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RESEARCH ARTICLE

False memories formation after a retention period spent asleep or awake in individuals with insomnia and good sleepers: a polysomnographic study

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Summary

False memories are a possible by-product of sleep-related memory consolidation processes when delayed testing is performed after a retention interval spent asleep. To date, the effect of a retention period spent asleep or awake on false memories formation has been addressed only in healthy subjects, while neglecting sleep-disordered populations. In the present study, we investigated this effect in 17 insomniacs and 15 good sleepers through the Deese–Roediger–McDermott paradigm. In both groups, the encoding phase was followed by an 8-h retention period spent in polysomnography monitored sleep (S-condition) or wake (WK-condition). We observed that, at free recall, insomniacs produced more false recalls in the WK-condition compared to the S-condition, whereas the good sleepers showed more false recalls in S-condition than in the WK-condition. Moreover, false recalls were higher in good sleepers than in insomniacs in the S-condition. Both groups produced more veridical recalls in the S-condition than in the WK-condition. For recognition, hits (correctly recognised words) were more numerous in the S-condition than in the WK-condition. Our results confirm previous data on sleep-related false memories production in good sleepers. Additionally, they show that, in insomniacs, false memories production is reduced after a sleep relative to remaining awake. These data suggest that false memories formation, reflecting adaptive memory reshaping processes going on during sleep, could occur at awakening as long as the sleep episode is efficient enough. A notable methodological issue was also identified, in that the Deese–Roediger–McDermott paradigm can be useful to investigate sleep-dependent memory processes for false memories only when a more cognitively demanding task is employed (i.e., free-recall instead of recognition tasks).

Serena Malloggi and Francesca Conte contributed equally to this work.

KEYWORDS
Deese–Roediger–McDermott paradigm, false memories, insomnia, polysomnography, sleep quality, sleep-related memory consolidation

1 | INTRODUCTION

Research over the past few decades has shown that sleep plays a relevant role in memory consolidation. Sleep after learning not only promotes a strengthening of newly acquired memory traces but also a qualitative change in memory representations thanks to an active system consolidation process (Rasch & Born, 2013). This process leads to the re-organisation of memory traces in several ways (Conte & Ficca, 2013; Landmann et al., 2014). For instance, a retention period spent in sleep rather than wake has been shown to facilitate the formation of associative schemata, the integration between new and old memory traces, and the extraction of hidden rules from sets of information. A possible by-product of this memory 'reshaping' (Conte & Ficca, 2013) is the emergence of new memory contents that have not been directly learned, that is, false memories (FM), considered as an expression of a process of 'gist' abstraction occurring during sleep (e.g., Diekelmann et al., 2010; Payne et al., 2009).

Several studies support the role of sleep in the development of FM. Specifically, several sleep studies have employed the Deese–Roediger–McDermott task (DRM; Deese, 1959; Roediger & McDermott, 1995), which is commonly used to study FM formation in laboratory settings. This paradigm comprises testing memory for lists of words that are semantically associated with an unstudied critical word (e.g., *door*, *glass*, *pane*, *shade*, *ledge*, *sill*, *house*, *open*, *curtain*, all related to *window*) and it reliably produces high rates of FM for unstudied critical words (Roediger & McDermott, 1995; Seamon et al., 2002). Payne et al. (2009) found that a retention period spent asleep increases FM production at the DRM task compared to an equivalent period of daytime wakefulness and these findings have been replicated by other authors (Diekelmann et al., 2010; Pardilla Delgado & Payne, 2017). Moreover, the sleep effect for FM has also been observed for emotionally negative words (McKeon et al., 2012) and appeared resistant across long delays (Pardilla Delgado & Payne, 2017).

