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https://www.tandfonline.com/toc/pmem20/current

**Citation:**

**Riley, G.A., Pearce, A. (early online). Wakeful rest during storage and consolidation enhances priming effects for those with acquired memory impairment. *Memory.***

**https://doi.org/10.1080/09658211.2021.1907414**

**Wakeful rest during storage and consolidation enhances priming effects for those with acquired memory impairment**

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Word count: Total = 6,331 excluding abstract, references, figures and tables

Running head: Wakeful rest and priming

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**Wakeful rest during storage and consolidation enhances priming effects for those with acquired memory impairment**

**Abstract**

A period of rest after learning results in better explicit memory for the material than a period of unrelated mental activity. This study investigated whether the same applies to priming. Thirty-four people with memory impairments due to acquired brain injury took part. In a repeated measures design, participants studied word lists; then either engaged in a relaxation technique (wakeful rest condition) or completed visuo-spatial tasks (control condition); and finally completed two priming tasks. Priming effects were significantly larger in the wakeful rest condition. This result is difficult to explain in terms of some of the explanations used to account for the benefits of wakeful rest on explicit memory, and alternative explanations are considered. One possibility is that the attentional demands of the control task resulted in inhibition of activity in neocortical areas associated with perception that contributed to the priming effect. The findings have implications for memory rehabilitation. Acquired memory impairments typically impact on explicit memory, and implicit memory is often relatively intact. It is important to find ways of enabling those with more severe explicit impairments to make best use of their implicit memory as a way of compensating for the deficits in their explicit memory.

**Keywords**: Wakeful rest, priming, memory rehabilitation, relaxation, inhibition, brain injury

**Wakeful rest during storage and consolidation enhances priming effects for those with acquired memory impairment**

Recent literature suggests that, compared to a period of activity, a period of wakeful rest following the learning of material can enhance subsequent explicit memory for that material (Dewar, Alber, et al., 2012; Humiston et al., 2019; Martini et al., 2019). For example, in the study by Dewar, Alber, et al. (2012) participants listened to two stories. One story was followed by 10 minutes of resting quietly with eyes closed in a darkened room and the other by 10 minutes of playing a spot-the-difference game. In retrieval tests at both 30 minutes and 7 days, recall of the story was better following wakeful rest.

The present study investigated whether this advantage for wakeful rest over mental activity also applies to implicit memory and specifically to priming. This is an issue of theoretical and practical interest. The main theory put forward to account for the advantage is that wakeful rest, through the reduction of sensory input, provides an opportunity for memories to be covertly reactivated within the hippocampus and transferred to more permanent storage (Dewar, Alber et al., 2012; Craig et al., 2016). Given the differences between explicit and implicit memory and uncertainty about the role that the hippocampus plays in priming effects (Hannula & Greene, 2012; Schacter & Buckner, 1998), a finding that wakeful rest also confers an advantage for priming effects would highlight the need to consider the generalizability of this explanation to priming.

The practical importance of the issue relates to memory rehabilitation. The beneficial effects of wakeful rest on explicit memory have been reported in several studies involving participants with acquired memory impairments (Dewar, Pesallaccia et al., 2012; McGhee et al., 2020). This is valuable information, but it would also be useful to know if the benefits apply to implicit memory. Acquired memory impairments associated with conditions such as brain injury and dementia are typically characterised by difficulties with explicit memory, and implicit memory abilities are often relatively spared (Schacter & Buckner, 1998). It is important, therefore, to find ways of enabling those with typical memory impairment, particularly when this is more severe, to make best use of their implicit memory as a way of compensating for the deficits in their explicit memory (Riley & Venn, 2015; Wilson & Fish, 2018).

**Method**

Ethical approval for the study was provided by the STEM Ethical Review Committee of the University of Birmingham (reference number ERN\_17-1612). All participants provided informed written consent.

