Sleep promotes analogical transfer in problem solving

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Abstract

Analogical problem solving requires using a known solution from one problem to apply to a related problem. Sleep is known to have profound effects on memory and information restructuring, and so we tested whether sleep promoted such analogical transfer, determining whether improvement was due to subjective memory for problems, subjective recognition of similarity across related problems, or by abstract generalisation of structure. In Experiment 1, participants were exposed to a set of source problems. Then, after a 12-hour period involving sleep or wake, they attempted target problems structurally related to the source problems but with different surface features. Experiment 2 controlled for time of day effects by testing participants either in the morning or the evening. Sleep improved analogical transfer, but effects were not due to improvements in subjective memory or similarity recognition, but rather effects of structural generalisation across problems.

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1. Introduction

To be an effective problem solver, one must apply learning from previous experiences to new contexts. This application of knowledge is not simply a function of recalling previous information, because two situations are rarely identical. Consider the problems shown in Figure 1. Applying the tree problem solution to the matchsticks problem requires remembering the initial solution, evaluating the similarity between the two problems, and restructuring the first solution to apply to the matchsticks (e.g., remapping trees to matchsticks, and the hill to constructing matches in a third dimension above the working surface). Thus, in addition to explicit information recall, one must identify the procedural steps that led to success in the previous event and adapt them to apply to the current context (Gentner & Markman, 1997; Holyoak, 2012). This process is referred to as analogical reasoning and has been considered as the major contributor to humans' mental agility (Gentner & Colhoun, 2010) and the bedrock of human cognition (Hofstadter, 2001).

Despite the importance of analogical reasoning to problem solving, people are notoriously poor at translating solutions from a previously attempted (source) problem to novel but structurally related (target) problems (Gick & Holyoak, 1980; Vendetti, Wu, & Holyoak, 2014). Unfortunately, people only effectively transfer if the source and target problems have a high degree of surface similarity (e.g., Bassock & Holyoak, 1989) or if attention is extensively and explicitly directed to the abstract schema underlying both the source and target problems' solutions (e.g., Catrambone & Holyoak, 1989). Consequently, discovering less intrusive means by which such transfer can be facilitated has become a major theoretical goal with important practical consequences.

There is good reason to believe that analogical transfer could benefit from something as simple as sleep. As analogical transfer depends in part on memory of the source problems, sleep can enhance transfer because sleep improves memory for previously experienced information (see Rasch & Born, 2013, for a review). Additionally, analogical transfer requires recognition of similarity between source and target problems, and sleep can assist in identifying similarities across experiences (Lewis & Durrant, 2011; Wagner, Gais, Haider, Verleger, & Born, 2004) subsequently creating a problem schema common to both source and target problems.

Here, we investigated whether sleep between exposure to source problems and related target problems improved analogical transfer. Previous studies of sleep have not tested transfer for complex problems with low surface similarities (e.g., Beijamini, Pereira, Cini, & Louzada, 2014; Cai, Mednick, Harrison, Kanady, & Mednick, 2009; Sio, Monaghan, & Ormerod, 2013; for review see Chatburn, Lushington, & Kohler, 2014). Further, we distinguished whether any facilitatory effects of sleep for problem solving were captured by subjective memory of the source problems or recognition of structural similarities between source and target problems (Experiment 1). We tested participants around their natural day-night sleep cycle which necessarily introduced a confound in time of day of testing. Experiment 2 ensured time of day was not driving the apparent effects of sleep from Experiment 1 (Fröberg, 1977).

2. Experiment 1: Effect of Sleep on Analogical Transfer

2.1. Method

2.1.1. Participants. Sixty students at Lancaster University (17 males, 43 females) with mean age 20.1 (*SD* = 1.6) years volunteered to participate in the study. Participants were randomly allocated to a sleep (7 males, 23 females) or wake group (10 males, 20 females). Sample size was determined from a study by Payne, Schachter, Propper, Huang, Wamsley et al. (2009), who tested effects of sleep on high-level memory processes with 30 participants in a sleep and a wake group (referred to in their paper as the "Merrimack" participants).