To date, the effect of a retention period spent asleep on FM production has been investigated in healthy subjects, while neglecting sleep-impaired populations. To our knowledge, only two recent studies from our research group have addressed the topic of FM formation in individuals with insomnia symptoms. Here we found that, in immediate testing conditions, insomniacs were more susceptible to producing FM than good sleepers, probably due to a source monitoring failure occurring during the memory retrieval process (Malloggi, Conte, De Rosa, Cellini, et al., 2022; Malloggi, Conte, De Rosa, Righi, et al., 2022). These data were obtained by administering the classical DRM paradigm, that is, with the re-test procedure performed immediately after the learning phase, so that they shed light on the diurnal cognitive functioning (i.e., FM production) characterising individuals with different habitual sleep quality. However, in these above-mentioned studies, we did not address how sleep quality affects the sleep-dependent memory reshaping process, by comparing a sleep and a wake condition in individuals with insomnia. Therefore, it remains unexplored how sleeping *after* learning (i.e., a retention period spent asleep versus awake) affects FM formation in the same population. Previous literature (reviewed in Cellini, 2017) suggests that sleep-related memory consolidation is impaired in insomnia due to chronically altered sleep patterns. However, no data are available on the impact of this disorder on the qualitative reorganisation of memories occurring during sleep (Landmann et al., 2014). Indeed, it is reasonable to expect that this more complex memory process is also affected by the sleep alterations characterising insomnia, resulting in differences in FM production between individuals with insomnia and good sleepers.

In the present study, we addressed this hypothesis by investigating the effect of a retention period spent asleep or awake on FM production at the DRM task in individuals with insomnia compared to a control group of good sleepers.

2 | METHODS

2.1 | Participants

The recruitment procedure and the inclusion criteria for participants in the 'insomnia group' (IN group) and 'good sleep group' (GS group) were analogous to those adopted in our previous work (Malloggi, Conte, De Rosa, Righi, et al., 2022).

Based on scores at the screening instruments and the clinical interview, we recruited 34 university students and included them in either the IN group ($n = 17$) or the GS group ($n = 17$).

Two subjects were excluded from analyses, the first one due to technical problems occurring during data collection, whereas the second one did not comply with the request of keeping habitual sleep–wake schedules. Thus, the final sample included 17 subjects with insomnia (IN group; four males, 13 females; mean [SD] age 26.6 [6.71] years) and 15 good sleepers (GS group; five males, 10 females; mean [SD] age 27.3 [6.18] years).

The local Ethics Committee approved the research protocol, and all participants signed a consent form. There was no money or credit compensation for participating in the study.

2.2 | Procedure

In a mixed design, the IN and GS groups participants were administered two DRM task sessions (learning and test phase) in two conditions, in which the retention period (i.e., the interval between learning and testing, of ~8 h) was spent either asleep (S-condition) or awake

(WK-condition). Conditions were administered at a 1-week interval and their order was balanced between participants.

To minimise confounds linked to experimental settings and to preserve ecological validity, the procedure was conducted at the participants' homes; also, the times of DRM sessions (both learning and test phases) were not predetermined but defined according to each subject's sleep habits and chronotype. Therefore, during the 5 days preceding each condition, subjects were requested to complete a detailed sleep log to verify the regularity of their sleep–wake habits and to determine their average bedtime, rise time, and sleep duration.

Specifically, in the S-condition the DRM learning session was administered in the evening immediately before the subject's habitual bedtime, while the timing of the test session was determined as 30 min after the subject's rise time to allow for sleep inertia dissipation. Furthermore, in the S-condition, which followed an adaptation night, subjects underwent polysomnographic recording after the learning session (electrode montage was performed immediately before the session).

In the WK-condition, the timing of sessions was scheduled according to subjects' circadian preference, in order to perform the test session at the chronotype vigilance peak (3:00 p.m. for morning types, 5:00 p.m. for intermediates, 7:00 p.m. for evening types), with the duration of the retention period corresponding to that of the subject's habitual sleep time (determined through the sleep logs) plus 30 min (to equal those added in the S-condition for sleep inertia dissipation).

Both during the WK-condition retention period and in the S-condition, on the day of recording, subjects were requested to avoid falling asleep and engaging in cognitively demanding activities (e.g., reading, playing cards, etc.), as well as to keep daily activities as habitual as possible. To control for these factors, we asked subjects to complete a short ad hoc diary on daily activities.

To control for factors potentially affecting memory processes, before learning and test sessions participants completed a Karolinska Sleepiness Scale (KSS, Akerstedt & Gillberg, 1990) and rated their concentration and motivation levels on a 5-point Likert scale (from 1 – 'not at all' to 5 – 'very much').

