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BRIEF REPORT

Bedding down new words: Sleep promotes the emergence of lexical competition in visual word recognition

Hua-Chen Wang[1] · **Greg Savage**[1] · **M. Gareth Gaskell**[2] · **Tamara Paulin**[1] · **Serje Robidoux**[1] · **Anne Castles**[1]

Abstract Lexical competition processes are widely viewed as the hallmark of visual word recognition, but little is known about the factors that promote their emergence. This study examined for the first time whether sleep may play a role in inducing these effects. A group of 27 participants learned novel written words, such as *banara*, at 8 am and were tested on their learning at 8 pm the same day (AM group), while 29 participants learned the words at 8 pm and were tested at 8 am the following day (PM group). Both groups were retested after 24 hours. Using a semantic categorization task, we showed that lexical competition effects, as indexed by slowed responses to existing neighbor words such as *banana*, emerged 12 h later in the PM group who had slept after learning but not in the AM group. After 24 h the competition effects were evident in both groups. These findings have important implications for theories of orthographic learning and broader neurobiological models of memory consolidation.

Keywords Visual word recognition · Lexical competition · Word learning · Lexical consolidation · Sleep

Lexical competition is proposed to be a key mechanism supporting accurate and fluent visual word recognition. According to several models, when a printed word is presented to a reader, multiple word representations become active within an integrated lexicon in long-term memory and these representations compete with one another. Identification of the word is successful when one representation becomes dominantly active and suppresses the activity of other words (e.g., Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981).

Evidence for such a lexical competition mechanism has come from a range of sources (e.g., Andrews & Lo, 2012; Davis & Lupker, 2006; Grainger, O'Regan, Jacobs, & Segui, 1989). One key demonstration comes from the word-learning study of Bowers, Davis, and Hanley (2005; following the paradigm in the spoken word domain of Gaskell & Dumay, 2003). Here, adult participants learned a set of novel written words (e.g., *banara*) that were visually similar neighbors of "lexical hermits": familiar words with no existing neighbors (e.g., *banana*). At test soon after learning, participants were not significantly slower at performing semantic judgments on the familiar word neighbors (although there was a nonsignificant trend towards an effect). Interference grew significantly stronger across two subsequent tests the next day. Bowers et al. interpreted this finding as indicating that novel words such as *banara* had become increasingly integrated into the lexicon and in doing so had begun to compete with familiar words such as *banana* during the word recognition process.

An important unanswered question in relation to lexical competition effects in visual word recognition concerns when and how these effects emerge: When a new written word is learned, what factors promote the process by which that word becomes integrated into the lexicon and begins to interact with and influence the processing of other words? One possibility is that engagement in competition for new written words is supported by a sleep-associated memory consolidation process that leads to a stronger, more robust, or better integrated representation (Walker & Stickgold, 2010). The Bowers study included another training session between the later testing

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✉ Hua-Chen Wang
huachen.wang@mq.edu.au

[1] Department of Cognitive Science, ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Sydney, NSW 2109, Australia

[2] Department of Psychology, University of York, Heslington, York, UK

points, making it hard to tease apart effects of training versus time or sleep. A subsequent study using similar methods (Bakker, Takashima, van Hell, Janzen, & McQueen, 2014; Experiment 3) also found competition effects 24 h after training with no effect soon after learning, but once again the key interaction that might implicate a role of consolidation was not significant. Thus, both the above studies hint at a role for consolidation in the engagement of new words in lexical competition, but convincing evidence is lacking, and neither of the above studies attempted to separate the roles of sleep and time.

Studies of spoken words have been more revealing. Dumay and Gaskell (2007) examined the effect of a period of sleep on lexical competition within a spoken-word learning paradigm. They presented novel spoken items to two groups of adult participants: one in the evening and the other in the morning. Learning was measured 12 h after initial exposure, with the evening group sleeping in the intervening period and the morning group remaining awake. The results revealed the emergence of lexical competition in the evening but not the morning group, suggesting that, at least for spoken language acquisition, a period of sleep promotes the consolidation process.

