

## The effects of sleep restriction and sleep deprivation in producing false memories



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### ABSTRACT

False memory has been claimed to be the result of an associative process of generalisation, as well as to be representative of memory errors. These can occur at any stage of memory encoding, consolidation, or retrieval, albeit through varied mechanisms. The aim of this paper is to experimentally determine: (i) if cognitive dysfunction brought about by sleep loss at the time of stimulus encoding can influence false memory production; and (ii) whether this relationship holds across sensory modalities. Subjects undertook both the Deese-Roediger-McDermott (DRM) false memory task and a visual task designed to produce false memories. Performance was measured while subjects were well-rested (9h Time in Bed or TIB), and then again when subjects were either sleep restricted (4h TIB for 4 nights) or sleep deprived (30h total SD). Results indicate (1) that partial and total sleep loss produced equivalent effects in terms of false and veridical verbal memory, (2) that subjects performed worse after sleep loss (regardless of whether this was partial or total sleep loss) on cued recognition-based false and veridical verbal memory tasks, and that sleep loss interfered with subjects' ability to recall veridical, but not false memories under free recall conditions, and (3) that there were no effects of sleep loss on a visual false memory task. This is argued to represent the dysfunction and slow repair of an online verbal associative process in the brain following inadequate sleep.

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### 1. Introduction

Sleep is vital for optimal functioning during wakefulness, and sleep loss has wide ranging effects on overall neurocognitive performance (Ratcliff & Van Dongen, 2009). Numerous studies have shown that sleep loss has a deleterious impact on basic elements of cognitive functioning, such as attentional processing (Van Dongen, Maislin, Mullington, & Dinges, 2003), response inhibition (Drummond, Paulus, & Tapert, 2006) and working memory (Drummond, Anderson, Straus, Vogel, & Perez, 2012; Turner, Drummond, Salamat, & Brown, 2007); as well as elements of higher cognitive functioning, such as rule based learning (Whitney, Hinson, Jackson, & Van Dongen, 2014), memory encoding (Drummond et al., 2000; Mander, Santhanam, Saletin, & Walker, 2011; Saletin & Walker, 2012; Yoo, Hu, Gujar, Jolesz, &

Walker, 2007) and the ability to plan and implement intentions (Diekelmann, Wilhelm, Wagner, & Born, 2013a, 2013b). Sleep has also recently been suggested to play a role in associative memory formation (Lewis & Durrant, 2011; Payne, 2011; Stickgold & Walker, 2013); for instance, in the selective learning of relevant (as opposed to irrelevant) information (van Dongen, Thielen, Takashima, Barth, & Fernández, 2012; Wilhelm et al., 2011), rules governing sets of stimuli (Durrant, Taylor, Cairney, & Lewis, 2011) and the generalisation of specific learning for general application (Lau, Alger, & Fishbein, 2011). The impact of sleep loss on these latter functions is, however, relatively unknown.

It must also be acknowledged that the impacts of sleep on cognitive functioning are not always obvious (Killgore, 2010). For instance, studies have found differential effects of sleep loss on different components of both working memory (Drummond et al., 2012; Turner et al., 2007) and executive functioning (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010). This is likely due to the fact that the cognitive systems of the brain are comprised of interacting subcomponents, and rarely does a cognitive

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task rely on only a single brain region. Sleep loss may similarly influence memory in a non-uniform fashion. For instance, sleep loss reduces the amount of information remembered by individuals both by negatively impacting the capacity for encoding new memories (Mander et al., 2011; Payne & Kensinger, 2010; Tononi & Cirelli, 2014), as well as through the loss of sleep-based benefits in terms of memory consolidation (Diekelmann & Born, 2010a; Rasch & Born, 2013). This pattern is likely to hold for associative memory as well, given that associative linkages between individual memories have been found to occur both during wakeful encoding (Staresina & Davachi, 2008, 2009, 2010) and across a range of processes during sleep (Chatburn, Lushington, & Kohler, 2014; Ellenbogen, Hu, Payne, Titone, & Walker, 2007; Payne et al., 2009).