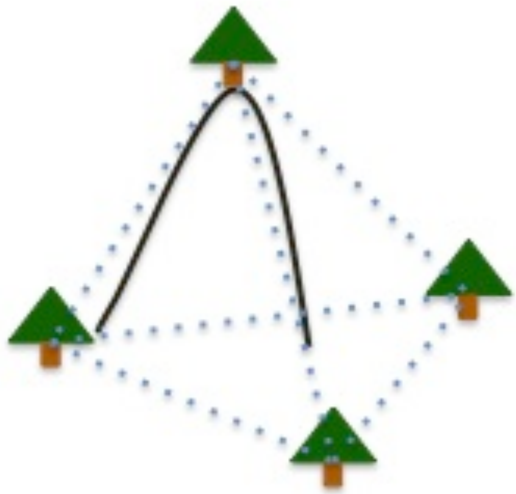
2.1.2. Materials. We selected 6 pairs of source and target problems from the analogical transfer literature (Gick & Holyoak, 1980; Gick & McGarry, 1992; Needham & Begg, 1991). Target and source problems had similar structural relations between problem information and solution, but different surface features (see Supplementary Materials for list of problems). An additional problem was used as a practice item.

We collected information on sleep habits and amount of sleep the night before the second session using a questionnaire, and also used the Stanford Sleepiness Scale (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973).

Subjective memory for source problems was measured using a questionnaire that asked participants how accurately they remembered the solution to each of the 6 source problems. Responses to each problem were on a 7-point Likert scale from 1 (don't remember) to 7 (remember accurately). We measured subjective recognition of similarity of source and target problems by asking participants the extent to which they noticed relations between pairs of problems, with a 7-point Likert scale from 1 (not similar) to 7 (very similar), adapted from Lockhart, Lamon, and Gick (1988). In both questionnaires, problems were referred to by very brief descriptions (e.g., referring to Figure 1 problem: "the problem about planting trees"). Questionnaires are available in Supplementary Materials.

Source problem: How can a gardener plant four trees so that the trees are equidistant? (Metcalfe & Weibe, 1997).

Answer: plant one on a hill



Target problem: Assemble six matches to form four equilateral triangles, each side of which is equal to the length of one match (Scheerer, 1963).

Figure 1. Example of a source and target problem in an analogical transfer task.

2.1.3. Procedure. There were two testing sessions, 12 hours apart. Participants in the wake group were tested between 9am and 10am in the first session, and between 9pm and 10pm on the same day for the second session. Participants in the sleep group were tested between 9pm and 10pm in the first, and 9am to 10am the next day for the second session. The wake versus sleep manipulation was conducted around participants' diurnal cycle, such that they either stayed awake or slept according to their usual sleep routine.

In the first session, participants were instructed to try to remember the solution to the problems they were attempting, as they might be relevant to later problems. Expectation of future memory use has been shown to enhance memory consolidation associated with sleep (Wilhelm et al., 2011). Each source problem was presented for 3 minutes on a computer screen, during which time participants wrote their workings and solution on paper. Then, participants were shown the answer, which they studied for 1 minute before the next problem was presented. Participants were asked to abstain from alcohol, caffeine and daytime naps during the course of the study, and to maintain their usual sleep and wake routine during the study. Participants then left the laboratory. All participants conformed to these requests, determined by self-report questionnaires at the second session.

In the second session, participants completed the sleep questionnaire, the Stanford Sleepiness Scale, and the memory for the source problems questionnaire. The 6 target problems were then presented on a computer screen for 3 minutes each, whilst participants wrote down their workings and solution on paper. Then, the source and target problem similarity ratings questionnaire was given to participants.

