Brief Communication

Sleep increases explicit solutions and reduces intuitive judgments of semantic coherence

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Sleep fosters the generation of explicit knowledge. Whether sleep also benefits implicit intuitive decisions about underlying patterns is unclear. We examined sleep's role in explicit and intuitive semantic coherence judgments. Participants encoded sets of three words and after a sleep or wake period were required to judge the potential convergence of these words on a common fourth associate. Compared with wakefulness, sleep increased the number of explicitly named common associates and decreased the number of intuitive judgments. This suggests that sleep enhances the extraction of explicit knowledge at the expense of the ability to make intuitive decisions about semantic coherence.

[Supplemental material is available for this article.]

In everyday life we sometimes make decisions based on a “gut feeling” without knowing the exact reasons for why we decided in this way. Intuitive processing has been conceptualized as the preliminary detection of meaning in the environment by recognizing “some pattern, structure, or organization [that] exists prior to its detection” (Bowers et al. 1997). Intuitive processes are assumed to draw on tacit knowledge stored in semantic memory networks. This tacit knowledge may be momentarily inaccessible to conscious awareness, but can be activated by environmental cues to draw on tacit knowledge stored in semantic memory networks. This tacit knowledge may be momentarily inaccessible to conscious awareness, but can be activated by environmental cues.

In a classical task measuring intuition, participants are asked to make semantic coherence judgments on three presented words, like SALT DEEP FOAM (e.g., Bolte and Goschke 2005; Topolinski and Strack 2009). Semantic coherence is defined by the existence of a fourth word that the word triad's constituents (remotely) have in common, the common associate (OCEAN in this example). Studies have shown that participants perform above chance level in correctly judging coherent triads as coherent even if they are not able to name the common associate. This process of generating the feeling of semantic associativity has been conceptualized in the framework of automatic spread of activation. According to this, the encounter of the triad automatically triggers the activation of related concepts stored in semantic memory resulting in a coherence impression. This first implicit coherence impression can become consciously accessible if enough activation has accumulated to cross a threshold of awareness resulting in the ability to explicitly name the common associate (Bowers et al. 1990). Even though intuitive decision making has been behaviorally described in several studies (e.g., Bolte and Goschke 2005; Topolinski and Strack 2009), the physiological mechanisms underlying this phenomenon are largely unknown (Volz and Zander 2014).

Sleep is well-known to facilitate the consolidation of newly encoded material by strengthening and integrating new memory representations into the long-term store (e.g., Diekelmann and Born 2010; Stickgold and Walker 2013). For example, sleep facilitates the generalization and abstraction of schema-like information from single encoded elements (Lewis and Durrant 2011). Sleep also supports the conversion of implicitly learned regularities into explicit knowledge about those regularities, allowing for “insight” into underlying patterns (Fischer et al. 2006; Yordanova et al. 2008; Drosopoulou et al. 2011; Verleger et al. 2013). Along these lines, Monaghan et al. (2015) observed that sleep improves analogical transfer in problem solving by abstracting and structurally generalizing rules and/or task solutions across different problems. Such processes are assumed to rely on the covert reactivation (“re-play”) of learning-related neuronal activity during sleep (Cousins et al. 2014; Diekelmann et al. 2016).

Sleep also enhances associative memory processes (Stickgold et al., 1999). Two recent sleep studies applied the remote associate task (RAT), in which participants are asked to find a semantic concept that forms a link between three presented words (for instance HEART SIXTEEN COOKIE, solution: SWEET). The RAT is similar to the semantic coherence task described above but tests for explicit solutions only, while not assessing intuitive responses. Cai et al. (2009) found that sleep facilitates the ability to explicitly name solution words in the RAT, yet only when solution words were primed before sleep. Sio et al. (2013), using similar RAT stimuli, showed that sleep can increase the generation of explicit solutions even without priming, but this effect was restricted to difficult RAT items. Although these studies provide a first hint that under certain conditions sleep increases the generation of explicit RAT solutions, the effect of sleep on intuitive judgments remains unknown.

