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Markers of automaticity in sleep-associated consolidation of novel words

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ABSTRACT

Two experiments investigated effects of sleep on consolidation and integration of novel form-meaning mappings using size congruity and semantic distance paradigms. Both paradigms have been used in previous studies to measure automatic access to word meanings. When participants compare semantic or physical font size of written word-pairs (e.g. BEE–COW), judgments are typically faster if relative sizes are congruent across both dimensions. Semantic distance effects are also found for wellestablished words, with semantic size judgements faster for pairs that differ substantially on this dimension. English-speaking participants learned novel form-meaning mappings with Mandarin (Experiment 1) or Malay (Experiment 2) words and were tested following overnight sleep or a similar duration awake. Judgements on English words controlled for circadian effects. The sleep group demonstrated selective stronger size congruity and semantic distance effects for novel word-pairs. This benefit occurred in Experiment 1 for semantic size comparisons of novel words, and in Experiment 2 on comparisons where novel pairs had large distances and font differences (for congruity effects) or in congruent trials (for semantic distance effects). Conversely, these effects were equivalent across sleep and wake for English words. Experiment 2 included polysomnography data and revealed that changes in the strength of semantic distance and congruity effects were positively correlated with slow-wave sleep and sleep spindles respectively. These findings support systems consolidation accounts of declarative learning and suggest that sleep plays an active role in integrating new words with existing knowledge, resulting in increased automatic access of the acquired knowledge.

1. Introduction

The idea that sleep benefits declarative learning stems from research on memory consolidation, which describes the process whereby a new memory representation becomes more resistant to forgetting over time (Stickgold and Walker, 2005). The active role of sleep in declarative memory consolidation is often explained by two-stage systems consolidation models (Frankland and Bontempi, 2005; McClelland, McNaughton, and O'Reilly, 1995), which incorporate both hippocampal and neocortical memory components. In these models, the hippocampal system encodes information swiftly, whereas the neocortical system is a slower learning, longer-term repository that gradually integrates new knowledge with existing long-term memories (Frankland and Bontempi, 2005; O'Reilly and Norman, 2002). In an offline state, such as sleep, new memory representations are reactivated in the hippocampal system to promote neocortical storage. After multiple overnight cycles of offline reactivation, memory representations may become independent of the hippocampal system (Diekelmann and Born, 2010). Although there is debate over the aspects of sleep architecture involved in memory consolidation (Inostroza and Born, 2013), both slow-wave sleep (SWS) and sleep spindles (11–15 Hz activity in non-rapid eye movement (NREM) sleep) have been hypothesised to play an important role in the reactivation of memories in systems consolidation models (for reviews see Diekelmann and Born, 2010; Rasch and Born, 2013).

Although a link between sleep and the strengthening of new declarative memories is well established, few studies have examined the integration of new information into existing memory networks through the association between new and existing knowledge. In a novel-word learning experiment, Dumay and Gaskell (2007) provided evidence for the benefit of sleep on integration of new information with existing knowledge in a study that examined whether learning novel spoken word forms (e.g. "cathedruke") would inhibit the recognition of familiar words (e.g.

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"cathedral"). Such an effect would suggest that the novel word had been integrated with existing neocortical knowledge, thus influencing the normal process of lexical competition in spoken word recognition (Gaskell and Dumay, 2003). This inhibitory effect on recognition of familiar words was absent soon after learning the novel forms, but emerged only after participants had slept overnight. These results suggest that the process of integrating new knowledge with existing knowledge is associated with sleep, in line with a systems consolidation account[3]. Using a similar paradigm, Tamminen et al. (2010) found that components of sleep may play specific roles in consolidation and integration of novel word forms. SWS was related to the strengthening of individual word memories in a speeded recognition memory test, whereas the inhibitory effect of the novel words on their existing neighbours during recognition was found to be correlated with spindle activity, suggesting that sleep spindles may play a crucial role in integrating novel words with existing lexical knowledge.

One way of thinking about the inhibitory effect discussed above is that it represents a change in the degree of *automaticity* involved in the access to the novel word form following sleep. Integration in the neocortex may enhance the automatic activation of the novel word when similar words are encountered. Automaticity is often thought of as a graded phenomenon, associated with a cluster of overlapping features. One description of such features is provided by Moors and De Houwer (2006), who analysed eight features characteristic of automatic processing: unintentional, purely stimulus driven, uncontrollable, autonomous, goal-independent, unconscious, efficient and fast. Depending on the nature of the task being investigated, these eight features may be present and relevant to different extents.