**Participants**

A convenience sample was recruited from Headway, a UK charity providing support to people with acquired brain injury. Participants were required to be over the age of 18; capable of giving informed consent; fluent in English; to have sustained an acquired brain injury no earlier than 6 months previously; and to have self-reported current memory difficulties as a result of this injury. Thirty-four participants were recruited to meet the requirements of a power analysis focused on the detection of a moderate interaction effect (f=.25) in a two-factor repeated measures ANOVA with alpha set at .05 and power at 0.8. A meta-analysis reported by Humiston et al. (2019) suggested that the effect size of wakeful resting on explicit memory in healthy control participants is only moderate. In addition to the 34 participants who provided full data sets, a further six participants provided partial data sets that have not been included in the analysis. Four of these declined to complete the study stating that they were no longer interested in taking part, and the remaining two were withdrawn because of concerns about their ability to provide ongoing informed consent.

Demographic and neuropsychological information about the sample is contained in Table 1. The neuropsychological data indicate a relatively high level of functional and memory impairment.

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| --- | --- |
| **Demographics** |  |
| Gender | 61% male; 39% female |
| Age | Mean = 50; SD = 10; range = 24 to 66 |
| Highest educational qualification | None/CSE/O Level = 47%; A Level/ Diploma/NVQ = 24%; Graduate = 12%; Postgraduate = 6%; no information provided =12% |
| Pre-injury occupation | Professional = 6%; Skilled = 18%; Semi-skilled = 53%; unskilled = 24% |
| Post-injury occupation | One person in unskilled part-time employment |
| **Neuropsychological data** |  |
| Type of injury | Traumatic brain injury = 38%; Stroke = 35%; Tumour = 12%; Surgery = 6 %; Infection = 6%; Anoxia = 3% |
| Time since injury | Mean = 13 years; SD = 9; range = 2 to 36 |
| Pre-injury IQ estimated from TOPF | Mean = 99; SD = 12; range = 81 to 121  (Excludes 5 cases for which estimate considered invalid) |
| WMS Immediate Story Recall (age-related scaled scores) | Mean = 3.2; SD = 1.9; range = 1 to 8  (For general population, mean = 10) |
| WMS Delayed Story Recall (age-related scaled scores) | Mean = 4.1; SD = 2.3; range = 1 to 9  (For general population, mean = 10) |
| DKEFS Tower Test (scaled score) | Mean = 6.8; SD = 3.9; range = 1 to 13  (For general population, mean = 10) |
| EBIQ (possible scores range from 1 to 3) | Mean = 2.0; SD = 0.4; range = 1.08 to 2.76 |
|  |  |

TOPF = Test of Pre-Morbid Functioning – UK Version (Wechsler, 2011)

WMS = Wechsler Memory Scale -Third UK Edition (Wechsler, 1997)

DKEFS = Delis-Kaplan Executive Function System (Delis et al., 2001)

EBIQ = European Brain Injury Questionnaire (Teasdale et al., 1997)

An individual’s score on the EBIQ is the mean obtained across all items, which are scored in terms of the extent to which an individual experiences a particular problem, with the response options of 1= not at all, 2 = a little or 3 = a lot. For a normative sample with a range of acquired brain injuries, the mean was 1.68 (Teasdale et al., 1997).

Table 1: *Demographic and neuropsychological information about the sample*

**Design and procedure**

The study was a two-factor repeated measures design in which all participants took part in all conditions. The procedure is summarised in Table 2. Each participant took part in three sessions. In the first, they tried four different relaxation techniques and chose one for use in the experimental sessions which followed in the second and third sessions. In both these sessions, participants first studied two word lists. Words were presented one at a time on a computer screen with the two lists intermingled in a random order. To ensure attention to the perceptual features of the word, the participant was required to say the word out loud, to state the third letter and to indicate whether it contained the letter ‘e’. Following the presentation of the word lists, participants either relaxed using their chosen technique (wakeful rest condition) or completed a series of visuo-spatial tasks presented on video (control condition). Following this, they completed the two priming tasks (stem completion and identification). The interval between initial exposure to the word lists and the priming tasks was approximately 10 minutes in total. Each priming task involved one of the pre-studied lists coupled with an unstudied list; the words from both lists were presented intermingled in a random order. Four word lists were compiled for use in the stem completion task, and four for the identification task. The design was counterbalanced in terms of the order in which participants completed the two experimental conditions (i.e. half completed the wakeful rest condition first and half the control condition), the pairing of word list with condition (i.e. each of the four lists appeared an equal number of times in the control and wakeful rest conditions) and the pairing of word list with prior study (i.e. each of the four lists appeared an equal number of times as a studied and unstudied list). However, the stem completion task was always completed before the identification task. Collection of the demographic and neuropsychological data was spread across the three sessions, and always took place after the activities listed in Table 2 had been completed.