False memory; memory for events or items which were never actually experienced by the individual, serves as an example of the effects of sleep loss on complex associative memory processing. False memories can occur across all stages of memory processing, albeit from differing mechanisms and may, depending on the circumstances, represent both memory errors (Read, 1996; Reyna & Lloyd, 1997; Smith & Hunt, 1998) as well as the natural associative processes of human memory (Stickgold & Walker, 2013). That is, false memories can arise from: (1) spreading activation in neural networks and self-referential encoding; (2) competing imagery during encoding; (3) memory reactivation and generalisation during consolidation; or (4) monitoring errors during retrieval (Straube, 2012). Sleep and sleep loss have also been found to differentially impact false memory generation. Sleep (in comparison to wakefulness) has been found to reduce false memories when using recognition-based retrieval procedures (Fenn, Gallo, Margoliash, Roediger, & Nusbaum, 2009). However, sleep (relative to sleep deprivation) has also been found to simultaneously increase both correct recall and false memory using recognition procedures (Darsaud et al., 2011). Finally, sleep (relative to wakefulness) has been found to simultaneously increase both correct recall and false memory when free recall procedures are used, although this may preferentially effect those with lower memory performance (Diekelmann, Born, & Wagner, 2010; Payne et al., 2009). Other than consolidation effects, sleep deprivation at memory retrieval has been linked with increased endorsement of false memories (Diekelmann, Landolt, Lahl, Born, & Wagner, 2008; Diekelmann et al., 2010), as has sleep deprivation at encoding (Frenda, Patihis, Loftus, Lewis, & Fenn, 2014). Overall, the behavioural evidence is broadly in support of the idea of false memories arising from multiple mechanisms during the different stages of memory processing, with both sleep and sleep loss playing a role in at least some of these.

Further work is required before it can be determined if false memories in regards to sleep are predominantly memory errors, a product of associative mechanisms, or both. Sleep deprivation and memory studies to date have typically used either total (TSD) or partial sleep deprivation (PSD), but not compared the effects of each. The impact of different doses of sleep and sleep loss in producing false memory specifically has also not been thoroughly studied, and all studies to date have used either wake or total sleep deprivation paradigms to study the phenomenon. Given that partial sleep loss is likely to be more common than total sleep deprivation in the general population and organisational settings (Durmer & Dinges, 2005), an understanding of the genesis of false memory under well-rested and also under conditions of total (TSD) and partial sleep deprivation (PSD) is important. In this study, new information must be learned and utilised immediately during sleep loss, brought about by either PSD (4h TIB for 4 nights) or TSD (30h total SD), without the benefit of a sleep-based consolidation period. It should be noted that the sleep literature has so far taken a singular approach to studying false memory; the vast majority of studies have used the DRM false memory task (Roediger & McDermott,

1995). While this is a valid and reliable method of eliciting false memories, false memories can occur in nonverbal domains as well (Frenda et al., 2014). In all, there are still several issues that need to be addressed in the false memory, sleep and memory, and sleep research literatures before a comprehensive understanding of false memory in the context of sleep is available.

Here, we address some of these issues by assessing the impact of both TSD and the purportedly equivalent period of PSD (i.e., sleep loss (SL) of either 30h time awake; and 4h TIB for four nights; Van Dongen et al., 2003), in comparison to a well-rested baseline (WR), on false memory generation in both the verbal and visual domains. This allows us to test: whether false memory generation is differentially impacted by PSD and TSD; whether different modalities of false memory are influenced in the same manner as one another; and whether different types of memory (free recall and recognition) are differentially effected by PSD and TSD. We hypothesised that: (i) PSD and TSD will not significantly differ in their effects on veridical and false memory; (ii) sleep loss (PSD and TSD) will increase the rates of false memory production; and that (iii) sleep loss will increase false memory in both verbal and visual modalities.

## 2. Methods

### 2.1. Participants

44 healthy, normally functioning individuals (25F, 19 M;  $M_{\text{age}} = 24.9 \pm 5.29\text{y}$ ) gave informed consent and participated in the study. Subjects were screened for sleep disorders, drug use, axis I psychiatric conditions and medical disorders through a combination of structured interview and laboratory testing. To be included in the study, subjects had to report maintaining regular sleep-wake schedules (7–9h TIB, with bed times of 2000–0000 and wake times of 0600–0800).