2.1.4. Scoring. Problem solutions were each scored by two researchers, using a 3-point ordinal scale, which indicated no, partial, or full solution (Hosenfeld, van der Maas, & van den Boom, 1997; Stevenson, Touw, & Resing, 2011; Tunteler, Pronk, & Resing, 2008), see Supplementary Materials for the precise coding scheme. Inter-rater reliability was assessed using weighted kappa (Fleiss & Cohen, 1973). For first session scores, $\kappa = .96$, for second session scores, $\kappa = .91$. The small number of scoring differences was resolved in further discussion between the scorers.

Table 1. Means and standard deviations of sleep and wake groups (Experiment 1) and morning and evening control groups (Experiment 2), for the first and second test session problem, and the subjective judgment measures.

Group	Source Problems		Target Problems		Sleep duration (hours)		Stanford Sleepiness		Memory Judgments		Similarity Judgments	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Wake	.29	.12	.36	.19	7.6	1.1	3.2	1.2	5.94	.96	5.54	.86
Sleep	.30	.17	.51	.23	6.4	1.8	2.8	1.3	6.06	.82	5.58	1.03
Morning	.26	.16	.27	.12	6.8	2.3	3.5	1.1	6.04	.59	4.55	.73
Evening	.40	.22	.34	.16	6.9	1.4	3.3	1.0	5.58	.90	4.93	.54

2.2. Results

The dependent variable was the proportion of the maximum possible score (out of 2) for each problem. Analogical transfer was indicated by target problem solution scores. Descriptive statistics are shown in Table 1. To test the effect of sleep, we conducted a repeated-measures ANOVA for the sleep versus wake groups, with question pair (1-6) as within subjects factor to control for variation across the problems, session (source or target problems) as within subjects factor accounting for individual variation in problem solving ability, and group (sleep versus wake) as between subjects factor.

There was a significant main effect of session, $F(1, 58) = 26.04$, $p < .001$, $\eta_G^2 = .14$, with performance in the second session better than the first session. There was a significant main effect of group, $F(1, 58) = 4.47$, $p = .039$, $\eta_G^2 = .05$, with sleep group performance better than the wake group. Critically, there was a significant interaction between session and group, $F(1, 58) = 5.77$, $p = .020$, $\eta_G^2 = .03$ (see Figure 2), with no differences between the sleep and wake groups in the first session, $t(58) = .36$, $p = .719$, $d = .10$, but higher scores for the sleep group compared to the wake group in the second session, $t(58) = 2.72$, $p = .009$, $d = .70$.

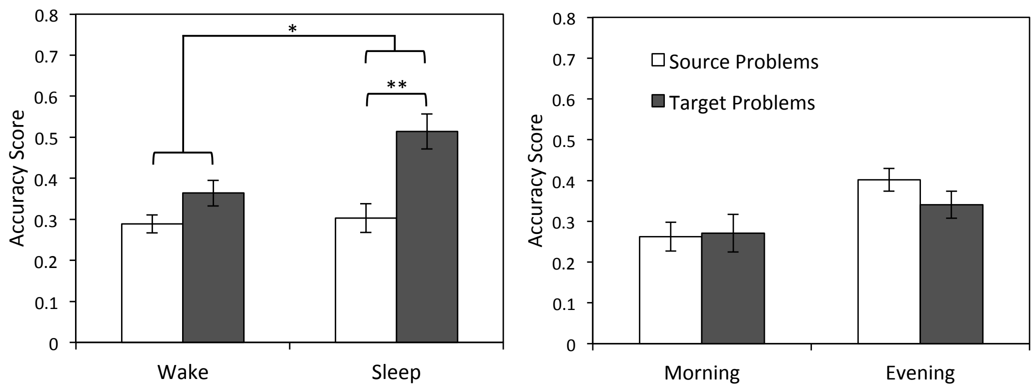


Figure 2. Mean accuracy scores per problem for source and target problems for (left panel) sleep and wake group in Experiment 1, and (right panel) morning and evening group in Experiment 2. Error bars show ±1 SEM. * indicates $p < .05$, ** $p < .01$.

