sleep must occur shortly after the encoding phase to consolidate newly acquired memories (Ellenbogen et al., 2009; Ellenbogen, Hulbert, et al., 2006; Gais et al., 2006; Payne et al., 2012; Talamini et al., 2008). The

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aforementioned studies examined how sleep, either immediately after learning or within hours, affected various forms of memory performance throughout a 24-hr period. They found that when learning happened right before sleep, as opposed to before a day of wakefulness, memory retention was considerably higher. Furthermore, these studies, by manipulating the level of interference in different conditions, showed that sleep has a beneficial role on memory by making memory traces more resistant to future interferences. However, other studies were unable to demonstrate the active role of sleep in memory consolidation, despite using the same experimental design and materials (Bailes et al., 2020; Pöhlchen et al., 2021). Besides, they showed that the detrimental effects of interference learning are essentially the same after a period of sleep or wakefulness.

More recently, a study conducted by Zhang et al. (2022) reported that when participants slept shortly after the encoding phase of a word-paired association task (sleep first, SF), they performed significantly better 12 hr after encoding compared with participants who remained awake (wake first, WF). Similar results were found by Carollo et al. (2022) using a recognition task with neutral and emotional pictures as stimuli. This indicates that memory consolidation is more effective following a period of sleep compared with wakefulness, suggesting the shielding effect of sleep from interference. However, after 24 hr from the encoding, when all participants experienced a period of both sleep and wakefulness, memory performance in the two conditions was similar, failing to demonstrate a stabilizing effect of sleep (i.e. the strengthening of newly encoded memories against later interference).

To further understand the role of sleep and its time-dependent effect on the consolidation of declarative information, in this study, we examined the contribution of immediate or delayed sleep (and wakefulness) on factual memory consolidation throughout 24 hr. We employed a multi-sensory "flashcard-like" memory task (audio + visual information) that involved an encoding phase and three recall tests: immediately after the encoding (T0); 12 hr later (T1); and 24 hr later (T2). We employed a within-subject protocol with two experimental conditions where participants slept immediately after the encoding (SF) or spent 12 hr awake after the encoding (WF). We hypothesied that: (i) memory retention at T1 would be better in the SF condition; (ii) the better memory retention in SF would persist at T2 even after a period of wakefulness, due to the active effect of sleep, which should protect information from future interferences that could occur in wakefulness; (iii) memory retention after the night of sleep (T1 for SF and T2 for WF) would be better in SF, due to the shorter time delay between learning and sleep.

2 | MATERIALS AND METHODS

2.1 | Participants

Fifty-four young adults between the ages of 18 and 34 years participated in the study (M = 24.37 years, SD = 4.18; 31 F). They completed an online questionnaire on Google Forms aimed at gathering general information, including their sleeping habits and possible psychological symptoms that could affect both their sleeping patterns and their mental abilities, namely anxiety and depression. Additionally, they were asked to avoid naps during the three experimental days to exclude possible interfering effects of diurnal sleep on memory performance. Besides, they were told to avoid substance use and excessive alcohol drinking to control for possible interferences with cognitive functioning.

Given the within-subjects nature of the study, all participants completed both experimental conditions, that is, SF and WF, following a counterbalanced order. The two conditions (each lasting for 2 days) could be separated by an interval of a maximum of 3 days so that the experiment could be completed within 1 week.

Six participants were excluded from the final analysis due to low performance levels (performance at T0 lower than 25%, close to the first quartile of the data distribution: 22.5%). Therefore, the final sample for behavioural analyses included 48 participants (M = 24.5 years, SD = 4.23; 27 F). Three additional participants were excluded from the physiological analyses due to sleep recording issues. Consequently, the physiological analyses were performed on 45 participants.

2.2 | Procedure

After signing the informed consent, participants received a link to complete the first general assessment using Google Forms. Six questionnaires were included to investigate the participants' characteristics, listed hereafter. The Epworth Sleepiness Scale (ESS; Vignatelli et al., 2003) was included to assess the participant's general level of daytime sleepiness. The Pittsburgh Sleep Quality Index (PSQI; Curcio et al., 2013) was used to evaluate the participant's sleep quality and possible sleep-related disturbances over the previous month. The Beck Anxiety Inventory (BAI; Sica & Ghisi, 2007) and the Beck Depression Inventory-II (BDI-II; Sica & Ghisi, 2007) were administered to reveal possible psychiatric symptoms, respectively anxiety and depression. The Insomnia Severity Index (ISI; Castronovo et al., 2016) was employed to account for possible insomnia episodes over a 2-week time window. Lastly, the reduced version of the Morningness–Eveningness Questionnaire (MEQ-r; Natale et al., 2006) was administered to evaluate individual differences in chronobiology, that is, the time of the day in which the participant's alertness level reaches its peak.