Several studies have provided further evidence for the effect of sleep on consolidation of spoken word learning, in both adults (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010) and children (Henderson, Weighall, Brown, & Gaskell, 2012). These effects have been interpreted in the context of Complementary Learning Systems theory (McClelland, McNaughton, & O'Reilly, 1995; O'Reilly & Norman, 2002). This theory proposes a dual learning process whereby new information is initially encoded temporarily in the hippocampus, and then subsequently transitions to more stable, long-term representations in the neocortex. In particular, the word learning studies suggest a process of transition from hippocampal to neocortical lexical memory systems, facilitated by sleep (Davis & Gaskell, 2009).

In light of these findings in the oral language domain, it seems reasonable to predict that sleep might play a similar role in visual word recognition. However, this is by no means certain. For a start, an emerging literature on consolidation effects in spoken word learning has led to a rich pattern of results, with some hallmarks of lexical status emerging straight after learning, others emerging after a night's sleep, and still others requiring a longer consolidation profile (McMurray, Kapnoula & Gaskell, 2016). Where visual lexical competition might fit into this array of possibilities is hard to predict, but important to know so that we can better understand the relationship between consolidation and lexical integration. Lexical competition processes in written and spoken word recognition have quite different properties. Written word competition is thought to be processed extensively in a parallel way where all letters of a word are immediately available, whereas spoken word competition is more constrained by the sequential availability of auditory input (Gaskell & Dumay, 2003).

Furthermore, the competition paradigm developed by Bowers and colleagues is of particular interest as it has revealed immediate competition effects in a recent study using a style of learning known as "fast mapping." Coutanche and Thompson-Schill (2014) showed that when a new written word was learned in the context of one novel and one known referent (e.g., an unfamiliar insect and a cricket) using a mutual exclusivity inference (e.g., "Are the antennae of the *banara* pointing upwards") enhanced inhibition in recognition of the hermit neighbor (e.g., *banana*) was observed immediately. Partly through contrasting their results with the auditory literature described above, Coutanche and Thompson-Schill argued for a dissociation in the consolidation profile of fast mapped and explicitly encoded items. However, given the many differences between the methods and stimuli used in the auditory and visual studies, the exact cause of that dissociation remains unclear. Therefore it becomes even more important to find out what the consolidation profile is for explicitly learned words in terms of visual lexical competition.

The present study adapted the design of the Bowers et al. (2005) written word learning experiment to include a sleep manipulation: Adult participants learned novel words and were then tested for the emergence of lexical competition effects using a semantic categorization task. We hypothesized that competition effects would become evident after a period of sleep, but not after a corresponding period of time during which sleep did not occur. We also assessed participants on their explicit free recall of the learned items and predicted based on previous findings that sleep would benefit overall retention (e.g., Dumay & Gaskell, 2007).

Method

Participants

Sixty-five undergraduate students (*M* age = 21.5 years, *SD* = 5.6 years; 42 females) were recruited from Macquarie University for course credit. All participants were native English speakers and had no history of learning or sleep-related disorders. The sample size was based on Bowers et al. (2005), where a significant effect was found with a group of 30 participants. We doubled this number as we had two groups of participants (sleep/no sleep), and added five to guard against potential data loss.

Material

Bowers et al.'s list of 40 low frequency, six-letter hermit words was used, with 20 of them categorized as naturally occurring entities (e.g., *banana*) and 20 as man-made artefacts (e.g., *anchor*). A second list of 40 novel words to be learned contained one substituted letter of the 40 hermit words (e.g., *banara* vs. *banana*). In addition, a list of 40 distractor items (six letters long and matched in frequency) was used for the semantic categorization task.