### 2.2. Procedure

Subjects maintained their normal sleep schedules for one week prior to participation. Adherence to at-home schedules was verified with wrist actigraphy, voicemail call-ins and sleep diaries. They then undertook both a well-rested condition (9h TIB for six nights; 4 at home followed by 2 in the laboratory) and either a total sleep deprivation (30h total) or sleep restriction (4h TIB for four nights) condition. Participation in the partial or total sleep loss conditions was randomised, and order of condition (rested or deprived) was counterbalanced across subjects. The well-rested sleep schedule was based on each subject's habitual sleep schedule at home. If they did not report normally spending 9h in bed per night, sleep time was extended from their habitual schedule equally in the evening and morning to achieve a 9-h window. Similarly, the sleep restriction schedule was determined by shrinking time in bed equally in the evening and the morning. While in the laboratory, subjects were monitored with actigraphy throughout the day and night, and were monitored with polysomnography during sleep periods. Wakefulness during total sleep deprivation (TSD) and partial sleep deprivation (PSD) was guaranteed through staff interaction, and subjects were allowed to play games, watch television and browse the internet. Stimulant and alcohol consumption was prohibited 48h before entering the laboratory and during the lab stay. Test administration was scheduled at 5h post habitual wake time in the TSD condition and 7h post habitual wake time in the PSD and well-rested conditions. This variation was due to constraints imposed by other aspects of the study design. Given the relatively neutral circadian time represented by the mid-day

hours, we do not believe this slight variation in testing time affected the results.

### 2.3. Tasks

#### 2.3.1. Mood and sleepiness scales

Prior to each test session, we administered the Karolinska sleepiness scale (KSS) as well as a self-report visual-analog mood scale assessing 6 different mood states. For each mood, the directions asked “How \_\_\_ do you feel?” where the blank was completed with the following mood words: sad, happy, calm, anxious, relaxed, stressed, and irritable. Subjects responded by marking a spot on a 10 cm long line corresponding to their current mood state. The line was anchored with the terms “very little” and “very much.” The end of the line, which was marked little vs much (i.e., the left vs right end of the line), was counterbalanced across all questions. Subjects were alerted to pay attention to which end was anchored with which valence. The questionnaire was scored by measuring the distance marked from “very little”, such that low numbers represent little current experience of the emotion and large numbers represent experiencing a lot of the given emotion.

#### 2.3.2. Verbal false memory (DRM)

False memory in the verbal domain was assessed through the DRM task (Roediger & McDermott, 1995). The DRM task is a reliable and commonly used tool for generating false memory through the learning of semantically-related word lists, with subjects tested for recall of both learned words, as well as false recall of ‘theme’ words that are highly semantically related to the list, but were not actually presented. Subjects were presented with 3 sets of 12 words and then completed a free recall test. The recall form was then removed and the subjects saw another 3 sets of 12 words. There were a total of 4 “trials” (each with 3 sets of the DRM words), each of which was followed by free recall testing. Following the presentation of all lists, subjects performed a recognition memory test. Each recognition memory test contained 108 words, with 54 words being previously seen and 54 words being new. The previously seen words consisted of 6 randomly selected words from each study list. The new words consisted of each of the 12 lures, plus 42 foils randomly selected from unused DRM lists and matched for frequency, word length and concreteness.

#### 2.3.3. Visual false memory task

To assess visual false memory, we adapted a task previously published in Slotnick and Schacter (2004, 2006). Briefly, subjects were presented with 144 abstract shapes (i.e., 16 sets of 9 shapes). Shapes were presented for 2.5 s each, with an ITI of 3 s. Subjects were required to remember each shape while maintaining fixation on a central cross. At recall, subjects were presented with 96 shapes (i.e., 12 sets of 2 previously seen shapes, 2 similar but previously unseen lure shapes and 4 new shapes). Subjects were required to indicate if each shape was old or new, and were instructed to respond quickly but without sacrificing accuracy.

Both the verbal and visual tasks were administered during the same test battery, counterbalanced across participants. Test times were: 7h post habitual wake time for the well-rested condition, at 30h total sleep deprivation, and after the 4th sleep restriction night, at 8h post habitual wake time.