The entire experiment was carried out remotely. Zoom sessions were used for administering the task, and Microsoft PowerPoint was used for presenting the stimuli.

The procedure is depicted in Figure 1. Depending on the condition, each participant could choose a time between 20:00 hours and 22:00 hours (SF condition), or 08:00 hours and 10:00 hours (WF condition) to complete the encoding phase. Once the encoding phase was concluded, an immediate memory test (T0) was administered via a Google Forms link. Two additional evaluations followed. The second one (T1) was administered after 12 hr of either

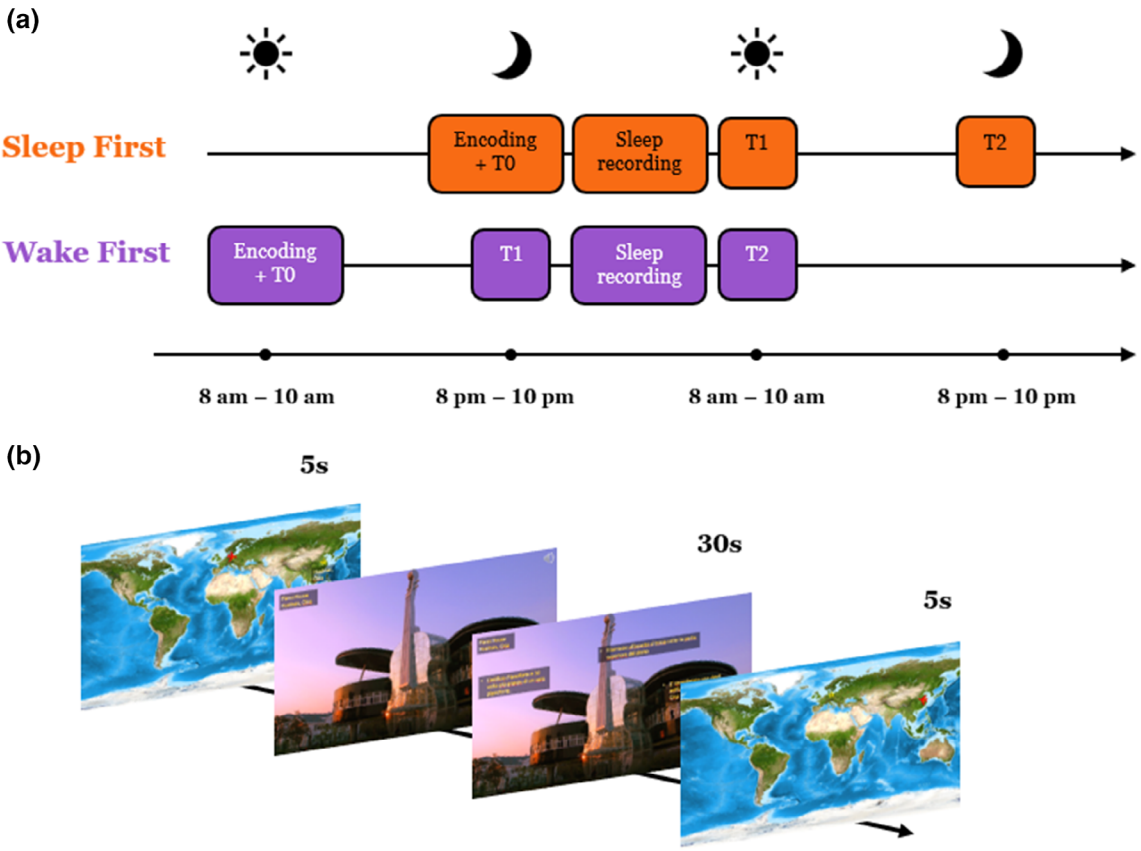

FIGURE 1 (a) The study protocol. Participants in the sleep first (SF) condition performed the encoding between 20:00 hours and 22:00 hours, followed by an immediate test (T0) and the sleep recording. The second evaluation was administered 12 hr later (T1), and the third one followed 24 hr after the encoding (T2). Participants in the wake first (WF) condition performed the encoding between 08:00 hours and 10:00 hours, followed by an immediate test (T0). After 12 hr, the second evaluation was administered (T1), followed by the sleep recording. The third evaluation was administered 24 hr after the encoding (T2). The entire experiment lasted for 4 days and had to be completed within 7 days. (b) Schematic excerpt of the encoding phase of the task. The world map used to mark the transitions between two locations, together with an example of location and relative facts. The transitions lasted about 5 s, while the pre-recorded narration lasted ~30 s.

