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The effects of total sleep deprivation on semantic priming: Event-related potential evidence for automatic and controlled processing strategies

Rocío López Zunini [a], Alexandra Muller-Gass [b], Kenneth Campbell [a,*]

[a] School of Psychology, University of Ottawa, Ottawa K1N 6N5, Canada
[b] Defence Research and Development Canada, Toronto M3K 2C9, Canada

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ABSTRACT

There is general consensus that performance on a number of cognitive tasks deteriorates following total sleep deprivation. At times, however, subjects manage to maintain performance. This may be because of an ability to switch cognitive strategies including the exertion of compensatory effort. The present study examines the effects of total sleep deprivation on a semantic word priming task. Word priming is unique because it can be carried out using different strategies involving either automatic, effortless or controlled, effortful processing. Twelve subjects were presented with word pairs, a prime and a target, that were either highly semantically associated (*cat…dog*), weakly associated (*cow…barn*) or unassociated (*apple…road*). In order to increase the probability of the use of controlled processing following normal sleep, the subject's task was to determine if the target word was semantically related to the prime. Furthermore, the time between the offset of the prime and the onset of the target was relatively long, permitting the use of an effortful, expectancy-predictive strategy. Event-related potentials (ERPs) were recorded from 64 electrode sites. After normal sleep, RTs were faster and accuracy higher to highly associated targets; this performance advantage was also maintained following sleep deprivation. A large negative deflection, the N400, was larger to weakly associated and unassociated targets in both sleep-deprived and normal conditions. The overall N400 was however larger in the normal sleep condition. Moreover, a long-lasting negative slow wave developed between the offset of the prime and the onset of the target. These physiological measures are consistent with the use of an effortful, predictive strategy following normal sleep but an automatic, effortless strategy following total sleep deprivation. A picture priming task was also run. This task benefits less from the use of a predictive strategy. Accordingly, in this task, ERPs following the target did not differ as a function of the amount of sleep.

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1. Introduction

Total sleep deprivation affects performance on several different cognitive tasks. The detriment in performance often appears as a slowing of reaction time (RT) or as a decrease in the accuracy of detection. Not all studies however report this detriment in performance, often suggesting that the maintenance of performance might be a result of a change of cognitive strategy in order to "compensate" for the effects of sleep deprivation (Lim & Dinges, 2008). In many instances, such compensation involves a strategy of increasing "effort". The present study is unusual in that it employs a semantic priming paradigm, a task in which performance can be successfully carried out using different cognitive strategies. The semantic priming task can be carried out using active, effortful processing, requiring therefore the maintenance of sustained attention. It can also however be carried out using effortless, automatic processing and thus does not require the maintenance of sustained attention. The former strategy might be appropriate when cognitive resources are readily available, following normal sleep. The latter might be appropriate when fewer cognitive resources are available, following sleep deprivation.

In word priming tasks, the subject is presented with an initial word (the "prime") that may or may not be semantically associated with a subsequent "target" word. There are several variants of the paradigm but often the subject is engaged in an incidental lexical decision task, having to determine if the target word is a valid word or not. When the prime is semantically associated with the target (e.g., *cat…dog*), RTs are faster and accuracy higher than when the prime is not associated with the target (e.g., *doctor…mouse*). This is referred to as the "priming effect". A common theory to explain the priming advantage proposes a spreading activation across a semantic memory network with strongly associated semantic concepts represented in neighbouring nodes and weakly associated

* Corresponding author.
E-mail addresses: rlope056@uottawa.ca (R. López Zunini), alexandra.muller-gass@drdc-rddc.gc.ca (A. Muller-Gass), kenneth.campbell@uottawa.ca (K. Campbell).

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concepts represented in more distant nodes. Thus, target words that are strongly semantically associated with the prime are activated rapidly and are therefore available to memory prior to the onset of the target. Targets that are only weakly associated with the prime are activated more slowly because of their representation in more distant nodes. Targets that are not associated with the prime cannot be retrieved within the semantic network and are thus not available to memory prior to the onset of the target (Collins & Loftus, 1975; Neely, 1991).

The search of the semantic network can be carried out using either automatic, effortless or controlled, effortful processing. Collins and Loftus (1975) initially claimed that the spreading activation across the semantic network occurred automatically, without the need for attention or effort. Support for this claim comes from priming studies in which the subject is asked to make a lexical decision about the target. The semantic association between the prime and the target is thus irrelevant to the lexical decision task. Even though attention is not directed to the nature of the semantic association between the prime-target word pair, and the subject may not be aware of their association, a strong priming effect still, seemingly automatically, occurs. Other authors indicate that even though attention might not be directed to the semantic association between the prime and the target, after a few trials, the subject may well become aware of the association. The subject might thus use an alternative, predictive expectancy-based strategy (Becker, 1980; Neely, 1976; Posner & Snyder, 1975). Subjects can therefore use the prime to intentionally generate an expectancy for a set of semantically associated target candidates. The set of expected targets for the prime *dog* might include *cat*, *poodle*, *bark*, *tail* and so forth. For this reason, expectancy-based strategies are effective only at longer stimulus onset asynchronies (SOAs), when the time interval between the onset of the prime and that of the target is sufficiently long to allow subjects to generate possible exemplars (den Heyer, Briand, & Dannenbring, 1983; Neely, 1976). The expectancy-based strategy does come at a cost – it does require active and sustained attention in order to search out possible target exemplar candidates and maintain them in working memory.

