



# Sleep spindles during a nap correlate with post sleep memory performance for highly rewarded word-pairs



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## ABSTRACT

The consolidation of new associations is thought to depend in part on physiological processes engaged during non-REM (NREM) sleep, such as slow oscillations and sleep spindles. Moreover, NREM sleep is thought to selectively benefit associations that are adaptive for the future. In line with this, the current study investigated whether different reward cues at encoding are associated with changes in sleep physiology and memory retention. Participants' associative memory was tested after learning a list of arbitrarily paired words both before and after taking a 90-min nap. During learning, word-pairs were preceded by a cue indicating either a high or a low reward for correct memory performance at test. The motivation manipulation successfully impacted retention such that memory declined to a greater extent from pre- to post sleep for low rewarded than for high rewarded word-pairs. In line with previous studies, positive correlations between spindle density during NREM sleep and general memory performance pre- and post-sleep were found. In addition to this, however, a selective positive relationship between memory performance for highly rewarded word-pairs at posttest and spindle density during NREM sleep was also observed. These results support the view that motivationally salient memories are preferentially consolidated and that sleep spindles may be an important underlying mechanism for selective consolidation.

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## 1. Introduction

One important aspect of language learning, in particular second language learning, is the formation of associations between words. A process thought to be vital to the successful consolidation of memories is sleep (Rasch & Born, 2013). Benefits of sleep have been reported in procedural as well as declarative memory tasks (Fischer & Born, 2009; Fischer, Hallschmid, Elsner, & Born, 2002; Lau, Tucker, & Fishbein, 2010; Marshall, Mollé, Hallschmid, & Born, 2004; Tucker et al., 2006; Walker, Stickgold, Alsop, Gaab, & Schlaug, 2005; Wilhelm et al., 2011). It seems that slow oscillations during slow-wave-sleep (SWS) and associated sleep spindles are particularly important for declarative memory consolidation (Born & Wilhelm, 2012; Cox, Hofman, & Talamini, 2012; Gais, Mollé, Helms, & Born, 2002; Marshall et al., 2004; Mednick et al., 2013; Saletin, Goldstein, & Walker, 2011; Schmidt et al., 2006). Consequently, SWS and associated physiological mechanisms are presumed to be important for the successful acquisition of new

associations which underpin some forms of language learning (Opitz & Friederici, 2004).

In one recent study demonstrating the benefits of SWS and sleep spindles for hippocampus-dependent memories, we used memory tasks with single words and non-related word-pairs to compare the impact of nap sleep on item memory vs. associative memory (Studte, Bridger, & Mecklinger, 2015). In the item memory task, single words were to be judged as learned or new, whilst in the associative task participants were required to distinguish between learnt, learnt but rearranged and new word-pairs. The former test requires only recognition of simple item memory, whereas the ability to retrieve associations between learnt word-pairs is necessary to perform the associative test. A beneficial effect of 90 min of nap sleep was only found for associative memory performance, and this manifested as a smaller decrease in associative memory performance over time. Associative recognition memory performance after sleep was also found to be associated with sleep spindle density at frontal sites during SWS, and performance before sleep was marginally correlated with sleep spindle density at frontal sites during non-REM (NREM) sleep. No corresponding correlations were observed for item memory, which underlines the strong association between associative memory performance and SWS mechanisms.

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Not all learnt information is retained after sleep however and which memories benefit from sleep and which do not remains to be fully specified. There is increasing evidence that sleep works as a filter by predominantly strengthening memories that are adaptive or of relevance to the future (Fischer & Born, 2009; Oudiette, Antony, Creery, & Paller, 2013; Saletin et al., 2011; Stickgold & Walker, 2013; van Dongen, Thielen, Takashima, Barth, & Fernández, 2012; Wilhelm et al., 2011). In one model of selective memory consolidation, Stickgold and Walker (2013) assume that consolidation of information will only occur if items are tagged as important during or after encoding. These tags could be induced by task relevance (Saletin et al., 2011; Wilhelm et al., 2011), emotionality (Payne, Stickgold, Swanberg, & Kensinger, 2008) or expected reward (Fischer & Born, 2009; Oudiette et al., 2013). Selective beneficial effects of sleep have been shown for both motor (Fischer & Born, 2009) and declarative memory tasks, such as word paired-associate tasks (Wilhelm et al., 2011) and object location tasks (Oudiette et al., 2013; van Dongen et al., 2012). In one pertinent demonstration of this, Wilhelm et al. (2011) asked participants to learn lists of semantically-related word-pair associates before 9 h retention intervals filled with either sleep or wakefulness. Critically, participants were randomly allocated to be either informed or uninformed that they would be later tested on their memory for these items after the retention interval. Participants who were informed that they would be later tested performed better on the final memory test than their uninformed counterparts, but only if they slept in the retention interval. These participants also demonstrated a robust increase in slow oscillation activity and sleep spindles during SWS; again in line with the association between these physiological mechanisms and preserved associative memory.