wakefulness or sleep (WF and SF condition, respectively), while the third one was administered 24 hr after the encoding phase (T2). Therefore, in the WF condition participants spent these 12 hr sleeping, while in the SF condition they spent these 12 hr awake. As depicted in Figure 1(a), participants slept at different times during the task. The only difference was the time of the day in which the encoding phase took place, namely in the morning (WF condition) or in the evening (SF condition). Before each session, participants rated their level of fatigue and sleepiness using the Samn–Perelli Scale (SAMN; Samn & Perelli, 1982) and the Stanford Sleepiness Scale (SSS; Hoddes et al., 1973), respectively.

During both nights, participants slept at their homes, and their sleep was recorded using the Dreem Headband 2 (DH2; Dreem SAS, Paris, France), a wearable device that has been validated as a portable alternative to polysomnography (PSG; Arnal et al., 2020). The headband includes five dry electrodes (O1, O2, FpZ, F7, F8) yielding seven bipolar electroencephalographic (EEG) derivations (FpZ-O1, FpZ-O2, FpZ-F7, F8-F7, F7-O1, F8-O2, FpZ-F8). Data recorded with the DH2 were available from a dedicated cloud service, where a validated automatic sleep scoring provides classical sleep metrics (e.g. sleep duration, time spent in different sleep stages). Participants were told to spend their evenings as usual and to turn the DH on and wear it right before sleeping. Participants were instructed about how to correctly wear and use the device when they received it, and further doubts were addressed during the first Zoom meeting, either before or right after the experimental session. After explaining how to start and end the PSG recording using the Dreem application, each participant also received an instruction sheet where the main steps were summarized. Additional support was provided via text message or Zoom call if needed.

2.3 | Stimuli and task

In this experiment, we used an adapted version of the Fact-Learning Task (FLT) that we previously developed and used to study the relationship between sleep and memory consolidation (Cellini et al., 2019). The task requires participants to learn and memorize facts associated with relatively unknown locations around the world. For this purpose, two sets of 20 locations each were used, one for

every condition, and randomly assigned to each participant following a counterbalanced order. Three versions of each set were created, in which stimuli were combined randomly. Microsoft PowerPoint has been used to create the FLT.

Participants were told that they would virtually navigate across 20 locations in the world. They would listen to an intriguing story of the locations, each containing three unique facts that they had to remember as they would be tested on the facts later. In detail, at the beginning of the test, a world map appeared with the icon of an airplane located in Washington DC, which started to move to the next location on a world map in order to direct participants' attention to its location (Figure 1b). This transition lasted 5 s. After the first location, the airplane icon always started from the previous location they had just learned about. Once the airplane reached its destination, a star appeared as a marker of the location as its sequential number (1–20) along with the name of the city or region and the country. Next, on the screen appeared a photo of the location, and a short pre-recorded audio (about 30 s) narrated a story about the location, which included the three relevant facts. All narration was recorded by the same female speaker. After the audio, the three facts to be remembered were presented one at a time on the screen, overlaid onto the photo. Each fact appeared for 4 s. Facts appearing earlier remained on the screen as newer ones appeared. After 10 locations, participants had a 30-s break. Overall, the encoding phase lasted about 20 min.

The testing phase of the task consisted of different questions, that is, one for each location, presented on Google Forms. Overall, participants were asked either to indicate a date or number (e.g. "*Indicate the average temperature in winter*") or to complete the sentence provided (e.g. "*The building is considered to be one of the ___ in China*"). Participants could not move to the following question before an answer was provided, nor could they move back to the previous one and change their response. Besides, they were encouraged to avoid answers like "*I don't know*" or "*I don't remember*". No feedback about their answer or the general accuracy was given to the participants during the tests. Also, we asked participants to not use any aids to remember the facts (e.g. writing facts down) and we controlled this behaviour through the Zoom video call.

2.4 | Statistical analyses

Both sample demographics and characteristics have been reported with mean and SD.

Concerning the behavioural data, responses to the three tests were scored by the experimenters with 0 when participants answered incorrectly or 1 when they answered correctly, and the performance for each test was converted into a percentage of correct responses. To assess the degree of forgetting over time, we also computed performance variations as the percentage change from one session to the previous one (e.g. ΔT1T0 is computed as $\frac{T1}{T0} \times 100$).