The 40 novel words (e.g., *banara*) were divided into two lists. Each participant learned 20 novel words from one of the two lists, with the two lists randomly assigned to participants and counterbalanced across groups. The important assumption here is that once the participants had learned the 20 novel words (e.g., *banara*), their one-letter-different hermit word neighbors (e.g, *banana*) became non-hermits (Non-hermit condition), and the other 20 unlearned novel word items remained hermits (Hermit condition). If learning and lexical consolidation takes place, words in the Non-hermit condition should produce lexical competition, showing slower semantic categorization times than those remaining in the Hermit condition.

Procedure and design

The experiment consisted of three sessions across two consecutive days, with each session taking place at 12-h intervals (see Table 1 for a summary of the experiment). Session 1 involved the training of the novel words followed by measures of how well the novel words had been learned and consolidated. The test measures included a semantic categorization task to measure lexical consolidation indexed by a lexical competition effect, and a free recall task to measure explicit memory of the learned items. Sessions 2 and 3 involved only test measures (i.e., the semantic categorization task and free recall task), with no further training or exposure on the learned novel words.

Following Dumay and Gaskell (2007), we manipulate whether sleep occurred after learning, and participants were randomly assigned into two groups: the PM group and the AM group (see Table 1). The critical comparison was performance of the two groups at Session 2, with one group having slept and the other group not. In order to rule out the possibility that any difference in learning was due to the fact that the two groups learned the novel words at different times of the day, a third session (Session 3) took place 12 h after Session 2, by which time the AM group had also slept (following Dumay & Gaskell, 2007). All stimuli were presented in 20 point Times New Roman font using the DMDX software (Forster & Forster, 2003).

Training Participants were instructed that a novel word that they had not seen before would appear onscreen and that they should type the word they saw as quickly and accurately as possible. The participants were also told to try and remember the novel words as they would be asked about them later. The novel word remained onscreen until the participant began typing. The participant was able to see the letters they typed, and they could use the backspace key to correct any errors. By the end of the typing task, participants had typed each of the 20 novel words ten times in total. The novel words were presented in blocks and the order of presentation was randomized.

Test and retest The participants were asked to complete a semantic categorization followed by a free recall task during test and retest.

Semantic categorization Participants were instructed to press keys to decide whether a word appearing on the screen should be classified as a naturally-occurring entity or a man-made artefact. Each trial began with a central fixation point (+) displayed for 800 ms, followed by a blank screen for 350 ms, and then the target word in the centre of the screen displayed for 500 ms. Participants were instructed to respond as quickly and accurately as possible. Feedback was provided at the end of each trial, and response latencies were recorded.

Free recall Participants were instructed to write down as many of the novel words from the typing task as they could remember. They were given a time limit of 3 min to complete the task. A score of 1 was allocated for each word correctly spelled, with 20 as the maximum score.

Activity logs After Session 1, the AM group were told not to nap during the day and the PM group to have at least 6 h of sleep (following Szmalec et al., 2012). The participants were also told that they would be asked to fill out a questionnaire regarding their overnight sleep activity (after Session 2 for the PM group and Session 3 for the AM group). The questionnaire included their number of hours of sleep on the night,

Table 1 Overview of the experimental procedure

	Day 1				Day 2		
	8 am		8 pm		8 am		8 pm
PM group			Session 1 (Train, Test)	*sleep*	Session 2 (Retest)	*awake*	Session 3 (Retest)
AM group	Session 1 (Train, Test)	*awake*	Session 2 (Retest)	*sleep*	Session 3 (Retest)		

whether the sleep was interrupted, and the quality of sleep (*poor, fair, good*).