|  |  |
| --- | --- |
| **Week 1** | **Choosing a relaxation technique:**  Participants sample four techniques and chose one for use in the experimental sessions. |
| **Week 2** | **First experimental session:**   1. Study: Participants study two word lists 2. Participants EITHER relax OR complete attention-demanding tasks 3. Stem completion task: Participants complete word stems (e.g. SHA\_\_\_) corresponding to one studied and one unstudied list 4. Identification task: Participants try to identify words presented for 40 milliseconds; words are taken from one studied and one unstudied list |
| **Week 3** | **Second experimental session:**  As for week 2 but involving the condition not completed in week 2 |

Table 2: *Summary of procedure*

**Wakeful rest and control conditions**

In many previous studies, the wakeful rest condition has involved simply instructing participants to close their eyes and wait for the next phase of the study (e.g. Dewar, Alber, et al., 2012). This means there is little control over what participants are actually doing. They might be rehearsing the material, in which case much or all of the advantage to wakeful rest could be due to extra rehearsal, a finding that is expected and uninteresting (Dewar et al., 2014; Humiston et al., 2019). Alternatively, they may be thinking about other things, unrelated to the study, that might be not be particularly restful (Varma et al., 2018). To address these issues, the wakeful rest condition in this study involved listening to a recording designed to help them relax and participants were instructed to focus on relaxing.

People differ considerably in how well they respond to various relaxation techniques (Manzoni et al., 2008). It was therefore decided to allow each participant to choose from a range of options the technique that they found most relaxing, and this technique was used for that individual in the wakeful rest condition. In a preliminary meeting, participants tried four different techniques, specifically guided visualization, progressive muscle relaxation, mindful breathing and relaxing music. Each one was presented on an audio recording and lasted between three and four minutes. Because some people are unsettled by instructions to keep their eyes closed, participants were not specifically instructed to close their eyes and were free to close or open them as they preferred. Heart rate was measured before and after each exercise, and these data were given to participants when they were asked to decide which technique they found most relaxing. Guided visualization and soothing music proved the most popular with 44% and 29% respectively choosing them; mindful breathing (18%) and progressive muscle relaxation (9%) were less popular.

The choice of task for the control condition has varied considerably in previous studies, and the rationale for the choice has not always been made clear. A major consideration is that the task should not resemble the material being learnt. An overlap could mean that the advantage of the wakeful rest condition is due to retrieval interference in the control condition, rather than to the facilitatory effect of wakeful rest on consolidation (Dewar, Alber et al., 2012). Participants were therefore asked to complete a series of visuo-spatial tasks to avoid overlap with the verbal tasks involved in the priming. Specifically, they watched a video lasting 3.5 minutes and were required to count the number of times someone kicked a football; to follow which of three upturned cups hid a small ball as the three cups were shuffled about; and to count the number of times someone jumped while skipping. For the participants in the study, these were relatively challenging tasks because of impairments in attention and concentration.

A heart rate reading was taken before and after the relaxation recording and control video in order to check whether the conditions differed in terms of their impact. A state of relaxation is associated with reduced heart rate (van Dixhoorn & White, 2005), and elevated attention is associated with an increased heart rate (Luque-Casado et al., 2016).

**Word lists**

Word lists were compiled using the data provided by Migo et al. (2010) about frequency and rates of word stem completion. Eight lists were created, each containing 10 words. All words were five, six or seven letters in length and, to ensure familiarity to the participants, were required to meet a minimum requirement about the frequency of their occurrence in printed material. The four lists used for the stem completion priming task were matched in terms of the frequency with which the three-letter word stem (e.g. sha\_\_\_\_) was completed with the word selected for the list (shark) by the normative sample. The four lists used for the identification priming task were matched in terms of the number of letters in each word, and the frequency of their occurrence in printed material.