To assess the performance as a function of the Condition (SF, WF) and Session (T0, T1, T2), a two-way repeated-measures ANOVA has been performed on the percentage of correct responses, with Condition and Session as within-subject factors, and generalized eta squared (η_G^2) as a measure of effect size. Post-hoc *t*-tests with Holm's correction were computed to further investigate the results obtained with ANOVA. *T*-tests have been used to compare performance changes over time (e.g. ΔT1T0) between the two conditions. Cohen's *d* was used as the effect size measure for all the *t*-tests performed.

The sleep parameters as extracted from the automatic scoring have been compared between the two experimental nights of the two conditions using *t*-tests. Lastly, we explored potential associations between sleep parameters and performance variation, and between participants' chronotype and performance at the encoding using Pearson's correlation.

All analyses have been conducted using R (R Core Team, 2022), with a significance level set to 5%.

TABLE 1 Means ± SDs of demographic and psychological variables.

	Mean ± SD
Age (years)	24.5 ± 4.23
Gender (M/F)	20/27[a]
ESS	7.83 ± 3.22
PSQI	5.54 ± 2.34
BAI	5.67 ± 5.81
BDI-II	9.10 ± 7.45
ISI	5.77 ± 4.06
MEQ-r	13.06 ± 4.01

Abbreviations: BAI, Beck Anxiety Inventory; BDI-II, Beck Depression Inventory-II; ESS, Epworth Sleepiness Scale; ISI, Insomnia Severity Index; MEQ-r, Morningness–Eveningness Questionnaire, reduced version; PSQI, Pittsburgh Sleep Quality Index.
[a]One participant did not indicate the gender.

3 | RESULTS

3.1 | Demographic results

Most of the participants did not report insomnia symptoms (ISI < 8). However, 13 participants (15%) reported subthreshold insomnia (8 < ISI < 14), and only one indicated moderate insomnia symptoms (15 < ISI < 21). Furthermore, nine participants (19%) reported excessive sleepiness (ESS > 12). According to MEQ-r scores, participants are on average intermediate types (11 < MEQ-r < 18), while 37.5% of them have an eveningness type and 10.5% have a morningness type. With regard to the psychological condition, both the average level of anxiety and depression are minimal (BAI < 8 and BDI-II < 14, respectively). However, four participants (8%) reported moderate anxiety (16 < BAI < 25), while seven (14%) were assessed as mildly moderately depressed (14 < BDI-II < 19), and four reported moderate–severe depression (20 < BDI-II < 28; Table 1).

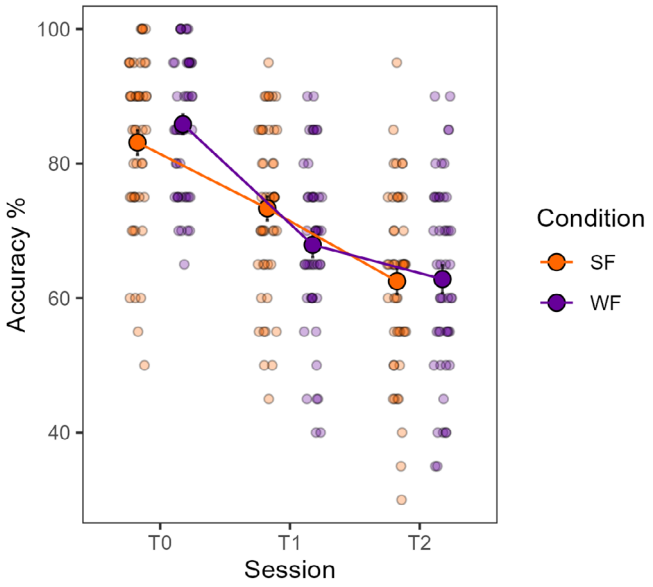

FIGURE 2 Accuracy (%) in the two conditions across the three sessions. SF, sleep first. WF, wake first. Each dot represents the performance of a single participant in that specific condition and session. Bigger dots represent the mean of the performance in that specific condition and session. Error bars represent the standard error of the mean.

TABLE 2 Performance variation in terms of mean and SD.

	ΔT1T0	ΔT2T1	ΔT2T0
SF condition	89.34 ± 15.80	85.59 ± 13.64	75.65 ± 14.29
WF condition	79.55 ± 14.44	93.83 ± 20.45	73.25 ± 15.11

Abbreviations: SF, sleep first; ΔT1T0: change in accuracy from T0 to T1; ΔT2T1, change in accuracy from T1 to T2; ΔT2T0, change in accuracy from T0 to T2; WF, wake first.