Results

Participants who did not attend all three sessions were excluded from the analysis ($N = 4$). Following the criterion of Szmalec et al. (2012), participants were also excluded for having had less than 6 h sleep overnight to avoid fatigued responses ($N = 2$), or sleep that was rated as *poor* ($N = 1$). For the semantic categorization task, trials with reaction times (RTs) less than 300 ms and more than 1,500 ms were removed from the analyses (4 % of trials), subjects making greater than 20 % errors were excluded ($N = 1$; following Bowers et al., 2005), and items with greater than 20 % errors on average were excluded ($N = 4$, *tendon*, *pebble*, *meadow,* and *galaxy*). The number of hours of sleep in the two groups did not differ ($M = 7.02$ h, $SD = 0.85$, and $M = 7.33$ h, $SD = 0.41$, respectively), $F(1, 40) = 1.43$ $p = .24$, $\eta_p^2 = .03$, and neither did self-rated sleep quality ($M = 2.82$, $SD = 0.39$, and $M = 2.80$, $SD = 0.41$, respectively), $X^2(1) = .02$, $p = .88$.

In the following sections, we first report how well the participants retained the trained items over time in the free recall task. Following this, we report on the results of the key investigation of the emergence of lexical competition effects in the semantic categorization task.

Free recall We predicted that sleep would benefit retention and hence that the PM group would show better retention between Sessions 1 and 2 than the AM group. Between Sessions 2 and 3 we predicted the reverse: More forgetting in the PM group (who spent this time awake) than the AM group (who now had an opportunity to sleep). Mean numbers of items recalled are shown in Fig. 1. The free recall data were not scored on an item level and hence the data were analyzed using General Linear Models. There was a main effect of time, $F(2,54) = 23.82$, $p < .001$, $\eta_p^2 = .31$; an interaction between session (Session 1/Session 2/Session 3) and group (no sleep/sleep), $F(2, 54) = 7.44$, $p = .001$, $\eta_p^2 = .12$; and no main effect of Group, $F < 1$. Based on the prior predictions, we further analyse the interactions between group by both Sessions 1 and 2, and Session 2 and 3. We found that the predicted interaction for Session 1 and 2 was significant, $F(1, 55) = 15.54$, $p < .001$, $\eta_p^2 = .22$, reflecting the fact that the decline in performance between Sessions 1 and 2 was larger for the AM group ($M = 2.89$, $SD = 2.17$) than the PM group ($M = 0.79$, $SD = 1.80$). For Session 2 and 3, the predicted reverse interaction between session and group was significant, $F(1, 55) = 8.72$, $p = .005$, $\eta_p^2 = .14$. The performance over time suggested that sleep aided retention, and this was reflected in a quadratic trend over sessions for the AM group, $F(1, 26) = 60.11$, $p < .001$, $\eta_p^2 = .70$, but a linear trend for the PM group over three sessions, $F(1, 28) = 6.29$, $p = .018$, $\eta_p^2 = .22$.

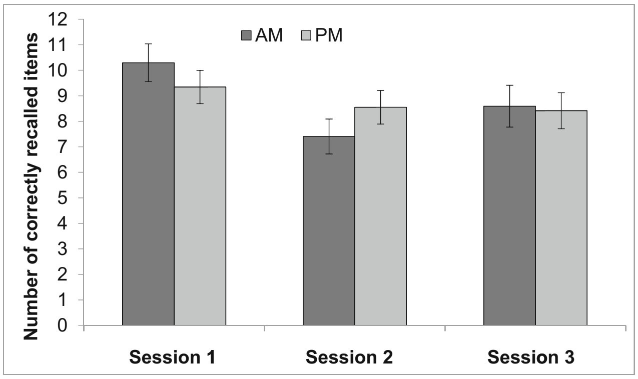

Fig. 1 The mean free recall scores for both the PM and AM groups across sessions. Error bars represent standard errors

Semantic categorization This task assessed the emergence of competition effects, and whether these were modulated by sleep. Our predictions were that: (1) there would be a three-way interaction between group (sleep/no sleep), competition (non-hermit/ hermit), and session (1 vs. 2); (2) this three-way interaction would be characterized such that the effect of competition would be larger in Session 2 than in Session 1, but only for the PM group; (3) since all participants would have slept by Session 3, the two-way interaction present during Session 2 would disappear in Session 3.