### 2.4. Statistical analysis

Mood data were analysed using *t*-tests with Bonferroni correction for multiple comparisons ( $p < 0.007$ ). All between groups comparisons were performed with repeated measures ANOVA. Following the methods used in previous sleep and false memory

research (Berndt, Diekelmann, Alexander, Pustal, & Kirschbaum, 2014; Diekelmann et al., 2008, 2010), discrimination indices for both recognition and free recall measures in both modalities were computed from raw scores by subtracting the number of study foils endorsed from the hit rates of both correct and false memory. I.e.,  $\text{Pr}(\text{veridical}) = (\text{proportion of hits} - \text{proportion foils recalled})$  and  $\text{Pr}(\text{false}) = (\text{proportion of false memories recalled} - \text{proportion of foils recalled})$ . This allows for direct comparison with previous research, and allows us to control for baseline tendency to accept items as old (either correctly or falsely) between our experimental groups (Diekelmann et al., 2008, 2010). Note that this held even for the visual task, in which prototype shapes were used as lures and analogous to critical lures in the DRM task. A response bias index (Br) was also computed for all time points, and was computed as  $\text{foils}/(1-\text{Pr})$ . Bias indices were analysed using one way ANOVA.

## 3. Results

### 3.1. Mood and sleepiness

Subjects reported being significantly sleepier during sleep loss compared to the well-rested condition  $t(41) = -7.43$ ,  $p < 0.001$ . Only one mood measure survived correction. Subjects reported being more stressed during sleep loss than during the well-rested condition  $t(39) = -2.89$ ,  $p = 0.006$ . However, we note the stressed scores during sleep loss were only 2.0 out of 10 (compared to 1.0 during the well-rested condition), suggesting subjects felt very little stress even during sleep loss. All *p* values for other mood measures were  $>0.05$  (Cf. Table 1). No mood variables were significantly related to outcome measures once corrected for multiple comparisons. This indicates that non-specific stress effects are unlikely to have influenced our results.

### 3.2. Response bias

There were no significant group difference in response bias between groups at any time point. All *p* values were  $>0.05$ .

### 3.3. Sleep restriction vs sleep deprivation

See Table 2.

### 3.4. Veridical and false memory after sleep loss

#### 3.4.1. Recognition memory for DRM word lists

The omnibus analysis of DRM word lists revealed a significant main effect of sleep loss on veridical recognition memory, such that veridical recognition decreased as a result of sleep loss. There was no significant main effect of SL type (i.e., partial and total sleep deprivation groups did not perform significantly differently), nor was there a significant interaction of SL type by sleep loss (i.e.,

**Table 1**  
mood and KSS scores for subjects in WR and SL conditions.

	WR(SD)	SL(SD)	t(df)
Sleepy (KSS)	2.79(1.29)	5.55(2.26)	-7.44(41)
Happy	6.33(2.96)	5.69(2.67)	1.73(39)
Calm	7.96(2.83)	6.87(3.10)	2.70(39)
Relaxed	7.38(3.13)	6.71(2.93)	1.34(39)
Stressed	1.02(1.67)	2.03(2.36)	-2.89(39)*
Sad	0.74(1.23)	0.62(0.80)	0.68(39)
Anxious	1.11(1.44)	1.57(1.78)	-1.88(39)
Irritable	1.58(2.77)	2.45(2.83)	-1.60(39)

\*  $p < 0.01$  following correction for multiple comparisons.

**Table 2**  
Repeated measures ANOVA results: Mean/SD, F-values and  $\eta^2$ .

	TSD		PSD		Sleep loss	$\eta^2$	SL type	$\eta^2$	Sleep loss $\times$ SL type	$\eta^2$
	WR(SD)	SL(SD)	WR(SD)	SL(SD)						
Veridical recognition (DRM)	0.83(0.09)	0.74(0.18)	0.85(0.07)	0.78(0.11)	10.67*	0.22	1.24	0.03	0.44	0.01
False recognition (DRM)	0.68(0.17)	0.57(0.19)	0.64(0.22)	0.56(0.24)	6.67**	0.15	0.62	0.02	0.84	0.02
Veridical recall (DRM)	78.7(20.6)	66.62(25.5)	63.2(19.9)	60.31(22.72)	6.4**	0.14	2.95	0.07	1.89	0.05
False recall (DRM)	0.61(2.39)	-0.67(3.04)	-0.6(2.89)	-1.22(4.3)	3.17	0.08	1.5	0.04	0.31	0.008
Veridical recognition (shapes)	0.68(0.17)	0.64(0.22)	0.58(0.25)	0.52(0.24)	1.16	0.03	3.31	0.07	<0.001	<0.001
False recognition (shapes)	0.63(0.19)	0.58(0.22)	0.54(0.23)	0.54(0.24)	0.33	0.008	1.27	0.03	0.55	0.01

WR = well-rested; SL = sleep loss; PSD = partial sleep deprivation; TSD = total sleep deprivation.