3.2 | Behavioural results

The two-way repeated-measures ANOVA performed to analyse the accuracy in the two conditions (SF, WF) across the three sessions (T0, T1, T2) showed a significant main effect of Session ($F_{2,94} = 129.29$, $p < 0.001$, $\eta_G^2 = 0.34$), with a general decrease of accuracy from T0 (M = 84.47, SD = 11.55) to T2 (M = 62.65, SD = 13.84). Although the main effect of Condition was not statistically significant ($F_{1,47} = 0.25$, $p = 0.62$, $\eta_G^2 = 0.001$) and the general accuracy of the SF condition (M = 72.98, SD = 15.32) did not differ from the accuracy of the WF condition (M = 72.18, SD = 15.95), a significant interaction effect of Condition × Session was observed ($F_{2,94} = 6.80$, $p < 0.001$, $\eta_G^2 = 0.018$; Figure 2). To further investigate the interaction effect, a post-hoc analysis has been conducted, using Holm's correction for multiple comparisons. At T0 and T2 the performance was similar in both conditions (T0: $t_{47} = -1.36$, $p = 0.36$, $d = -0.23$; T2: $t_{47} = -0.15$, $p = 0.88$, $d = -0.02$), with a decline from T0 to T2 for both the SF ($t_{47} = 11.64$, $p < 0.001$, $d = 1.58$) and WF conditions ($t_{47} = 12.12$, $p < 0.001$, $d = 1.84$).

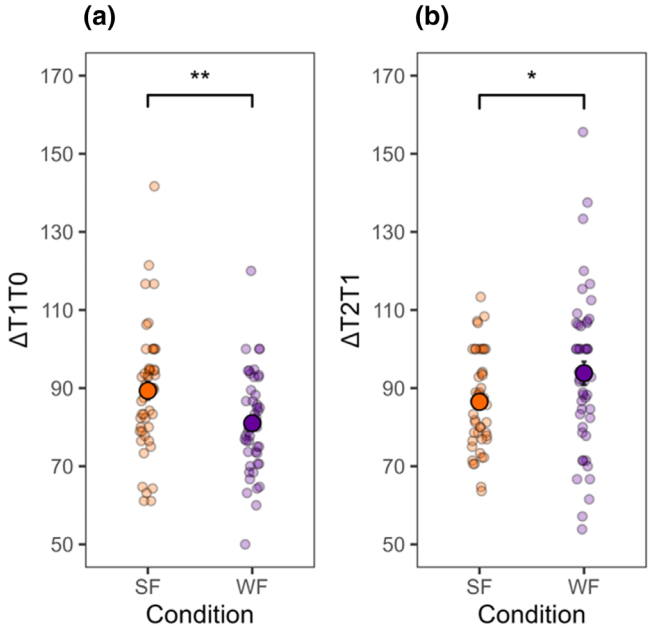

FIGURE 3 Performance level variation depending on the session. (a) Change in accuracy from T0 to T1. (b) Change in accuracy from T1 to T2. SF, sleep first; WF, wake first. Each dot represents the performance of a single participant in that specific condition and session. Bigger dots represent the mean of the performance in that specific condition and session. Error bars represent standard error of the mean. *$p \leq 0.05$; **$p \leq 0.005$.

As for the performance variation over time (referred to as Δ; Table 2), compared between the two conditions, we found a smaller memory decline in the SF than WF condition from T0 to T1 (ΔT1T0; $t_{47} = 3.23$, $p = 0.001$, $d = 0.65$; Figure 3). It is worth remembering that, between T0 and T1, participants in the SF condition had the opportunity to sleep, while participants in the WF condition were awake. This result confirmed that memory performance is better after a night of sleep than after a day of wakefulness. However, the opposite result is found when comparing ΔT2T1 between the two conditions. Here, a smaller decline of the performance in WF than in SF can be observed between T1 and T2, separated by nocturnal sleep in WF and by wakefulness in SF (ΔT2T1; $t_{47} = -2.55$, $p = 0.007$, $d = -0.47$; Figure 3). This finding shows a mere passive effect of sleep on memory performance. However, when comparing performance in ΔT1T0 for WF and ΔT2T1 for SF, both separated by wakefulness, we observed less forgetting in the SF condition ($t_{47} = 2.14$, $p = 0.036$, $d = 0.43$; Figure S1, see supplementary material), which might be interpreted as a protection of sleep from interference in the subsequent period of wakefulness. However, once participants in both conditions slept (i.e. ΔT1T0 in SF and ΔT2T1 in WF), no significant differences were noted in terms of performance variation ($t_{47} = -1.25$, $p = 0.216$, $d = -0.24$; Figure S2). Therefore, it seems that whether sleep occurs immediately after encoding or after 12 hr, the effect is similar.