**Priming tasks**

For the stem completion task, participants were presented with the three-letter word stems corresponding to the word list they had studied at the start of the session and those from an unstudied list, intermingled in a random order. Stems were shown one at a time via a computer screen and the participant was instructed to say the first word that came to mind or to indicate if no word came to mind. A priming effect was evidenced by an increased probability of completing the stems using words from the studied list compared to the unstudied list. For the identification task, participants were shown words one at a time for 40 milliseconds with pre and post-exposure masking, and instructed to identify the word. Again, words came from one studied and one unstudied list, and were presented in a random order. A priming effect was evidenced by greater success in identifying words from the studied list compared to the unstudied list.

**Results**

Subsidiary analyses indicated that performance on the priming tasks was not affected by the order of completing the experimental conditions (i.e. wakeful rest or control condition first); differences between word lists or word-list-and-condition combinations; or differences between the relaxation techniques chosen for the wakeful rest condition. Analysis of the before and after heart rate data indicated that, as expected, the wakeful rest condition led to a significant decline in heart rate; Before M = 77.65 beats per minute, SD = 7.04, After M = 72.38, SD = 7.30; t (33) = 4.60, p<.001: and the control condition led to a significant increase; Before M = 76.88 beats per minute, SD = 8.20, After M = 79.73, SD = 7.90; t (25\*) = 3.81, p<.001 (\*some data were missing because of equipment failure). These results are consistent with the assumption that participants were more relaxed in the wakeful rest condition and were at a heightened level of attention in the control condition.

The main hypothesis was tested using the scores on the two priming tasks, with a separate analysis for each task. Inspection of the scores on the identification task indicated that there were no outliers and that the data met the assumptions for the planned two-factor ANOVA (the two factors being primed vs. unprimed, and wakeful rest vs. control). The data are summarised in Figure 1. There was a significant main effect of priming; studied words were identified more accurately than non-studied words; M for primed = 4.65, SD = 3.38, M for unprimed = 3.38, SD = 3.02; F(1,33) = 39.32, p<.001. The effect of experimental condition was not significant, F(1,33) = 3.88, p = .057. The main hypothesis of the study was that the priming effect would be greater in the wakeful rest condition than in the control condition. This was supported by a significant priming-x-condition interaction effect, F(1,33) = 5.09; p = .031. When variance associated with other factors was excluded, approximately 13% of the variance was explained by the interaction effect, partial η2 = .13, 95% CI [+0.01, +0.31]. The generalized eta-squared provides an estimate of what the eta-squared would be if a between-groups design was used (Olejnik & Algina, 2004) and this was .03. To allow a direct comparison with the meta-analytic summary effect reported by Humiston et al. (2019) in relation to comparisons of wakeful rest and control conditions in explicit memory studies, *priming effect scores* were calculated by subtracting the number of correctly identified items that were not shown to the participant in the first stage of the experimental session (i.e. unprimed items) from the number of correctly identified items that were shown (i.e. primed items). The distribution of these scores is shown in Figure 2., Cohen’s d was calculated by comparing the priming effect score in the wakeful rest condition (M = 1.85, SD = 1.71) with the priming effect score in the control condition (M = 1.00, SD = 1.74). For the identification task, d = 0.43, 95% CI [+0.05, +0.91]. This compares with a meta-analytic summary d of 0.38 reported by Humiston et al. (2019) and suggests a relatively modest effect size.