2.3 | The DRM task and performance measures

The DRM paradigm (Deese, 1959; Roediger & McDermott, 1995) was adopted to investigate FM production. In the learning phase, participants were presented with eight word lists, each made up of 15 words all semantically related to a critical word, defined as the 'lure', that was not presented (e.g., 'bridge', 'fish', 'dam' with 'river' as the lure). As in Roediger and McDermott (1995), the words in each list were presented in order of associative strength with the lure (from strongest to weakest).

The lists were selected from those previously translated into Italian by Iacullo and Marucci (2016). Two different sets of eight lists were balanced and assigned to either the S-condition or WK-condition and employed in the corresponding condition.

As for task administration (learning phase), the experimenter read the lists aloud with an interval of 30 s between lists. Participants were instructed to memorise the words as accurately as possible and were informed that they would be tested on them later.

In the test phase (administered after the retention period), participants performed a free-recall task followed by a recognition task. At free recall, they were allotted 10 min to write on a blank piece of paper any words they remembered from the previously presented lists. As for recognition, they were presented a list of 56 words (printed on a paper), made up of the eight lures plus 24 studied words (taken from serial positions one, eight, and 10 of the eight studied lists, as in Roediger & McDermott, 1995) and 24 distractors (not presented during the learning phase and unrelated to the lures). The order of the 56 words was randomised between subjects. For each word, participants had to give an old/new judgement (i.e., they had to indicate with an 'x' whether or not the word had been presented during learning). In addition, as in Roediger and McDermott (1995), they had to provide, for words judged as 'old', a confidence rating for their answer on a 3-point scale (1 = 'I *remember* hearing the word'; 2 = 'I *know* the word was presented'; 3 = 'I had to guess').

To avoid possible biases linked to the DRM lists oral presentation, the experimenters were trained by a senior experimenter to correctly read the words, solve possible inflections, to respect the pauses within the lists, as well as to ensure a clear procedure's explanation to the participants.

Outcome measures were:

- for the free-recall task: the number of 'false recalls' (i.e., falsely recalled lures), number of 'veridical recalls' (i.e., words correctly recalled from the studied lists), and number of 'intrusions' (i.e., falsely recalled words not corresponding to either studied words or lures).
- for the recognition task: the number of 'false recognitions' (i.e., 'old' responses given to lures), number of 'hits' (i.e., 'old' responses given to studied words), number of 'false alarms' (i.e., 'old' responses given to unrelated distractors), and confidence ratings attributed to false recognitions, hits, and false alarms.

2.4 | Sleep recordings

Polysomnographic recordings were performed in the S-condition by recording six electroencephalographic (EEG channels: F3, F4, C3, C4, O1, O2, referenced against contralateral mastoids A1 and A2), two electro-oculographic (LOC-A2, ROC-A1), and a bipolar submental electromyogram channels, according to standard guidelines (Iber et al., 2007). Data were acquired by means of a BluNet multichannel recording system (Ne.Ro SRL, Florence, Italy) at a sample rate of 200 Hz. Sleep recordings were band-passed (0.3–35 Hz) and then visually scored according to standard criteria (Iber et al., 2007) by an expert technician. To verify scoring reliability, 10 randomly selected sleep recordings were scored by another technician. The inter-rater agreement was 92%.

TABLE 1 Age, gender distribution, circadian preference, and total scores in the Epworth Sleepiness Scale, Pittsburgh Sleep Quality Index, and Insomnia Severity Index in the two groups

Variable, mean (SEM)	IN group	GS group	Statistical test
Age, years	26.6 (6.71)	27.3 (6.18)	$t = 0.29$, $p = 0.769$
Gender, *n*	4 males, 13 females	5 males, 10 females	$\chi^2 = 0.38$, $p = 0.538$
MEQr score	14.4 (3.58); *intermediate chronotype*	13.6 (2.56); *intermediate chronotype*	$t = 1.12$, $p = 0.271$
ESS score	6.71 (3.60)	6.47 (3.58)	$t = -0.18$, $p = 0.852$
PSQI score	7.75 (2.44)	4.00 (1.04)	$t = -5.34$, $p < 0.001$
ISI score	10.88 (3.32)	3.20 (2.21)	$t = -7.52$, $p < 0.001$

Note: Student's *t* test is reported for between-groups comparisons for all variables except gender. Results of the chi-squared test are reported for differences in gender distribution.
Abbreviations: ESS, Epworth Sleepiness Scale; GS group, good sleep group; ISI, Insomnia Severity Index; IN group, insomnia group; MEQr, Morningness–Eveningness Questionnaire (reduced version); PSQI, Pittsburgh Sleep Quality Index.