TABLE 3 Sleep variables in terms of mean and SD.

	Night between T0 and T1 (SF)	Night between T1 and T2 (WF)	t_{44}	p	Cohen's d
TIB (min)	433.45 ± 64.64	450.77 ± 61.01	−1.91	0.061	−0.27
TST (min)	404.62 ± 62.01	421.31 ± 61.33	−1.84	0.071	−0.27
SOL (min)	11.61 ± 10.53	11.16 ± 8.02	0.23	0.813	0.04
WASO (min)	14.97 ± 13.08	15.93 ± 9.03	−0.47	0.638	−0.08
SE (%)	93.32 ± 3.26	93.39 ± 3.09	−0.12	0.898	−0.01
N1 (min)	22.72 ± 13.63	23.46 ± 11.32	−0.45	0.650	−0.05
N1 (%)	5.61 ± 3.18	5.61 ± 2.62	−0.006	0.995	−0.0007
N2 (min)	196.82 ± 46.78	199.35 ± 45.83	−0.31	0.751	−0.05
N2 (%)	48.46 ± 7.50	47.15 ± 7.14	0.96	0.341	0.17
N3 (min)	87.25 ± 31.34	90.42 ± 26.59	−0.72	0.472	−0.10
N3 (%)	21.84 ± 7.91	21.84 ± 6.70	−0.0009	0.99	−0.0001
REM (min)	98.21 ± 30.77	108.5 ± 34.71	−2.31	0.025	−0.31
REM (%)	24.17 ± 6.15	25.48 ± 6.07	−1.24	0.220	−0.21

Abbreviations: REM, rapid eye movement; SE, sleep efficiency; SF, sleep first; SOL, sleep-onset latency; TIB, time in bed; TST, total sleep time; WASO, wake after sleep onset; WF, wake first.

3.3 | Sleep parameters

Sleep architecture was similar in the two conditions, except for the amount of time spent in rapid eye movement (REM) sleep (Table 3). Specifically, the WF condition spent significantly more time in REM sleep ($p = 0.025$) than the SF condition.

Exploring the associations between sleep parameters, as N2%, N3%, non-rapid eye movement (NREM)%, REM%, sleep efficiency (SE)% as well as total sleep time (TST), and performance variations over time, as ΔT1T0 for the SF and ΔT2T1 for the WF condition, no correlation was found (all $p > 0.05$).

3.4 | Exploratory correlations

To control for potential influences of participants' chronotype on encoding occurring in the morning (WF) or in the evening (SF), correlations were examined between chronotype and performance at T0. These analyses were conducted separately for both the WF and SF conditions. The correlations did not yield significant results for either the morning (WF) or evening (SF) encoding conditions (all $p > 0.77$), indicating that the circadian preference did not exert an influence on participants' encoding in either experimental condition.

We also explored whether fatigue (SAMN) and sleepiness (SSS) levels could impact participants' performance, but linear correlations showed no significant results (all $p \geq 0.065$).

Lastly, we explored the potential associations between the general sleepiness level (ESS), depression, and anxiety levels (BDI-II and BAI, respectively), but again no significant association emerged (all $p \geq 0.25$).

4 | DISCUSSION

The present study aimed to investigate the role of sleep and its time-dependent effect on the consolidation of factual information. Specifically, we aimed to investigate whether sleeping shortly after the encoding of declarative information would benefit memory retention compared to sleeping hours later. To this end, we designed a within-subject study with two experimental conditions, where participants slept immediately after (SF) or 12 hr later than (WF) the encoding of factual information taken from an ecological memory task.

As expected, we observed a general memory decline across the testing sessions (i.e. T0, T1 and T2) in both experimental conditions, indicating a classical memory forgetting as a function of the time passed from the encoding. This result is in line with the forgetting curve hypothesis, that is, the non-linear function that relates the observed probability of memory retention to the delay between the encoding and recall phases (Averell & Heathcote, 2011), first investigated by Ebbinghaus (1885). However, the magnitude of the decline across time was different between conditions. Specifically, without a significant effect of the circadian preference on the encoding, participants forgot less after a night of sleep (between T0 and T1 for SF, and between T1 and T2 for WF) compared with a period of wakefulness, highlighting a classical *sleep effect*, irrespective of when sleep occurred (shortly or hours after the encoding).