The effects of sleep deprivation on priming have not been studied extensively. Swann, Yelland, Redman, and Rajaratnam (2006) employed a repetition priming task following normal sleep and following two consecutive nights of restricted sleep (40% less than normal sleep). Subjects were presented with a brief duration 56 ms initial prime word and at its offset, a 500 ms target. The target was either a real word or a non-word and subjects were asked to button press if a real word had been presented. Two different prime-target pairs were employed. The identical (ID) prime was the same word as the target (e.g. *blue-blue*), and the all letters different (ALD) prime had letters that were different at each position in the letter string compared to the target (e.g. *sand-blue*). Following normal sleep, regardless of whether the target was a real word or not, RTs were faster in the ID condition, when the target matched the prime than in the ALD condition, when the target did not match the prime. Because the initial prime was masked and the subject could not consciously identify it, the faster RTs in the ID condition were explained by an automatic, nonconscious activation of lexical (or possibly sensory) memory prior to the onset of the target. Of course, the lexical memory for the ALD targets could not have been activated upon presentation of the prime. Interestingly, RTs were faster for the ID targets following sleep deprivation compared to normal sleep indicating that the automatic processing of the target was preserved, but were slower for the ALD targets. Thus, the overall repetition priming effect was enhanced by sleep deprivation. Swann et al. (2006) suggested that this might be because of the use of compensatory effort, possibly involving the recruitment of additional cognitive resources. Importantly, repetition priming does not access the strength of semantic association networks. Nevertheless, the results of this study do endorse the notion that tasks that only require automatic, effortless processing, such as those involved in the access of the lexical network, are well-preserved following sleep deprivation.

A problem with studies that rely strictly on performance measures, such as RT and accuracy, is that conclusions about information processing strategies must be inferred and cannot directly be observed. In semantic word priming tasks, as noted, it is possible for subjects to employ at least two different strategies (involving either automatic or controlled processing). Depending on the availability of attentional resources, subjects may favour one strategy over another. It is thus possible that the behavioural performance of the subjects who are sleep-deprived will not differ from those who have slept normally. A failure to find a difference in performance cannot be used as evidence of a similarity of cognitive strategies. Many laboratories therefore employ physiological measures, such as event-related potentials (ERPs), to measure cognitive processes prior to, at the time of, and following a behavioural decision. ERPs are the minute changes in the electrical activity of the brain that are elicited by an external physical, sensory stimulus or an internal, cognitive event. ERPs consist of a series of negative- and positive-going components thought to reflect different stages of information processing. In the study of semantic priming, ERPs can be recorded during the entire interval from the time of presentation of the prime and continue for a period of time after the presentation of the target, providing an elegant means to monitor the use of different cognitive strategies.

A number of studies have investigated the effects of sleep deprivation on many different ERP components. Most of these studies have however recorded ERPs during tasks that require active, sustained vigilance. For example, a negative deflection peaking at about 150–200 ms associated with sustained attention to a visual stimulus has been shown to be reduced in amplitude following sleep deprivation (Hoedlmoser et al., 2011; Smith, McEvoy, & Gevins, 2002; Trujillo, Kornguth, & Schnyer, 2009). Similarly, a later positive component, P300 (also labelled as P3b), associated with the detection of a rare target stimulus during vigilance tasks has also been shown to be attenuated following sleep deprivation (Corsi-Cabrera, Arce, Del Rio-Portilla, Perez-Garci, & Guevara, 1999; Gosselin, De Koninck, & Campbell, 2005; Morris, So, Lee, Lash, & Becker, 1992; Smith et al., 2002). Subjects often make more errors following sleep deprivation. An error-related negativity (ERN), thought to be related to error detection or response conflict, and a subsequent positivity (Pe), related perhaps to the actual error recognition may also be attenuated by sleep deprivation (Hsieh, Tsai, & Tsai, 2009; Murphy, Richard, Masaki, & Segalowitz, 2006; Scheffers, Humphrey, Stanny, Kramer, & Coles, 1999).

An ERP component that is consistently modulated by manipulations of semantic context is the N400, a negative-going waveform peaking at about 400 ms. In semantic studies, the amplitude of the N400 is large when the target stimulus is presented without any context. It is attenuated (less negative) when a target word is preceded by a semantically congruent context (Kutas & Federmeier, 2011). Thus in word priming tasks, N400 is large to targets that are semantically unassociated with the prime or only weakly associated with it and small to targets that are strongly associated with the prime (Bentin, McCarthy, & Wood, 1985; Chwilla & Kolk, 2005; Holcomb, 1988; Phillips, Segalowitz, O'Brien, & Yamasaki, 2004). The effects are similar across different modalities such as picture–word naming and association tasks (Blackford, Holcomb, Grainger, & Kuperberg, 2012; Hurley et al., 2009; Khateb, Pegna, Landis, Mouthon, & Annoni, 2010). Importantly, the N400 can be elicited whether subjects use an automatic or a controlled expectancy-based strategy (Deacon, Uhm, Ritter, Hewitt, & Dynowska, 1999). The present study was designed to optimise the probability

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