2.5 | Statistical analysis

After testing for variables normality with the Shapiro–Wilk test, a mixed analysis of variance (ANOVA) was performed on DRM performance measures with 'Condition' (S-condition and WK-condition) as within factor and 'Group' (IN group and GS group) as the between factor measure. The partial eta squared (η_p^2) was reported as a measure of effect size. Least significant difference post hoc comparisons were performed where appropriate.

For post hoc comparisons, Cohen's *d* was reported and post hoc power analyses were conducted using the software G*Power.

Between-group differences in subjective sleepiness levels, concentration, and motivation in the two conditions, as well as in demographic variables, were analysed using the Student's *t* test for independent samples. For these analyses, the Cohen's *d* was reported as a measure of effect size.

The chi-square test was carried out for all binomial variables.

Analyses were performed using Jamovi (version 2.2.5; The Jamovi Project, 2021) and the statistical significance level was set at $p < 0.05$.

An a priori power analysis was conducted based on the ANOVA test (repeated measures and between factors) using the software G*Power. Considering an a priori effect size of 0.50, $\alpha = 0.05$, two groups of participants, and two measurements, the analysis testified a power of 0.96 with a sample size of 30 subjects.

3 | RESULTS

3.1 | Demographic characteristics, circadian preference, habitual daytime sleepiness, and sleep quality in the two groups

Table 1 displays the characteristics of the final sample included in the analyses. The two groups did not differ in age, gender, and habitual daytime sleepiness (measured through the Epworth Sleepiness Scale; Vignatelli et al., 2003). All participants presented an intermediate circadian preference, assessed through the reduced version of the Morningness–Eveningness Questionnaire (Natale et al., 2006). Instead, there were significant between-group differences in sleep quality, assessed by the Pittsburgh Sleep Quality Index (Curcio et al., 2013), and in the insomnia symptoms, as assessed by the Insomnia Severity Index (Castronovo et al., 2016) scores (Table 1).

We identified different insomnia subtypes within the IN group. Specifically, the group comprised the following individuals: four with 'sleep onset latency insomnia' (*SOL-insomnia*), four with *SOL-insomnia* and 'wake after sleep onset insomnia' (*WASO-insomnia*), three with both *SOL-insomnia* and 'early morning awakening insomnia' (*EMA-insomnia)*, four with both *WASO-insomnia* and *EMA-insomnia*; two with *SOL-insomnia*, *WASO-insomnia* and *EMA-insomnia*.

3.2 | The DRM performance

Table 2 displays descriptive statistics of DRM performance for both groups in the S-condition and WK-condition.

3.2.1 | Free-recall task

As for false recalls, the ANOVA revealed a significant Group × Condition interaction ($F[1,30] = 12.01$, $p = 0.002$, $\eta_p^2 = 0.29$), whereas the main effects of Group ($F[1,30] = 0.260$, $p = 0.614$, $\eta_p^2 = 0.009$) and Condition ($F[1,30] = 0.09$, $p = 0.755$, $\eta_p^2 = 0.003$) were not significant. Post hoc comparisons showed that the IN group produced more false recalls in the WK-condition compared to the S-condition ($t[30] = -2.30$, $p = 0.029$, Cohen's $d = -0.57$, power = 0.96), whereas the GS group participants showed an opposite pattern, with more false recalls in the S-condition than in the WK-condition ($t[30] = 2.59$, $p = 0.015$, Cohen's $d = 0.65$, power = 0.98; Figure 1). Moreover, the GS group falsely recalled more lures than the IN group in the S-condition ($t[30] = 2.47$, $p = 0.019$, Cohen's $d = 0.87$, power = 0.56; Figure 1).