Here, we asked whether sleep affects intuitive and explicit semantic coherence judgments. We hypothesized that sleep increases the number of explicit responses as well as the number of intuitive judgments. This was based on the automatic spread of activation account: We assumed that concepts, comprising core and remote associations, with a relatively strong activation before sleep would be boosted during sleep to cross the threshold of awareness, resulting in more explicit solutions. Concurrently, weakly activated concepts should be boosted during sleep as well, such that after...
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Sleep and semantic coherence judgments were allowed to sleep for 8 h in the laboratory, with polysomnographic data continuously being recorded. Standard polysomnography included electroencephalography (EEG, at positions C3 and C4), electrooculography (EOG), and electromyography (EMG). Sleep stages were determined offline according to the standard criteria by Rechtschaffen and Kales (1968). Participants showed normal sleep patterns with a total sleep time of 443.67 ± 9.34 min (see Supplemental Table S1 for detailed sleep data). During testing in the morning (~07:30), participants performed the semantic coherence judgment task first and then were tested on their explicit memory for the encoded word triads in a cued recall and a recognition task. Participants then performed the vigilance task and rated their subjective sleepiness again (see Supplemental Table S2 for all control data; none of the control data revealed any differences between groups). The wake group started encoding in the morning (~09:00), following the same procedure as the sleep group. After the encoding session, participants left the laboratory and went about their daily activities. Testing took place in the early evening (~17:30), again following the same procedure as the sleep group.

For the semantic coherence judgment task, participants slowly encoded 200 word triads (100 coherent, 100 incoherent; Fig. 1B). Encoding was embedded in a vowel counting task. The three words of each triad were presented for either 2 sec (short encoding) or 4 sec (long encoding) and subjects were instructed to count the number of vowels in the three words and give their response within 3 sec. At testing after the sleep/wake interval, half of the previously encoded word triads (50 coherent and 50 incoherent) were randomly presented for 4 sec and subjects had to indicate whether the triad was semantically coherent or incoherent. Irrespective of their response, participants were asked to type in a common associate right after their coherence judgment. Common associates were counted as correct if the exact word or a plausible synonym was produced. For explicit coherence judgments, the percentage of correctly produced common associates was calculated, irrespective of prior coherence judgments. To assess intuitive coherence judgments, we computed the intuition index defined as the difference between hits (coherent triads correctly classified as coherent, but without a correct common associate) and false alarms (incoherent triads falsely classified as coherent) (cf. Bolte et al. 2003). Intuitive coherence judgments were only computed for triads for which participants did not come up with a correct common associate; therefore explicit coherence judgments and the intuition index consist of different trial types (note that both measures were not correlated with each other, in the overall sample, \( r = -0.13, p = 0.49 \), as well as in the sleep group, \( r = 0.06, p = 0.84 \), and in the wake group, \( r = 0.25, p = 0.36 \), separately).

The overall response pattern of the coherence judgments is illustrated in Table 1. Analysis of explicit coherence judgments showed that sleep participants produced significantly more common associates than wake participants (sleep: 50.74 ± 3.97%, wake: 40.53 ± 2.38%; main effect *sleep/wake*: \( F_{1,28} = 5.15, p = 0.031 \)), suggesting that the likelihood of becoming aware of explicit solutions was higher after sleep than wakefulness (Fig. 2A). This sleep–wake difference was...
not affected by the duration of encoding (interaction effect "sleep/wake" × "short/long": \(F_{1,28} = 0.19, p = 0.66\)). However, triads that had been encoded for 2 sec before the sleep/wake interval had a generally higher likelihood of being explicitly solved than triads that had been encoded for 4 sec (short: 65.96 ± 3.16%; long: 24.64 ± 2.43%; main effect "short/long": \(F_{1,28} = 189.28, p < 0.001\)).

In contrast to explicit judgments, sleep participants showed significantly fewer intuitive judgments than wake participants (sleep: 8.77 ± 2.41%; wake: 21.16 ± 2.16%; main effect "sleep/wake": \(F_{1,28} = 14.71, p < 0.001\)), suggesting that sleep compared with wakefulness distinctly reduced the ability to make intuitive decisions (Fig. 2B). Importantly, both intuition indices, for the sleep and wake groups, were significantly higher than chance level (chance level = 0; sleep: \(t_{15} = 3.63, p < 0.005\); wake: \(t_{15} = 9.78, p < 0.001\)). Since the intuition index is calculated as the difference between hits and false alarms, we analyzed these measures separately to examine whether the lower intuition index in the sleep group resulted from lower hits or from higher false alarms. Sleep participants showed significantly fewer hits compared with wake participants (29.41 ± 5.41% versus 51.77 ± 5.16%; \(t_{28} = -2.89, p = 0.006\)), whereas false alarms did not differ significantly (20.64 ± 4.61% versus 30.60 ± 4.51%; \(t_{28} = -1.53, p = 0.14\)). Like for explicit responses, the difference between sleep and wakefulness in the intuition index was independent of encoding duration.