Note: The range of all indices is 0.0–1.0, with the exception of veridical recall (DRM) which is 43.0–96.0.

\*  $p < 0.05$ .

\*\*  $p < 0.01$ .

PSD and TSD did not respond differently as a result of time). These effects are depicted in Fig. 1.

Our analysis also demonstrated a significant main effect of sleep loss for false memory recognition, such that false memory endorsement decreased as a result of sleep loss. This result is depicted in Fig. 2. Once again, we find no significant main effect of SL type, nor a significant interaction between sleep loss and SL type.

### 3.4.2. Free recall memory for DRM word lists

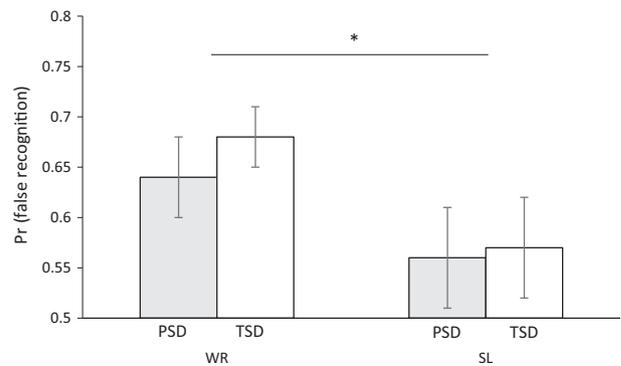
The omnibus ANOVA revealed a significant main effect of sleep loss, such that well-rested subjects recalled significantly more old words than when under sleep loss conditions (see Table 2 and Fig. 3). There was no significant main effect of SL type, nor a significant sleep loss $\times$ SL type interaction. There were no significant main or interaction effects for free recall false memory.

### 3.5. Visual memory task

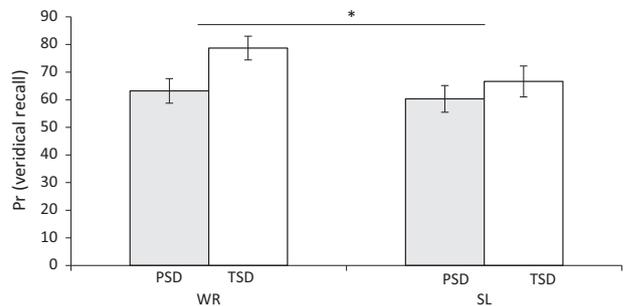
The omnibus ANOVA revealed no significant interaction or main effects for either veridical or false recognition in the visual false memory task (see Table 2).

## 4. Discussion

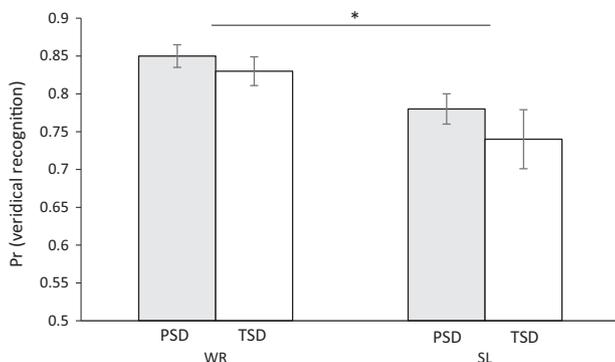
Here, we have studied both false and veridical memory across different sensory modalities and using different types of memory retrieval procedures (recognition and recall), and compared these across well-rested and sleep loss conditions. We found that: (i) both total sleep deprivation over a 30h period and sleep restriction (4h per 24h) over a period of 4 days, resulted in equivalent changes in both veridical and false memory in healthy adults; (ii) for verbal



**Fig. 2.** Endorsement of lures in the DRM task between well-rested and sleep loss conditions for both partial and total sleep loss subjects. Error bars reflect standard error of the mean; \*  $p = 0.01$ . WR = well-rested; SL = sleep loss; PSD = partial sleep deprivation; TSD = total sleep deprivation.