A main effect of Condition emerged for veridical recalls ($F[1,30] = 0.39$, $p = 0.017$, $\eta_p^2 = 0.18$), with participants correctly recalling more studied words in the S-condition than in the WK-condition ($t[30] = 2.52$, $p = 0.019$, Cohen's $d = 0.45$, power = 0.82). Neither the

TABLE 2 Descriptive statistics of Deese–Roediger–McDermott task performance (free recall and recognition tasks) in the two groups in both conditions. Means and standard deviations are reported

	IN group		GS group	
Variable, mean (SD)	S-condition	WK-condition	S-condition	WK-condition
False recalls, *n*	1.53 (1.23)	2.53 (1.84)	2.87 (1.81)	1.67 (1.40)
Veridical recalls, *n*	22.12 (12.27)	18.41 (7.88)	25.07 (9.78)	20.20 (9.46)
Intrusions, *n*	2.35 (1.80)	2.41 (1.77)	3.00 (2.03)	2.60 (2.64)
False recognitions, *n*	5.62 (2.21)	5.12 (2.44)	6.33 (1.54)	5.66 (1.49)
Hits, *n*	17.00 (4.27)	15.75 (3.94)	18.40 (3.16)	16.66 (4.25)
False alarms, *n*	3.31 (2.84)	2.75 (2.95)	3.07 (3.13)	2.67 (2.44)

Abbreviations: GS group, good sleep group; IN group, insomnia group.

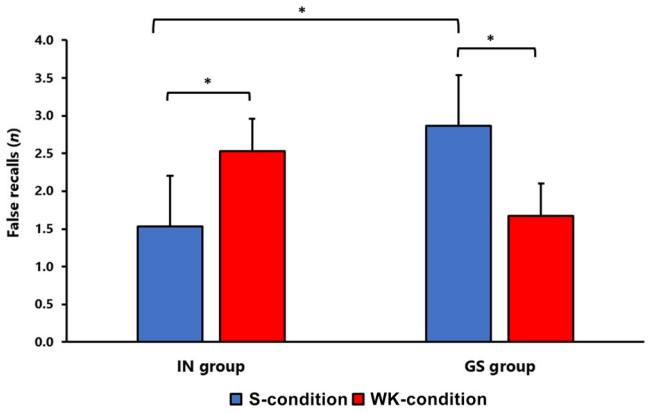

FIGURE 1 Number of false recalls in the sleep (S-condition) and wake (WK-condition) conditions in the two groups. *$p < 0.05$. Error bars represent standard errors. GS group, good sleep group; IN group, insomnia group

main effect of Group ($F[1,30] = 0.58$, $p = 0.452$, $\eta_p^2 = 0.019$) nor the Group × Condition interaction ($F[1,30] = 0.12$, $p = 0.735$, $\eta_p^2 = 0.004$) were significant.

As for intrusions, we observed no significant effect of Group ($F[1,30] = 0.52$, $p = 0.475$, $\eta_p^2 = 0.017$) or Condition ($F[1,30] = 0.14$, $p = 0.709$, $\eta_p^2 = 0.005$), nor any Group × Condition interaction ($F[1,30] = 0.84$, $p = 0.617$, $\eta_p^2 = 0.008$).

3.2.2 | Recognition task

No significant effect of Group ($F[1,29] = 1.02$, $p = 0.320$, $\eta_p^2 = 0.084$), Condition ($F[1,29] = 0.27$, $p = 0.111$, $\eta_p^2 = 0.034$), nor any Group × Condition interaction ($F[1,29] = 0.05$, $p = 0.816$, $\eta_p^2 = 0.002$) emerged for false recognitions.

As for hits, there was a main effect of Condition ($F[1,29] = 4.27$, $p = 0.036$, $\eta_p^2 = 0.14$): participants correctly recognised more studied words in the S-condition than in the WK-condition ($t[29] = 2.20$, $p = 0.036$, Cohen's $d = 0.39$, power = 0.72]. Instead, we observed no main effect of Group ($F[1,29] = 0.87$, $p = 0.359$, $\eta_p^2 = 0.029$) and no Group × Condition interaction ($F[1,29] = 0.13$, $p = 0.724$, $\eta_p^2 = 0.004$).