Reaction times (RTs) for the semantic categorization task are shown in Table 2 and the differences in mean RT between the non-hermit and hermit conditions are shown in Fig. 2. The RT data were log transformed for a more normally-distributed pattern based on visual observation. These data were analyzed with linear mixed-effect models using the lme4 package in R. We followed Barr, Levy, Scheepers, and Tily (2013)'s suggestion and included a maximal model structure, where random intercepts and slopes were included for each fixed effect, and interactions when appropriate in the context of the experimental design. However, the maximal model for this experimental design failed to converge so we removed one random effect at a time for the next maximal model. The final model we used included fixed effects of group, competition, session, and all of the interactions between these fixed effects (see Appendix

Table 2 Mean reaction times (RTs; in ms, with standard deviations in parentheses) for the non-hermit and hermit conditions in the PM and AM groups across sessions

	Session 1		Session 2		Session 3	
	AM	PM	AM	PM	AM	PM
Non-hermit	719 (120)	709 (111)	637 (103)	749 (171)	655 (127)	715 (141)
Hermit	705 (112)	719 (125)	635 (111)	686 (121)	612 (94)	655 (115)

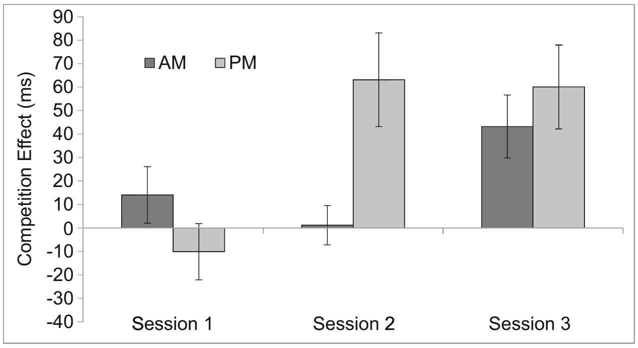

Fig. 2 The lexical competition effect (non-hermit-hermit mean reaction times) for the PM and AM groups across sessions. Error bars represent standard errors

for the full model, parameter estimates, and statistics for all of its effects).

We undertook planned contrasts to test each of our predictions. First, we predicted that the competition effect would differ between Sessions 1 and 2 as a function of group. We found a three-way interaction between group, competition, and session (1 vs. 2, z = 3.34, p = .003). Second, we unpacked the interaction based on our predictions by conducting two further contrasts. As predicted, the three-way interaction reflected the fact that the interaction between group and competition was significant in Session 2 (z = 3.99, p <.001) but not in Session 1 (z = 0.77, p = .550). The final planned contrast tested the prediction that by Session 3, the interaction between group and competition would not be significant, which was what we found, z = 1.09, p =.550. The p-values for these four contrasts were adjusted using the Holm-Bonferroni sequential correction for multiple comparisons.

Discussion

This study investigated the role of sleep in the emergence of lexical competition effects in visual word recognition. Replicating Bowers et al. (2005), we found that semantic categorization times for words like *banana* were slower after participants had learned novel neighbor words like *banara* than they were prior to those words having been exposed. Building on the findings and paradigm examining sleep effect in novel spoken word learning by Dumay and Gaskell (2007), the present study demonstrated for the first time that sleep also modulates the emergence of lexical competition in the visual word domain. Twelve hours after learning, lexical competition was observed in the group that had experienced an intervening period of sleep, but not in the group that had remained awake. Importantly, when the semantic categorization task was administered again on the subsequent day, after both groups had slept, both then showed evidence of lexical competition. Explicit free recall of the learned items also benefited from an interval of sleep soon after learning.