## Table 1. Response pattern in the semantic coherence judgment task

|               | Sleep group | Wake group |
|---------------|-------------|------------|
|               | Judgment    | Common associate | Judgment    | Common associate |
| Coherent      |             |              |             |              |
| Short encoding| Coherent no common associate | 27.64 ± 4.87 | 9.83 ± 2.01 | 21.35 ± 4.06 | 8.10 ± 1.57 |
|               | Coherent common associate | 54.90 ± 7.10 | 50.86 ± 6.67 | 57.05 ± 6.85 | 41.94 ± 5.51 |
| Coherent      | Incoherent  | 66.40 ± 5.36 | 13.53 ± 3.40 | 53.26 ± 5.74 | 8.60 ± 1.86 |
| Long encoding | Coherent no common associate | 13.33 ± 4.16 | 4.85 ± 2.59 | 16.69 ± 3.05 | 3.03 ± 0.85 |
|               | Coherent common associate | 20.00 ± 4.71 | 11.17 ± 3.00 | 29.53 ± 5.40 | 8.83 ± 1.60 |
| Incoherent    | Incoherent  | 81.06 ± 4.44 |               | 71.69 ± 4.47 |               |
| Short encoding| Coherent no common associate | 9.86 ± 2.78 | 2.78 ± 0.78 | 11.21 ± 2.20 | 11.21 ± 2.20 |
|               | Coherent common associate | 9.06 ± 3.23 |               | 17.09 ± 3.39 |               |
| Incoherent    | Incoherent  | 76.47 ± 4.86 |               | 66.82 ± 4.91 |               |
| Long encoding | Coherent no common associate | 10.16 ± 3.35 |               | 14.83 ± 3.64 |               |
|               | Coherent common associate | 13.08 ± 3.13 |               | 18.09 ± 4.32 |               |

For both groups (sleep/wake), the judgment as to whether the three possible response categories: incoherent, coherent but no common associate (coherent no common associate), and coherent and common associate immediately known (coherent common associate) are indicated, separately for coherent triads and incoherent triads as well as for triads that had been encoded for 2 sec (short encoding) or 4 sec (long encoding). Additionally, the percentages of correctly produced common associates are indicated for each response category for coherent triads (note that participants were asked to produce a possible common associate irrespective of their initial judgment, thus, some participants produced correct common associates despite initially judging the triad as incoherent or as coherent without immediately knowing the common associate). There was no correct common associate for incoherent triads. The number of incorrectly produced common associates was ∼ 2.6% for incoherent triads and ∼ 8.5% for coherent triads, across all groups and conditions. Means ± SEM are shown.

*Misses, number of coherent triads that were falsely classified as incoherent.

*Hits, number of coherent triads that were correctly classified as coherent (regardless of the common associate).

*Correct rejection, number of incoherent triads that were correctly categorized as incoherent.

*False alarms, number of incoherent triads that were falsely judged as coherent.

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Figure 2. Explicit responses (A) and intuitive responses (B) for the sleep and wake groups. The sleep group produced more explicit responses and less intuitive responses, independent of encoding duration. Explicit responses refer to the percentage of correctly named common associates for coherent triads. Intuitive responses were assessed with the intuition index for coherent triads for which participants were not able to name a common associate. The intuition index is calculated as hit rate (“coherent” judgment on coherent triads) minus false alarm rate (“coherent” judgment on incoherent triads). (Short encoding) trials that were encoded for 2 sec; (long encoding) trials that were encoded for 4 sec. Means ± SEM are shown. ***p < 0.001.
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Cued recall was also independent of the type of triad (coherent/incoherent) as well as of encoding duration (short/long) (all \( p > 0.10 \)). In the recognition test, all encoded word triads (100 coherent and 100 incoherent) were presented again together with new triads and subjects were asked to indicate for each triad whether it was old (i.e., encoded before) or new. Hits were defined as the percentage of old triads correctly recognized as old and false alarms were defined as the percentage of new triads falsely judged as old. The number of hits and false alarms was not different between the sleep group (hits: 45.20 ± 4.39%; false alarms: 14.57 ± 2.66%) and the wake group (hits: 51.60 ± 2.75%; false alarms: 14.65 ± 1.94%; both \( p > 0.22 \)) or between encoding duration (short/long) (all \( p > 0.51 \)). Across both encoding periods (short/long) and both groups (sleep/wake), participants recognized coherent triads (sleep: 47.06 ± 4.19%; wake: 53.63 ± 2.20%) better than incoherent triads (sleep: 43.33 ± 4.69%, wake: 49.84 ± 3.53%), main effect type of triad: \( F_{(1,28)} = 7.28, p = 0.012 \).