The number of false alarms showed no significant main effect of Group ($F[1,29] = 0.03$, $p = 0.854$, $\eta_p^2 = 0.001$) or Condition ($F[1,30] = 0.85$, $p = 0.363$, $\eta_p^2 = 0.029$). The interaction Group × Condition was also not significant ($F[1,30] = 0.02$, $p = 0.877$, $\eta_p^2 = 0.001$).

Finally, the interaction Group × Condition was not significant for confidence rating attributed to false recognitions ($F[1,28] = 0.15$, $p = 0.269$, $\eta_p^2 = 0.043$), hits ($F[1,28] = 0.21$, $p = 0.647$, $\eta_p^2 = 0.007$) and false alarms ($F[1,28] = 0.05$, $p = 0.942$, $\eta_p^2 = 0.001$). No main effects of Group or Condition were observed for these variables either (all $p > 0.05$).

3.3 | Sleepiness, concentration, and motivation

In the S-condition, no between-groups differences emerged in participants' subjective sleepiness, concentration, and motivation levels neither at the learning phase nor at the test phase (all $p > 0.05$). In the WK-condition, the IN group reported greater sleepiness ($t[30] = 2.73$, $p = 0.010$, Cohen's $d = -0.966$) and motivation ($t[30] = -2.29$, $p = 0.023$, Cohen's $d = -0.848$) than the GS group at the learning phase, with no differences in concentration neither at the learning phase ($t[30] = -0.991$, $p = 0.329$, Cohen's $d = -0.551$) nor at the test phase ($t[30] = -0.715$, $p = 0.023$, Cohen's $d = -0.258$) (see Table 3 for descriptive statistics).

4 | DISCUSSION

In this study, we investigated the influence of a retention period spent asleep versus one spent awake on FM production in individuals with insomnia and good sleepers. Our working hypothesis that is, that the clinical sample would display fewer FM than controls, is based on the assumption that, at delayed recall, FM preferentially arise from an efficient memory consolidation process (including semantic association mechanisms resorting in FM production) that requires a continuous, stable and organised sleep episode.

TABLE 3 Subjective ratings of sleepiness, concentration, and motivation (means and standard deviations) collected at the beginning of the learning and test phases in both groups in the two conditions.

	S-condition		WK-condition	
Variable, mean (SD)	IN group	GS group	IN group	GS group
DRM learning phase				
KSS score	4.47 (1.97)	5.20 (1.97)	4.18 (1.47)	2.80 (1.37)
Concentration	3.24 (0.83)	3.20 (0.86)	2.88 (0.86)	2.60 (0.73)
Motivation	2.24 (0.83)	2.27 (1.03)	2.94 (1.14)	2.07 (0.88)
DRM test phase				
KSS score	4.65 (1.83)	4.33 (1.87)	3.35 (1.45)	3.07 (1.59)
Concentration	3.12 (1.05)	3.00 (0.85)	2.88 (0.93)	2.64 (0.93)
Motivation	2.59 (0.87)	2.27 (0.79)	2.76 (1.25)	2.14 (1.09)

Abbreviations: DRM, Deese–Roediger–McDermott task; GS group, good sleep group; IN group, insomnia group; KSS, Karolinska Sleepiness Scale.

In line with the hypothesis, a 'sleep effect' for false recalls (i.e., more numerous false recalls produced after sleep compared to wake) emerged only in the GS group. This finding confirms previous research on healthy samples (Diekelmann et al., 2010; Pardilla Delgado & Payne, 2017; Payne et al., 2009) and is consistent with theoretical accounts on sleep-related memory processing. In fact, it is believed that, relative to an equivalent retention period spent awake, a good sleep episode facilitates the consolidation of new memory traces and their integration into pre-existing long-term networks (Rasch & Born, 2013): this process would induce FM production by facilitating the extraction of the *gist* trace from the recently encoded information. In this perspective, FM formation may be considered as a sort of 'side-effect' of efficient sleep-related memory processes. These processes would be impaired in individuals with poor sleep, as indexed by the absence of a facilitating effect of sleep on false recall at the DRM task in our IN group.