Our findings are consistent with those of Bowers et al. (2005) and Qiao and Forster (2013), showing that the acquisition of novel words can induce increased lexical competition in the recognition of existing neighboring words. They also offer support for models in which lexical competition is represented as a key feature of an integrated visual word recognition system (e.g., Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981). More broadly, together with previous studies on the effect on sleep on novel word learning, the findings provide support for a Complementary Learning Systems account of memory consolidation, in which the process of transition from hippocampal to neocortical memory systems is proposed to be facilitated by sleep (McClelland et al., 1995; O'Reilly & Norman, 2002).

It is worth noting that the paradigm used by Bowers et al. (2005) has not been universally accepted as a pure test of lexical competition. Qiao, Forster, and Witzel (2009) argued that the effect could instead be explained in terms of the impact of an episodic memory for the novel word triggering a post-access spelling check on the highly similar written word, leading to delays in response. Such an interpretation would need to explain why the episodic memory initially learned in training did not initially show an interference effect at first test in the Bowers study but then showed a stronger effect later on (with a 17-ms nonsignificant effect soon after learning growing to 33 ms and 48 ms in tests the next day). Possibly the initial episodic representation was too weak to show reliable effects at first but was then bolstered by further training on Day 2 and perhaps consolidation as well. However, the design and results of the current experiment are much harder to explain in this way. There was only one training session at the beginning of the experiment, and this led to good episodic memories of the novel words, as attested by the free recall data in Session 1. In fact, performance in Sessions 2 and 3 suggested some weakening of these episodic memories, with the effect of sleep being one of protection against loss rather than enhancement. Therefore, the episodic interpretation would predict the strongest competition effects for both groups in Session 1, with gradually weakening of effects in Sessions 2 and 3. As Fig. 2 shows, the reverse is in fact closer to the truth, with no competition effect for either group in Session 1, and increasing effects across session, strongly modulated by sleep. The current results therefore provide good evidence that the semantic categorization test is a suitable test of engagement in lexical competition for written words (see also Dumay & Gaskell, 2012, for parallel arguments in the auditory domain).

In demonstrating for the first time a sleep effect on visual word learning, the current study extends research on the influence of sleep on oral vocabulary learning (Dumay & Gaskell, 2007; Gaskell et al., 2014; Henderson et al., 2012; but cf. Szmalec et al., 2012). The evidence that sleep promotes the emergence of lexical competition within both of these domains suggests that the consolidation process operates in a broad modality-general fashion. In line with this idea, a recent study by Bakker et al. (2014) examined whether lexical competition effects can transfer across modalities. They presented novel words in their auditory forms and found evidence for lexical competition effects on the written form of those novel words (and vice versa when the words were presented in written forms and lexical competition was measured for auditory forms). Alternatively, instead of arguing that the sleep effect is domain general, it is also possible that there are two distinct sleep mechanisms promoting the emergence of visual and auditory lexical competition. It would be valuable for future research to examine the specific components of sleep that promote engagement in lexical competition across modalities.

As mentioned earlier, many aspects of lexical learning do not depend on a sleep-associated consolidation period (McMurray et al., 2016), and the challenge has now become to understand which properties do depend on sleep and why. The current results are beneficial in that they add to the evidence base supporting the association between sleep-associated consolidation and engagement in lexical competition. They are also useful in helping to understand the impact of learning style on consolidation profile. Specifically, the comparison between our study and Coutanche and Thompson-Schill (2014) is revealing because the studies are highly similar: They used the same written materials and the same test of lexical competition but differ on how the materials were learned. As described above, Coutanche and Thompson-Schill found that fast-mapping learning led to immediate lexical competition, whereas our study has revealed delayed, sleep-associated competition for more explicit or intentional learning. The delayed effects of explicit learning are easily explained in terms of a complementary systems account in which the hippocampus is recruited for the short-term retention of new words prior to sleep, whereas fast mapping may be able to exploit learning mechanisms that are less dependent on the hippocampus (Sharon, Moscovitch, & Gilboa, 2011; although cf. Warren & Duff, 2014). Potentially, the ability of fast mapping to circumvent the hippocampus and the consolidation process is due to the new word latching onto and modifying the representation of the known semantic neighbor that is presented during learning. If modifications to an existing representation can provide some (perhaps temporary) means of supporting retention of the novel item then there is less need for the hippocampus to become involved in the initial acquisition process (see also Mirković & Gaskell, 2016). However this intriguing dissociation is explained, our findings strengthen the case that the norm in terms of written and spoken word learning involves an initial encoding of the new word, followed by sleep-associated consolidation (Axelsson, Williams, & Horst, 2016).