The motivation for the present work was to test directly whether sleep enhances aspects of automaticity in the access of newly learnt information as a result of integration. We examined putative evidence for automaticity in the context of access to word meaning. This might be expected as a consequence of systems consolidation (consolidation of new information from the hippocampal networks into existing neocortical networks) that results in a more direct route to accessing word meanings (Davis and Gaskell, 2009). Furthermore, while previous work has shown evidence of sleep affecting integration of novel forms (e.g. Dumay and Gaskell, 2007; Tamminen et al., 2010), here we seek to provide evidence for integration and/or automaticity in the context of form to meaning mappings.

Two paradigms that are argued to demonstrate aspects of automatic access to word meanings are size congruity and semantic distance effects. When given the task to select the larger of two written words presented next to each other (i.e. physical size of font) or the larger of the referents of the words (semantic size), correct judgments are faster when the relative sizes are congruent (e.g. BEE–COW) as opposed to incongruent (e.g. BEE–COW) along the physical and semantic dimensions (Paivio, 1975). This is known as the size congruity effect. In contrast, the semantic distance effect describes the result that response times (RTs) are faster for relative size judgements when the referents of the words have large size differences (e.g. BEE–COW) compared with referents that are closer (e.g. BEE–DOG) on the relevant dimension-in this case the size of the animal (Moyer and Landauer, 1967; Van Opstal et al., 2008). Rubinsten and Henik (2002) investigated both effects by showing participants animal word-pairs that differed in physical font size and semantic size. The semantic distance effect was found in semantic comparisons only, whereas the size congruity effect was found in both physical and semantic comparison tasks. Rubinsten and Henik argued on the basis of these findings that meanings were rapidly and automatically activated during the word recognition process. Relating these two effects to the features of automaticity described above (Moors and De Houwer, 2006), both effects can be thought of as measures of efficiency and speed, as well as perhaps the level of controllability. The size congruity effect goes further in that it involves interference from an unattended variable, and so addresses features such as intentionality, goal-independence and autonomy. As such, the occurrence of the size congruity effect can be interpreted as revealing a greater level of sensitivity to automatic semantic access than the semantic distance effect (Rubinsten and Henik, 2002; Tzelgov et al., 1992; Tzelgov, 1999).

In the current paper, we used these properties of the size congruity and semantic distance effects to investigate the relationship between sleep and features of automaticity in the integration of new words into existing neocortical memory systems. We used a second language learning paradigm in which the novel forms share meanings with existing words in the participant's first language. Drawing from second language models such as the Revised Hierarchical Model, prior to integration, the relationship between the novel word forms and their meanings is hypothesised to be indirect and mediated by the translation from the existing word form (Kroll, Hell, Tokowicz, & Green, 2010) whereas it is plausible that after sleep-associated integration the access to the novel word's meaning is more direct (cf. Geukes et al., 2015). Another explanation relating to the complementary learning systems (CLS) account (Davis and Gaskell, 2009) of word learning suggests that when acquiring a second language (Lindsay and Gaskell, 2010), form-meaning cortical links for novel words are mediated by the hippocampal system during initial exposure. In this model it is predicted that after sleep-associated integration, there is a reduction in hippocampal mediation and a strengthening of more direct cortical links, resulting in more efficient and automatic access to the meanings.

2. Experiment 1

Using size congruity and semantic distance effects as hallmarks of established word representations, Experiment 1 explored the relationship between sleep and automaticity in novel word learning. Participants associated new Mandarin words with English animal names in the evening (sleep group) or morning (wake group), and were tested approximately 12 h later after a night of sleep or an equivalent time awake (see Fig. 1 for a summary of the design). It was hypothesised that if sleep benefits consolidation and integration of novel form-meaning pairings and more direct automatic access to those meanings, then participants who slept between learning and test would show greater semantic distance and size congruity effects than the wake group. Participants were also tested in the same way on established English words that were already fully consolidated in memory, in order to control for circadian confounds and fatigue. If effects found with the Mandarin words were due to sleep-associated consolidation, then we should not expect to find equivalent differences between the two groups of participants for the English words.

3. Method

3.1. Participants

Twenty-four monolingual native English speakers (9 males; mean age = 21.7 years, range = 18–31 years) with no known

[3] It should be noted that work by Lindsay and Gaskell (2013) suggests that integration can occur without sleep if new words are taught via spaced or interleaved learning.