In line with this idea is also the finding that, in the S-condition, GS group participants produced more false recalls than the IN group participants. Notably, this last result cannot be explained by a dissimilar degree of sleepiness between the IN and GS groups, as both groups showed comparable KSS scores before the learning and test sessions.

Interestingly, the IN group also showed a 'wake effect', that is, a significantly higher number of false recalls produced in the WK-condition compared to the S-condition. This finding may be explained by taking into account a different mechanism known to be involved in FM production. Indeed, a wide literature in the field of the psychology of memory describes FM as source-monitoring failures that can arise at retrieval as a consequence of impairments in prefrontal functioning (for a review see Schacter & Slotnick, 2004). In line with this hypothesis, we recently found that individuals with insomnia produced more false recalls than good sleepers in immediate DRM free-recall testing and that this result was likely due to impaired source monitoring ability (Malloggi, Conte, De Rosa, Cellini, et al., 2022; Malloggi, Conte, De Rosa, Righi, et al., 2022). In the present study, the WK-condition is not entirely comparable to the just-mentioned research, due to the different number of DRM word lists presented (eight instead of 16 or four) and the testing procedure involved (delayed retrieval instead of immediate retrieval). However, it is possible that, in the IN group, the susceptibility to FM production, coupled with possible interferences of external stimuli, could have influenced performance at delayed testing, promoting the recall of the DRM 'lure' words. In parallel, as previously mentioned, a poor efficient sleep-dependent memory reshaping process in the IN group could be the cause of the lower number of false recalls observed in the S-condition than in the WK-condition.

In fact, even assuming insomniacs as generally more susceptible than good sleepers to produce FM at the retrieval due to a source-monitoring deficit emerging during the diurnal period (as our previous works suggested), here we supposed that, after a sleep episode, the poor sleep may have hindered the consolidation of the gist memory trace over time. In this regard, the introduction of a baseline measure before sleep could be helpful to specifically address how poor sleep affects the gist memory traces compared to a wake period of comparable time, that is, whether it kept FM stable or diminished them from the originally encoded traces. Future studies are needed to address this topic.

Therefore, our results suggest that two different and not mutually exclusive mechanisms could influence FM production in relation to sleep (and its quality), in line also with Diekelmann et al. (2010): (i) the sleep-dependent memory reshaping (reduced in a poor sleep condition, as observed in the present study), (ii) an impaired source monitoring ability resulting from chronically disturbed sleep (making insomniacs at more risk of encountering FM than good sleepers during daytime, as observed by our previous studies).

An alternative or complementary explanation of the observed 'wake effect' may be found in the greater sleepiness reported in the WK-condition by the IN group relative to the GS group at the beginning of the learning phase. Sleepiness may have hindered the acquisition process resulting in increased FM at a later test. However, it must be underlined that the greater sleepiness was accompanied by higher motivation, a factor that is known to positively affect cognitive performance (Madan, 2017) and that could presumably have balanced the increased sleepiness levels.

The findings of our study shed some light on a methodological issue in the field of research about sleep and DRM research, that is the influence of the type of task (i.e., recall versus recognition) on FM and veridical memory retrieval. First, at variance with the free-recall task, we did not observe between-conditions nor between-groups differences in the number of false recognitions. This result is consistent with extant literature highlighting a more evident promoting effect of sleep on FM when adopting a free-recall rather than a recognition task (Newbury & Monaghan, 2019). Indeed, as in a previous study by Pardilla Delgado and Payne (2017), our participants performed the recognition task immediately after the free-recall task, therefore we cannot rule out an influence of the first task on the latter.