These findings show that, contrary to our hypothesis, sleep affected explicit and intuitive coherence judgments differently. When compared with the wakefulness retention interval, sleep resulted in a higher number of explicitly named common associates after sleep. The number of explicitly named common associates after sleep was significantly higher than the number in the wake group (sleep: 81.19 ± 4.69%; wake: 74.09 ± 3.93%; \( p = 0.048 \)).

Semantic associations that were only very weakly activated might even have become nullified after sleep, resulting in an accumulation of activation in the semantic memory network. This accumulation of activation during sleep may have helped the respective semantic concepts to cross the threshold of awareness, leading to an increase in the number of explicitly named common associates after sleep.

Semantic associations that were only very weakly activated before sleep, on the other hand, might have been weakened further and respective increases in connective strength from encoding might even have become nullified during sleep. It has been suggested that sleep has an important function not only in the strengthening of relevant information but also in the forgetting of irrelevant information (Crick and Mitchison 1983). The synaptic homeostasis hypothesis proposes that a central function of sleep is the restoration of synaptic homeostasis (Tononi and Cirelli 2006, 2014). While wakefulness is characterized by an increase in synaptic strength through constant learning, sleep renormalizes the overall synaptic strength in a process of “down-selection” (Tononi and Cirelli 2014). During this process, all synaptic connections become downscaled, while relatively strong connections might be downscaled to a lesser extent or might even be entirely protected from downsizing and very weak connections might be erased completely (Hashimi et al. 2013; Nere et al. 2013). Importantly, the basis for intuitive decisions is that weak activations of semantic concepts produce a feeling of coherence strong enough to decide upon intuitively even though no explicit reasons can be given. If sleep reduces or even eliminates these weak activations, there is not enough activation left to nurse the hunch necessary for intuition. Thus, sleep might help us extract explicit knowledge by strengthening sufficiently activated associations, but concurrently erases the basis for intuitive judgments by eliminating weakly activated associations.

Apart from the effect of sleep on explicit and intuitive judgments, we also observed a striking but unexpected effect of the encoding duration. With a longer encoding duration, participants produced fewer common associates as well as fewer intuitive coherence judgments compared with short encoding. In line with previous evidence, it could be speculated that the longer encoding duration led to deeper conscious processing of the word triads, which may have disrupted or interfered with early automatic semantic activation of the common associates (Topolinski and Strack 2008). This idea should be systematically tested in future studies.

A potential limitation of the present study relates to the comparison of nighttime sleep with daytime wakefulness and the corresponding circadian differences. Although we cannot fully exclude that circadian factors affected the present findings, we consider this unlikely as our control tasks (measuring general alertness, i.e., objective vigilance and subjective sleepiness) did not reveal any differences between groups. Moreover, a number of previous studies on sleep and memory, including one study on sleep and semantic processing, did not observe any circadian differences when directly controlling for such effects by introducing circadian control groups (e.g., Payne et al. 2008; Sio et al. 2013). As another potential limitation, it should be considered that the two measures assessing explicit solutions and intuitive judgments may not be entirely independent. Although both measures relied on different triad types and did not correlate, it is possible that the solved triads may have been somewhat easier, leaving the more difficult triads for the intuitive judgments. It is also possible that subjects judged certain triads as coherent intuitively at first, but then solved the triads within the time of giving the coherence judgment (yet this only rarely happened, in ~8% of triads on average). As a final limitation, with the present experimental design, we cannot disentangle potential mechanisms underlying sleep’s effect on semantic concepts. There are different possible scenarios how sleep may act on semantic processing: (1) sleep may strengthen the encoded words, increasing the likelihood that the common associate is generated spontaneously at testing, (2) sleep may directly strengthen the common associate that is generated already at encoding, (3) sleep may strengthen the associations between the encoded words and the concurrently activated common associate, or (4) sleep may directly generate the common associate via spreading (re-)activation of the encoded words, etc. These questions will be subject to future studies directly testing and manipulating potential influencing factors and mechanisms.

Acknowledgments

We thank Franziska Bröker for her help in data collection of the wake group as well as for her help in programming the vigilance
task. The authors also thank Elena Roson Roman for help in programming the coherence task. This project was funded by the Werner Reichardt Centre for Integrative Neuroscience (CIN) at the University of Tübingen (an Excellence Cluster within the framework of the Excellence Initiative EXC 307) as well as by the Collaborative Research Centre “Plasticity and Sleep” (TR-SFB 654), funded by the Deutsche Forschungsgemeinschaft (DFG).

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Received October 28, 2016; accepted in revised form August 25, 2017.