In addition to the semantic categorization task to index lexical competition, we also included a free recall task to index explicit recall of the novel words, and found sleep to be of benefit here as well. A facilitatory effect of sleep on the recall of previously learned items has been reported in several memory studies (Benson & Feinberg, 1975; Idzikowski, 1984; Lahl, Wispel, Willigens, & Pietrowsky, 2008) and the findings also align with demonstrations of a benefit of sleep in learning novel spoken words using recall tasks (Dumay & Gaskell, 2007, 2012; Kurdziel & Spencer, 2015). Here, we found that sleep after learning appeared to prevent decay of episodic memory for the newly learned items, and eventual sleep in the AM group arrested apparent decay, with some suggestion of improved recall to a level shown by the PM group. These findings are consistent with Dumay (2016), suggesting that sleep not only prevented forgetting but also improved access to previous encoded items (but cf. Schreiner & Rasch, 2016). Our demonstration of sleep-dependent establishment of lexical representations together with an impact on episodic recall of new vocabulary suggests a close relationship between the consolidation processes for these two types of learning.

In sum, the present study provides strong evidence that sleep, and not just the passing of time, facilitates the emergence of lexical competition in written word learning. As well as demonstrating that the influence of sleep can be extended across auditory and visual modalities, it provides key support for the proposal that lexical competition is a hallmark of skilled visual word recognition. More practically, it provides important guidance as to the optimal conditions for learning and retaining new written words.

Appendix

Table 3 Maximal model = lmer (log(rt)~(session1v2.c+session3v12.c)*group.c*competition.c+ ((session1v2.c+session3v12.c)*competition.c|subj)+(group.c*competition.c+(session1v2.c+session3v12.c) |item), data=sleep, control=lmerControl (optimizer="bobyqa"))

Fix effects	Estimate	Std. error	df	t	Pr(>|t|)	
(Intercept)	6.4940	0.0218	69.71	297.778	1.00E−05	***
Session1v2.c	−0.0564	0.0149	61.38	−3.787	0.000	***
Session3v12.c	0.0704	0.0147	56.33	4.787	1.27E−05	***
Group.c	0.0623	0.0410	56.40	1.522	0.134	
Condition.c	−0.0377	0.0100	52.49	−3.767	0.000	***
Session1v2.c:Group.c	0.1074	0.0281	55.54	3.828	0.000	***
Session3v12.c:Group.c	−0.0194	0.0286	55.09	−0.678	0.501	
Session1v2.c:Competition.c	−0.0356	0.0159	55.71	−2.231	0.030	*
Session3v12.c:Competition.c	0.0687	0.0181	87.70	3.803	0.000	***
Group.c:Competition.c	−0.0220	0.0201	51.81	−1.096	0.278	
Session1v2.c:Group.c:Competition.c	−0.1063	0.0318	55.07	−3.344	0.001	**
Session3v12.c:Group.c:Competition.c	−0.0094	0.0361	87.17	−0.260	0.795	

To improve interpretability of the parameters, all variables were contrast coded. Since session consisted of three levels, two contrast-coded variables were necessary. To ensure they were orthogonal, these two variables were coded as Session 1 vs. Session 2 (session1v2.c) and Session 3 vs. the average of Sessions 1 and 2 (session3v12.c). This coding scheme was selected to allow us to generate specific contrasts to test our a priori hypotheses

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