Concerning veridical memories, we found that sleep, regardless of its quality, promotes the consolidation of contextual, item-specific details of the experience to a greater extent than wake both in the free-recall and in the recognition tasks. Overall, these findings are in line with literature describing a beneficial effect of sleep, relative to wake, on consolidation of declarative memory traces (for a review see Diekelmann & Born, 2010). The lack of between-group differences in veridical memory performance could appear surprising in light of literature showing impairments of declarative memory consolidation in insomnia (for a review see Cellini, 2017). However, the specific features of the DRM task can explain this finding. In fact, the semantic association between the stimuli of each list reinforces memory traces and facilitates their subsequent retrieval (Aka et al., 2020; Silberman et al., 2005). This facilitation could have overcome, in the IN group, the effects of possible impairments of the consolidation process linked to their poor sleep quality. The specific nature of the task (i.e., the semantic association between words in each list) plausibly also explains the absence of between-groups and between-conditions differences in intrusions and false alarms (i.e., the false recall and recognition, respectively, of words that are unrelated to the studied words).

Our findings need to be considered in light of some limitations. First, we adopted the DRM paradigm that in sleep studies has some methodological issues to consider (Newbury & Monaghan, 2019). One of them is related to the DRM lists' testing procedures, as the sleep effect for FM seems to easily emerge with free-recall rather than recognition tasks (Newbury & Monaghan, 2019). Our findings are, in fact, in line with this assumption. Although this paradigm has been criticised for not replicating a real-life scenario, it is frequently used in laboratory settings and allows to clearly identify and control the three fundamental phases towards FM formation, namely the encoding, consolidation, and retrieval of the DRM word lists.

Another limitation of the present study concerns the order of the memory tasks that participants performed at retrieval. Here, the task's administration was not counterbalanced, as the free-recall test always preceded the recognition one, as in the study of Pardilla Delgado and Payne (2017). This procedure may have affected the performance on the recognition task in both groups. We argue that future studies should investigate whether poor sleep quality differently influences FM production when tested through the free-recall and recognition tasks separately. Moreover, other studies are needed to replicate our results by adopting different FM paradigms, such as the misinformation paradigm (Loftus et al., 1978), as well as to investigate the *reshaping* phenomenon in other relevant sleep disorders. Additionally, the IN group includes subjects with different subtypes of insomnia, making the sample heterogeneous. Future studies should select more homogeneous samples or explore possible differences in FM production in relation to insomnia subtypes.

In conclusion, our results support the role of sleep in FM formation and sustain the hypothesis that FM may be considered as a 'side-effect' of an efficient memory reorganisation process occurring during a continuous, stable, and well-organised sleep. Overall, although further studies are needed to verify that poor sleep quality negatively impacts the reshaping phenomenon, our findings encourage us to take into account the sleep quality variable when investigating the influence of sleep on FM production.

Our study also suggests that the DRM paradigm may be useful to investigate sleep-dependent memory processes for FM only when a more cognitively demanding task is employed (i.e., free-recall instead of recognition tasks). In particular, when a long sleep delay is considered, poor nocturnal sleep does not promote false-recalls production, probably due to an inefficient memory-reshaping process. On the contrary, after a long wake delay, chronic poor sleep quality increases the susceptibility to produce false recalls, probably because of a source-monitoring impairment coupled with possible interferences of external stimuli.

Finally, our results show that sleep, regardless of its quality, promotes the consolidation veridical memories both at the free-recall and recognition tasks of the DRM paradigm.

AUTHOR CONTRIBUTIONS

All authors contributed in a meaningful way to this manuscript. Conceptualisation: Serena Malloggi, Francesca Conte, Gianluca Ficca, and Fiorenza Giganti. Methodology: Serena Malloggi, Francesca Conte, Gianluca Ficca, Nicola Cellini, and Fiorenza Giganti. Formal analysis: Serena Malloggi, Oreste De Rosa, and Fiorenza Giganti. Investigation: Serena Malloggi, Oreste De Rosa, and Ilaria Di Iorio. Data curation: Serena Malloggi, Gioele Gavazzi, and Fiorenza Giganti. Writing – original draft preparation: Serena Malloggi and Fiorenza Giganti. Writing – review and editing: Serena Malloggi, Francesca Conte, Nicola Cellini, and Fiorenza Giganti. Supervision, Francesca Conte, Gianluca Ficca, and Fiorenza Giganti. Project administration: Gianluca Ficca and Fiorenza Giganti. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest, no personal financial support and involvement with an organization with financial interest in the subject matter of the paper.

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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