**Fig. 3.** Veridical recall in the DRM task. Error bars reflect standard error of the mean; \*  $p < 0.001$ . WR = well-rested; SL = sleep loss; PSD = partial sleep deprivation; TSD = total sleep deprivation.



**Fig. 1.** Correct recognition of previously seen DRM word list items between well rested and sleep loss conditions for partial and total sleep loss subjects. Error bars reflect standard error of the mean; \*  $p = 0.002$ . WR = well-rested; SL = sleep loss; PSD = partial sleep deprivation; TSD = total sleep deprivation.

information, sleep loss led to reduced veridical and false memory recognition, as well as reductions in veridical recall, but not false memory recall; (iii) neither veridical nor false memory for abstract shapes was significantly impacted by sleep loss. While the veridical memory results are consistent with previous results showing, broadly, that both sleep and sleep loss can influence memory, several of our findings are at odds with the current literature on sleep and false memory.

The finding of reduced veridical memory (under both free recall and recognition paradigms) in our verbal task under sleep loss conditions is parsimonious with the broader literature on the effects of sleep loss on the encoding of new memories (Drummond, Meloy, Yanagi, Orff, & Brown, 2005; Drummond et al., 2000; Mander et al., 2011; Saletin & Walker, 2012; Yoo et al., 2007). However, these findings are not in keeping with the previous literature on

sleep and false memory. Previous studies have found that TSD at retrieval increases false memory endorsement (Diekelmann et al., 2008), whereas, in our sample, both PSD and TSD were found to reduce false recognition memory. Similarly, whereas previous research using free recall procedures has noted both sleep periods as well as TSD across retention intervals to increase false memory (Diekelmann et al., 2010; Payne et al., 2009), our sleep loss intervention did not lead to significant group differences in recall of false memories. Increases in false memory as a result of TSD have previously been attributed to failures in source monitoring (Fenn et al., 2009), and increases in false memory across sleep periods to active memory consolidation (Diekelmann & Born, 2010a; Yassa & Reagh, 2013). We did not allow a retention interval between encoding and recall. Thus, our results cannot be explained, as in some previous studies, as being the result of either offline consolidation, or online rehearsal during a wake retention period. Instead, our results are most likely due to dysfunction occurring during either or both encoding and retrieval, both of which occurred in a sleep deprived state.

Despite encoding performance reaching threshold levels, our results could still be explained as sleep loss impacting the quality, if not the quantity of encoded information. This would be consistent with ‘fuzzy trace’ (Cabeza & Lennartson, 2005; Reyna & Brainerd, 1998; Straube, 2012) accounts. That is, that during encoding, both a veridical and gist trace of the information are formed. False memory is thought to arise from the recollection of the gist trace. The diminishment of cognitive resources leading to improper or incomplete encoding of these traces might account for our finding of reductions in both veridical and false memory following sleep loss. In other words, if the lists were not encoded properly to begin with (due to cognitive load and overtaxed memory systems), neither the verbatim nor the gist trace would form. The implication of this viewpoint would be that sleep loss has negative impacts on both the ability to learn individual items, and also to knit these into semantic, gist representations of the overall content of the learning exercise. Of course, we cannot entirely rule out the possibility that the traces were encoded adequately but that retrieval processes, for both veridical and false memories, were disrupted by sleep loss.

With the present data, we are also able to comment on differential effects of sleep loss on recognition and recall memory. We find that recognition memory and free recall are both affected: in each case, veridical verbal memory was negatively impacted by sleep loss. However, while we found an effect of sleep loss in reducing false memories in a recognition task, we did not find this for free recall. This is curious, given that previous work has demonstrated an effect of sleep loss on false recall (Diekelmann et al., 2010). It has been suggested that these differences between memory systems are due to the alternate mechanisms underlying free recall and recognition (Diekelmann et al., 2010). It is possible that free recall leads to greater false memory primarily from generalisation during consolidation, whereas recognition procedures primarily tag processes more vulnerable to distortion, such as encoding and retrieval errors. It is also possible that this is due to the method through which we tested free recall – i.e., following the presentation of every three DRM lists. This could potentially have engaged different encoding processes than in previous studies. Either of these alternatives could explain the discrepancy in our results, and this highlights the need for future research into false memory and sleep focussing on encoding and retrieval processes in addition to consolidation processes occurring during sleep itself.