The preceding considerations of the existent literature strongly indicate that sleep should preserve memory for word-pair associations that are tagged as relevant for the future. Moreover, data repeatedly demonstrating the engagement of SWS mechanisms predicts that the mnemonic benefits for information that undergoes a specific learning experience should be evident even after a 90-min nap, so long as this is sufficient for individuals to engage in a prolonged phase of SWS. In the current study, all participants learnt a list of word-pairs and were tested on their memory both before and after taking a nap. Critically, half of the word-pairs were preceded by a cue which indicated that later correct performance would be rewarded at a high level; whereas for the remainder, the cue indicated that the reward was relatively low (see Oudiette et al., 2013 for a similar approach to induce motivational salience). The logic behind this manipulation was that these reward cues should make high reward items motivationally more relevant and tagged for selective consolidation during sleep compared to low reward items. This should lead to better memory performance for high- than low-reward items after sleep, manifest as a significantly smaller decline in memory performance for high-rewarded associations over time (Studte et al., 2015). In line with the notion that the physiological variables during NREM/SWS sleep are associated with selective consolidation, however, specific predictions about the relationship between spindle density (SpD) and memory performance were explicitly considered. If a correlation between SpD and memory performance for high but not low rewarded items can be observed, this would provide evidence for a selective role of sleep in memory consolidation, in particular a role for sleep spindles in the selective tagging of memories from a specific learning experience, in our case memories for events with a high motivational value (Murty & Adcock, 2014).

In the current experiment therefore, behavioral and polysomnographic data were used to investigate how reward cues during encoding might interact with the benefits of nap

sleep on associative recognition and how this would relate to physiological variables during sleep. A final aspect of the current design was the employment of an associative recognition memory test as was the case in our former study (Studte et al., 2015), in which word-pairs were to be classified as either old, recombined or new. Responses to these categories were used to create two discrimination measures. An old/new discrimination Pr index (PrI-score), calculated by subtracting false alarms to new pairs from the hit rate for old pairs was taken to represent item memory performance whilst an associative PrA-score, calculated by subtracting the proportion of recombined pairs incorrectly classified as old (false alarms to recombined) from the hit rate for old pairs, was employed as a measure of recollection/associative memory (Bader, Mecklinger, Hoppstadter, & Meyer, 2010; Kriukova, Bridger, & Mecklinger, 2013). Sleep was expected to benefit associative but not item memory retention (Daurat, Terrier, Foret, & Tiberge, 2007; Drosopoulos, Wagner, & Born, 2005; Studte et al., 2015).

## 2. Methods

### 2.1. Participants

21 healthy young adults from Saarland University participated in this experiment. Data from 9 additional subjects were excluded due to (a) not sleeping (no occurrence of stage 2 sleep;  $n = 3$ ), (b) technical problems<sup>1</sup> ( $n = 3$ ) and (c) incorrect use of response buttons at pretest ( $n = 3$ ). The latter refers to two subjects who pressed two out of three possible buttons on at least 80% of all trials and one subject who consistently confused “old” and “recombined”. All three of these excluded participants had a discrimination score at least 2 SDs lower than the mean in at least one of the two reward categories. The final sample consisted of 14 females and 7 males with a mean age of  $21.7 \pm 2.6$ . All participants stated that they did not have any sleep disorders, no known neurological problems and that they were right-handed (Oldfield, 1971). All gave written informed consent and were paid 20 € or equivalent course credit plus an additional reward which was dependent on their test performance (average:  $9 \text{ €} \pm 3 \text{ €}$ ). The maximum additional reward was set to 20 €.

### 2.2. Stimuli

270 semantically unrelated German word-pairs were used as stimuli. All words were nouns with a length between 3 and 10 letters and a frequency between 6 and 869 (Baayen, Piepenbrock, & Gulikers, 1995). 180 of the word-pairs were used in the previous nap sleep study from our lab (Studte et al., 2015). The remaining 90 word-pairs were newly created and evaluated in terms of semantic relationship and suitability to build a compound in order to reduce the pre-experimental associations within pairs (Bader et al., 2010). 30 additional subjects who did not participate in the main experiment rated the relatedness and unitization ability of the new and recombined word-pairs and only word-pairs with low relation and low unitization values (each  $\leq 2$  on a scale from 1 to 4) were included as test stimuli. There were six different stimuli-sets for word-pairs which were counterbalanced across our sample so that all items appeared equally often in each category (high/low reward; old/new/recombined). Recombined pairs were always rearranged within either the low or high reward category.

<sup>1</sup> This refers to two instances in which the sleep EEG recording did not work and a further instance in which E-prime failed to record responses so the session had to be stopped after the pretest.

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