Therefore, we confirmed only the first of our initial hypotheses, that is, that memory retention at T1 would be better in the SF condition, while we failed to prove our last hypothesis, that is, that memory retention after the night of sleep (T1 for SF and T2 for WF) would be better in SF, due to the shorter time delay between learning and sleep. Instead, we partially confirmed our second hypothesis, that is, that the better memory retention in SF would persist at T2 even after a period

of wakefulness, due to the active effect of sleep. On the one hand, we observed a lower memory decline during wakefulness in SF, when the 12-hr wake period occurred after sleeping, compared with the wakefulness retention period in WF when sleep occurred after at least 12 hr of continuous wakefulness. This effect was small to medium (Cohen's $d = 0.43$), although we should acknowledge that the four *t*-tests conducted on differential scores were not corrected for multiple comparisons. Using a Holm correction, the comparison between ΔT1T0 for WF and ΔT2T1 for SF, both separated by wakefulness, would become non-significant ($t_{47} = 2.14$, $p = 0.073$, $d = 0.46$). Therefore, although we may interpret this result as a protection of sleep from interference occurring in the subsequent period of wakefulness, we should take this finding with caution. On the other hand, the change from T0 to T2 was similar in the two conditions, indicating that overall sleeping shortly and several hours after the encoding did not markedly affect memory retention 24 hr later. It is also possible that our participants reached a floor effect at T2, limiting the possibility of observing large differences between conditions, although performance was on average higher than 60%.

Although some studies have suggested that the timing of sleep after the encoding is an important factor in memory retention (Ellenbogen, Payne, & Stickgold, 2006), other studies have mainly shown a benefit of sleep on declarative memories even after a long delay between initial encoding and sleep (for review, see Mason et al., 2021). Indeed, it is parsimonious to expect that information acquired early in the day may have a similar probability of being reactivated during sleep as the more recent ones. Also, other factors may affect the likelihood and strength of the consolidation process of an information during sleep, such as the emotionality, salience or the future relevance of that information, although to a limited extend (for a critical review on these factors, see Davidson et al., 2021). Therefore, is likely that the retention of information over time depends on the combination of several factors, and not only the timing of sleep.

How to interpret our results from a theoretical point of view? Although this beneficial effect of sleep against memory detriment has been widely reported (Feld & Born, 2017), with the first experiments dating back to the early 1920s (Jenkins & Dallenbach, 1924), the underlying mechanisms are still under debate. Several theories have been proposed to explain this effect on a continuum between two opposite hypotheses (Ellenbogen, Payne, & Stickgold, 2006). On the one side, we can find the original hypothesis by Jenkins and Dallenbach (1924) conceiving the sleep's passive role in memory, that is, sleep is limited to protecting the to-be-remembered material from interference during offline periods (Ellenbogen, Payne, & Stickgold, 2006). On the other side, we find hypotheses related to an active role of sleep on memory consolidation, proposing that specific processing occurring during sleep would promote the reactivation, strengthening and reorganization of memory traces (Diekelmann & Born, 2010; Feld & Born, 2017; Rasch & Born, 2013). Although experimental evidence might apparently leave no doubt about the active role of sleep in strengthening memory traces and rendering them less vulnerable to forgetting (Ellenbogen, Payne, & Stickgold, 2006; Feld & Born, 2017), some authors strongly advise considering these results on memory stabilization gingerly, especially due to replicability issues with results (Cordi & Rasch, 2021). In terms of memory performance, the active role of sleep would result in an increased resistance to interference of the consolidated information over time (Bailes et al., 2020), which would be translated into a reduced detriment over time.

At first glance, the hypothesis of a passive role of sleep seems to better account for the results obtained in this study. That is, both the smaller effect on forgetting detected for the SF condition – and not for the WF – at T1 (i.e. after a period of sleep), and the similar result obtained for the WF condition – and not for the SF – at T2 (i.e. after a period of sleep) are consistent with the protective function exerted by sleep.

Therefore, the permissive consolidation hypothesis might be a bridge between the passive and active view of sleep on memory (Ellenbogen, Payne, & Stickgold, 2006). This theory proposes that sleep might indirectly benefit memory consolidation, enabling consolidation-related processes to be optimized by reduced interferences. Conversely, wakefulness would both weaken recently encoded memories and hamper their consolidation due to excessive interference (Ellenbogen, Payne, & Stickgold, 2006). Compared with the passive theory, this hypothesis conceives sleep as a relevant variable that mediates consolidation. A similar hypothesis that can account for the current result is the opportunistic consolidation hypothesis (Mednick et al., 2011), which proposes that memory consolidation occurs when the brain is not occupied with the encoding of new information.