In a follow-up ANOVA, we distinguished whether source problems were unsolved, or solved partially or fully as an additional factor. There were no significant main effects or interactions of source problem solution rates, all $F < 1$. Hence, providing the solution to participants was as effective in producing analogical transfer as the participant solving the problem independently. Under certain circumstances, not solving problems may even produce advantages for transfer (Gick & McGarry, 1992).

There was no significant difference in sleepiness scores between sleep and wake groups, $t(58) = 1.25$, $p = .217$, $d = .32$, but there was a difference in terms of sleep duration the night before the second test session (for the wake group this was amount of sleep the night before the day on which testing occurred), $t(58) = 3.10$, $p = .003$, $d = .80$. Sleep duration was significantly correlated with target problem scores in the sleep group (see Table 2), indicating a direct relationship between sleep and analogical transfer, but there was no such significant correlation for the wake group, and nor for the source problems (see Figure 3).

Table 2. Correlations between subjective judgment scores, sleep duration, and problem scores for the sleep and wake groups in Experiment 1, and the morning and evening control groups in Experiment 2.

Group	Source Problems	Target Problems
Wake		
Memory	.33*	.22
Similarity	.02	.17
Sleep duration	.19	.13
Sleep		
Memory	.15	.40*
Similarity	.12	.64***
Sleep duration	.02	.32*
Morning		
Memory	.07	.12
Similarity	-.35	-.04
Evening		
Memory	.16	.22
Similarity	.01	.12
All groups combined		
Memory	.11	.27**
Similarity	.27	.44***

Notes: Oneway: * $p < .05$, ** $p < .01$, *** $p < .001$. N is smaller for the morning and evening groups.

Table 2 also shows the correlations for subjective memory and similarity judgments. To test whether the effect of sleep was accounted for by enhanced subjective memory and similarity judgments, we conducted a mediation analysis that tested the effect of sleep versus wake on target problem scores, with memory and similarity judgments as mediating variables, and source problem scores as a covariate. The resulting models are shown in Figure 4. Sleep had a significant direct effect on target problem scores, which was not mediated by memory or similarity judgments. Using a bias-corrected bootstrapping procedure with 5000 resamples (Hayes, 2009), we found no significant change in direct relation between sleep or wake group and target problem scores with or without the mediating variables, 95% CI = [-.12, .08]. Sleep or wake group had no significant relation to memory or similarity judgment scores, but similarity judgments were significantly related to target problem scores. A further mediation model showed that the relation between source and target problem scores was not mediated by memory or similarity judgments using the same bootstrapping method, 95% CI = [-.09, .26], therefore justifying inclusion of source problem scores as a covariate, rather than a mediated variable.