We did not find a common relationship in terms of veridical and false memory generation between tasks in the visual and verbal modalities. That is, although we found effects of sleep loss for the verbally-based DRM false memory lists, we did not find an effect on an abstract image task which can also produce false mem-

ories (Slotnick & Schacter, 2004, 2006). This is perhaps surprising, given that sleep has been found to aid in the consolidation of procedural skills for texture discrimination, which has been previously linked with early visual processing areas (Gais, Plihal, Wagner, & Born, 2000; Mednick, Drummond, Arman, & Boynton, 2008; Mednick, Drummond, Boynton, Awh, & Serences, 2008). There are three main possibilities to explain our results here. First, it is tempting to suggest that the visual system may not be prone to false memory generation in conditions of sleep loss. Second, the effects reported are possibly related to strength of initial encoding; participants may not have learned the input stimuli well enough to generalise them to novel exemplars, in much the same manner as has been shown in research into the DRM lists on amnesic populations (Van Damme & d’Ydewalle, 2009). This is unlikely in the present sample, however, as indicated by small effect sizes. Finally, it is also possible that task differences, notably a lack of semanticisation in the visual task, may have contributed to this effect. Although the visual task used has been shown to generate visual false memories (Slotnick & Schacter, 2004, 2006), there are conceptual differences between this task and the DRM lists. Broadly, this relates to mechanisms for generating false memories: the DRM task functions through semantic relationships between list words (Cabeza & Lennartson, 2005), whereas the visual task functions through similarities between abstract images. Several studies have suggested that the brain processes semantic relationships between items during sleep (Diekelmann & Born, 2010a, 2010b; Walker & Stickgold, 2010). An important extension on this work is therefore to consider degrees of semantic relatedness in a visually-based memory task under sleep and sleep loss conditions.

Also importantly, these particular findings regarding discrepancies in results between the visual and verbal systems in the brain highlight the need for sleep and false memory research to move beyond the use of the DRM task as a sole measure of false memory. The DRM task, while a powerful tool for creating false memories in the laboratory, uses a single modality and does not represent the entirety of the processing options available to the human brain. It may also rely on only one of many potential mechanisms of false memory generation (Straube, 2012). While it must be noted that there have been some studies using classic misinformation-based false memory designs (Frenda et al., 2014), these are rare. Future research should continue to broaden the scope of false memory and sleep research through the inclusion of differing sensory modalities and tasks which involve different brain regions. In particular, the visual system, and whether it is susceptible to false memory under conditions of sleep loss or other stressors, would seem a fruitful target for such research.

Our investigation has led to several relevant findings for current research; however, it is not without its limitations. Firstly, our paradigm impacted all stages of memory. Although this has real-world relevance (and arguably has greater external validity than an approach which separates memory processes), it could also be seen to add noise to the analyses. A more thorough approach would be to selectively restrict sleep at differing stages of memory processing, similar to Diekelmann et al. (2008). This would be a complicated behavioural study design, and would necessarily be confounded by varying retention interval lengths. A second limitation of our work is that we present here purely behavioural findings and have no concurrent neuroimaging data to report. As such, we are unable to comment on neural processes underlying the veridical and false memories in conditions of sleep restriction, which would inform selection of theoretical models. This should be addressed in future research, and event-related potentials would be one suitable methodology for disentangling potentially differential effects of encoding and retrieval processes (Mograss, Godbout, & Guillem, 2006; Mograss, Guillem, Brazzini-Poisson, & Godbout, 2009; Mograss, Guillem, & Godbout, 2008). Incorporating

a mixed neurophysiological and behavioural design as delineated here would be of great value in further adding to the literature.

Sleep and the generation of false memories continues to be an important area of research, with both practical and theoretical relevance. Here we have presented an examination of the propensity for false memory in the context of well-rested wakefulness and both sleep restriction and sleep deprivation. Importantly, we have also examined false memory across modalities and with multiple memory retrieval methods. This has highlighted several potentially beneficial modifications for future research, such as the need to consider encoding and retrieval processes, and the need to generate false memories with a variety of cross-modal tasks. With this greater focus on whole-brain cognition, future findings will lead to a fuller understanding of false memory generation, and whether they represent memory errors or an adaptive mechanism of associative generalisation.

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