Recently, Zhang et al. (2022) proposed that sleep might have two distinct effects on memory depending on when it occurs with respect to wakefulness. A stabilizing effect – that is, the strengthening of newly encoded memories against later interference – is detected if sleep precedes wakefulness, while a rescuing effect – that is, the recovery of previously encoded memories after the waking period – is seen if sleep follows the wake period. Our data, however, do not support the stabilization hypothesis, meaning that sleep occurring before a period of wakefulness does not shield memories from future interference.

The findings of the present study should be interpreted only considering a 24-hr retention interval, and our study cannot provide information about how the stability of the memory traces develops further across time, that is, across days and weeks. Indeed, we cannot rule out that potential differences between conditions (SF versus WF) may become evident only after longer time intervals due to the nature of consolidation itself, which is likely to be a multi-night process where the repeated reactivation of the recently encoded material occurs for several sleeping periods (Born & Wilhelm, 2012, Fiebig & Lansner, 2014, Klinzing, Niethard & Born 2019). This issue may be addressed in future studies either by including additional nights in the experimental protocol or by testing participants again after a relatively long delay.

It should be noted that in the present study, we did not investigate sleep-mediated resistance to interference using a specific interference task (Ellenbogen, Payne, & Stickgold, 2006). Indeed, here we considered all the daytime experiences that occur between two sleep

episodes as a source of interference. This type of unspecific interference has been included in other study protocols (Zhang et al., 2022) and might further reinforce the ecological nature of the present study. In other words, we investigated the effects that sleep has on the stability of memory traces, mediated by a type of interference that usually characterizes everyday life. However, we acknowledge that this type of interference cannot be controlled in terms of quantity (e.g. how many interferences), timing (e.g. when, across the 12-hr, these interferences occurred), and quality (e.g. what type of interferences). Future research may try to combine ecological approaches to sleep and memory with more controlled interference situations.

The present results should also be interpreted in light of other limitations. First of all, we used a wearable EEG system to collect sleep information. Although the system has been previously validated against PSG (Arnal et al., 2020), it does not allow references to reliably investigate sleep microstructure, which would have been useful to try to draw more robust conclusions about the influence of sleep on memory performance. Nevertheless, the wearable PSG helped us to make the study more ecological, as participants were able to sleep in their usual environment without the discomfort of the unfamiliar laboratory setting and the wires.

However, while testing participants outside the lab makes the study more ecological, the home setting might potentially result in reduced levels of motivation, lower concentration levels, and even issues related to the correct use of the PSG device.

Additionally, although we controlled for potential confounding factors such as circadian preferences and sleepiness and fatigue level, we cannot completely rule out the role of the time of the day on memory performance.

Another limitation is related to our protocol, as some participants took part in both conditions on the same day (e.g. T2 for WF in the morning and T0 for SF in the evening of the same day). The influence of the stimuli presented in the first condition over the to-be-retained material of the second has not been assessed and might have been a source of interference affecting memory performance. Taking both the interference level and the type (i.e. interference of the first over the second condition, or unspecific interference due to the daytime experiences) into account might have provided a more accurate memory evaluation.

5 | CONCLUSION

Despite these limitations, this research work provided additional support for the study of sleep's influence on memory. The large sample size and the within-subjects design, together with the ecological validity of the protocol, both in terms of memory task and in terms of PSG recording, are two advantages that characterize this research.

Although the literature seems to agree on the amount of influence that sleep has in the memory field, Cordi and Rasch (2021) unveiled a set of replication failures that induce a reconsideration of the results so far averred as certain. As discussed in their paper, recent meta-analyses demonstrated that this effect is smaller, task-specific and less long-lasting than previously assumed. This noteworthy conclusion, rather than dismantling previous findings, sheds light on the need for more robust statistical analyses, revising sample size requirements, and increasing attention to results replicability.

All in all, here we showed that sleep provides a small yet beneficial effect on memory retention, regardless of the delay from the encoding.

AUTHOR CONTRIBUTIONS

Aurora Gasparello: Data curation; formal analysis; investigation; software; visualization; writing – original draft; writing – review and editing. **Angie Baldassarri:** Writing – original draft; writing – review and editing; visualization; software; formal analysis; data curation. **Giorgia Degasperi:** Writing – review and editing. **Nicola Cellini:** Supervision; writing – review and editing; writing – original draft; methodology; conceptualization; project administration; resources; validation; data curation.

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CONFLICT OF INTEREST STATEMENT

This is not an industry-supported study. None of the authors has potential conflicts of interest to be disclosed. All authors have seen and approved the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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