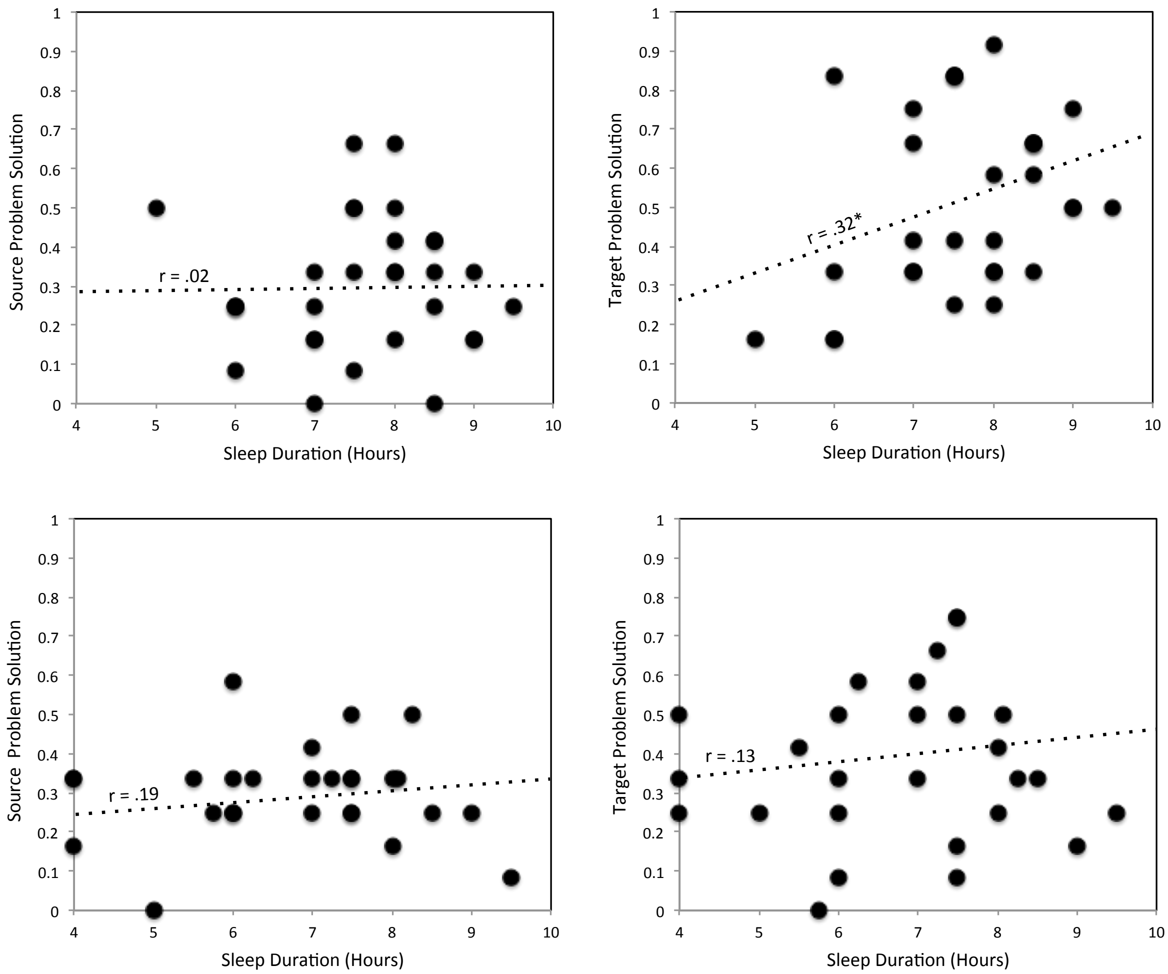


Figure 3. Scatterplots of relation for sleep duration with source and target problem scores for the sleep (upper row) and wake (lower row) groups in Experiment 1. For the correlations, * indicates $p < .05$.

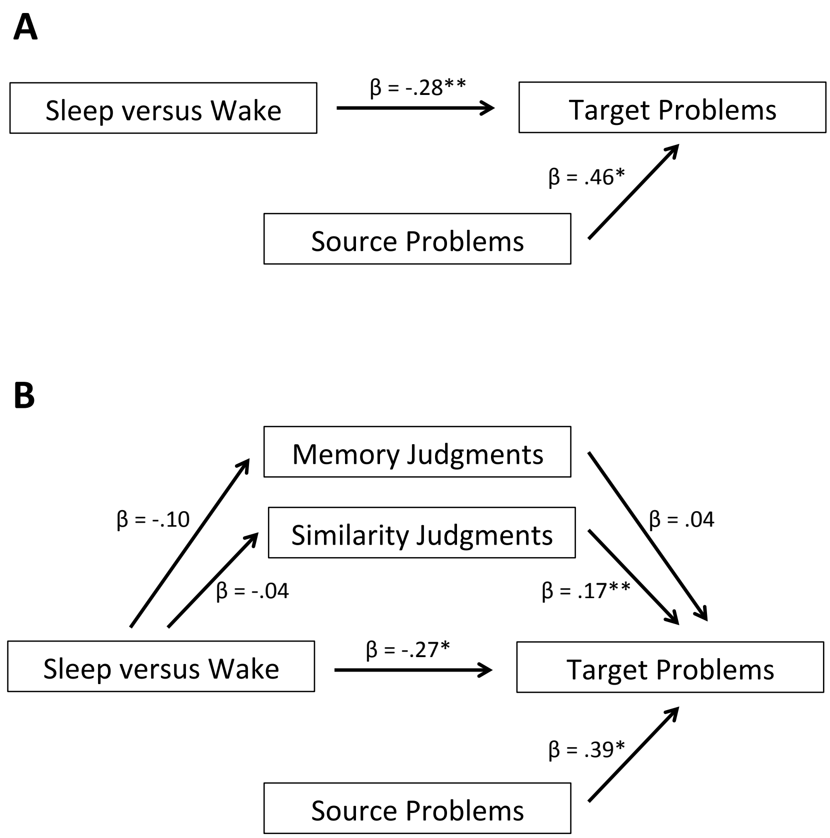


Figure 4. Effect of sleep versus wake on target problem scores (A) without and (B) with mediating variables of memory and similarity judgments in Experiment 1. Source problem scores are a covariate in the analysis.

3. Experiment 2: Effect of Time of Day on Analogical Transfer

3.1. Method

3.1.1. Participants. Forty-two students (11 male, 31 female) at Lancaster University participated for course credit. Mean age was 19.0, SD = 0.6. Participants were randomly assigned to a morning (N = 20, 6 male, 14 female) or an evening (N = 22, 5 male, 17 female) testing group. Again, sample size was determined from the evening/morning groups of Payne et al. (2009) Experiment 1, who were time of day controls for a sleep versus wake condition. Data collection was stopped when sample size in both conditions met the minimum of 20.

3.1.2. Materials. The Materials were identical to Experiment 1.

3.1.3. Procedure. The morning group participants were tested between 9am and 10am, the evening group were tested between 9pm and 10pm. The procedure was identical to Experiment 1, except that the first testing session, involving presentation of the source problems, was immediately succeeded by the second testing session, when the target problems were presented. Scoring was conducted in the same way as for Experiment 1 with two raters demonstrating reliable ratings, weighted $\kappa = .88$ for the source problems, and $\kappa = .95$ for the target problems.

3.2. Results

An ANOVA on problem solving scores, with group (morning or evening) and session (source problems, or target problems), and problem (to control for variation across the problems) as factors resulted in no significant effects of session, $F < 1$, but a significant effect of group, $F(1, 40) = 6.86$, $p = .012$, $\eta_G^2 = .09$, with higher scores overall in the evening than the morning group. Crucially, the interaction between session and group was not significant, $F(1, 40) = 1.06$, $p = .309$, $\eta_G^2 = .01$ (see Figure 2). Even though problem solving was higher in the evening group, the only group that demonstrated a significant improvement from source to target problems across both experiments was the sleep group. An omnibus ANOVA combining data from Experiment 1 and 2, with all four groups (sleep, wake, morning, evening), test session, and problem as factors resulted in a significant interaction between group and test, $F(3, 98) = 7.35$, $p < .001$, $\eta_G^2 = .08$. In Tukey's post hoc comparisons, the difference between source and target problems was larger for the sleep group than each of the wake, morning, and evening groups, $p = .085$, $p = .009$, $p < .001$, respectively. No other groups were significantly different, $p \geq .120$ The results demonstrate that sleep, rather than circadian effects, results in the enhancement of analogical transfer.

4. Discussion

Retrieving and identifying how previously encountered information applies to current situations is a challenging, but fundamental, task for human reasoning. Previous studies have shown that people require extended, overt instructions for them to effectively apply previously learned solutions to alternative situations that differ in their surface features (Catrambone & Holyoak, 1989; Gick & Holyoak, 1980; Kaminski, Sloutsky, & Heckler, 2013; Novick, 1988). Experiment 1 demonstrated that a 12-hour delay including sleep has a facilitating effect on such transfer compared to 12 hours awake.

Experiment 2 suggested that the improvement from source to target problem performance in the sleep condition was not due to circadian effects, because the sleep group demonstrated a significant increase in performance compared to the other three groups. However, the evening group demonstrated better performance for both source and target problems compared to the morning group. An alternative explanation for the effect of sleep could therefore be that participants perform better on problems in the evening, potentially resulting in better encoding of the source problems. However, this interpretation cannot explain why the sleep and wake groups did not differ on their source problem performance, nor why the evening group was unable to transfer solutions, i.e., no improvement in performance from source to target problems. The direct correlation between sleep duration and target problem solution for the sleep group would also require an additional explanation. Hence, analogical transfer being improved by sleep is the more parsimonious explanation of the data.

The mediation analyses demonstrated that the facilitating effect of sleep was not reducible to subjective memory of the source problems or similarity judgments about the relation between source and targe st problems, consistent with previous remote analogical memory studies that transfer can operate not only on surface similarities between problems (Wharton, Holyoak, Downing, Lange, Wickens, & Melz, 1994; Wharton, Holyoak, & Lange, 1996). However, self-report measures of memory are weakly correlated with objective memory measures (Chua, Schacter, Rand-Giovannetti, & Sperling, 2006), and future research testing objective memory for the source problems would provide a clearer picture of the role of memory in analogical problem solving. However, the mediation analyses did demonstrate that similarity judgments do predict target problem solution rates, and showed that this was in addition to the effect of sleep.

The effect of sleep on analogical transfer may then be at some other stage of processing than memory for previous problem information (Gentner & Colhoun, 2010; Knowlton, Morrison, Hummel, & Holyoak, 2012) and seems to be independent of explicit awareness of structural similarity. Though sleep has been found to improve explicit knowledge about structure of sequences in serial reaction time tests (Wilhelm, Rose, Imhof, Rasch, Büchel, & Born, 2013) and linguistic material (Batterink, Oudiette, Reber, & Paller, 2014) it may be that complex structural mappings do not become consciously available. We thus suggest that the effect of sleep appears to be more likely due to information restructuring. A possible mechanism for this is the sleep-dependent transfer of information from hippocampus to neocortex as a consequence of sleep (Diekelmann & Born, 2010), where new information is integrated with previous experience to highlight schemata that current problems share with previously solved problems (Chatburn et al., 2014). Experiencing a novel but related problem can then activate these previously stored relations between problem concepts and solution structures (Cai et al., 2009; Lewis & Durrant, 2011). As a consequence, broader semantic activations in long-term memory can be observed (Beijamini et al., 2014; Sio et al., 2013), enabling newly experienced problems to more effectively access consolidated associations in a schema that can apply to the current task.

An alternative account is that sleep instead protects against interference from additional stimulation (Mednick, Cai, Shuman, Anagnostaras, & Wixted, 2011). The wake group were exposed to the source problems, and then stayed awake conducting their normal daytime routine. They were therefore exposed to greater stimulation than the sleep group, which may have impeded analogical transfer of the problems. However, the wake group did not perform worse in terms of transfer than the morning and evening groups, indicating that interference during a 12 hour intervening period is no more of an impediment to transfer than no time at all between source and target problem presentation.

In these studies, we show that previously observed positive effects of sleep on problem solving extend to complex analogical transfer. It is apparent that lying down on the job has a role, and that sleep may well facilitate abstract restructuring of information affecting transfer of problem schemas, in addition to promoting memory for previously experienced information.

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