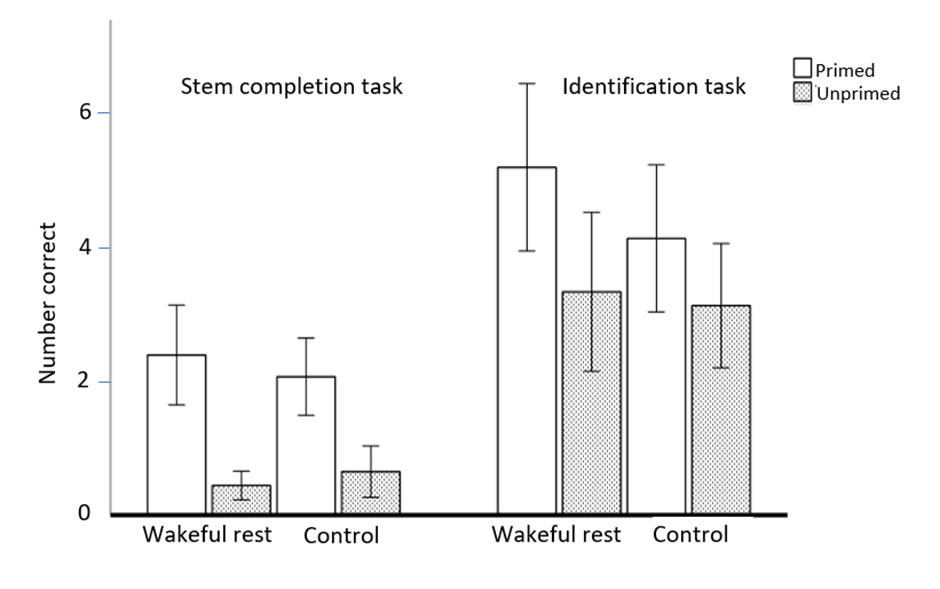


Figure 1: *Chart shows* *mean scores for primed and unprimed words in each condition (wakeful rest vs. control) for the two priming tasks (stem completion and identification). Error bars show 95% confidence intervals.*

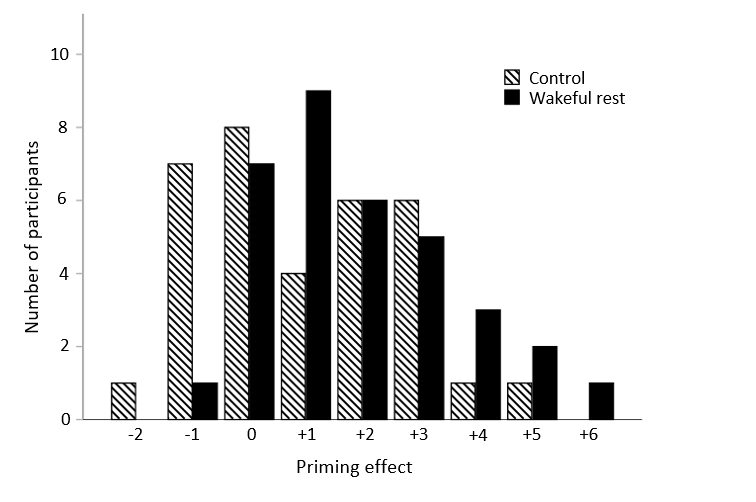


Figure 2: *Chart shows the distribution of priming effect scores (i.e. correctly identified primed items minus correctly identified unprimed items) on the identification task for the two conditions (wakeful rest vs. control).*

Figures 1 and 3 summarize the data for the stem completion task. Scores showed substantial floor effects, and this rendered them unsuitable for ANOVA. To check whether priming effects had occurred, Wilcoxon’s signed rank test was used on the raw scores. A comparison between the scores for the studied and unstudied lists showed that there was a significant priming effect in both the wakeful rest (24 positive differences, 3 negative differences and 7 ties; p<.001) and the control condition (24 positive differences, 0 negative differences and 10 ties; p<.001). To test the main hypothesis about relaxation leading to a greater priming effect, priming effect scores were used. These were obtained by subtracting the number of word stems completed with words from the unprimed list (i.e. the participant coincidentally completed the stem with a word from the list without having been exposed to that list in the first stage) from the number completed with words from the primed list (i.e. the list that the participant had been seen in the first stage). These were suitable for parametric analysis and a one-factor ANOVA was used. The priming effect was larger in wakeful rest compared to the control condition, M for wakeful rest = 1.94, SD = 2.09; M for control = 1.41, SD = 1.23; but this difference was not significant, F(1,33) = 2.57; p = .119). In terms of effect sizes, partial η2 = .07, 90% confidence intervals 0 to 0.23; generalized η2 = .02, and Cohen’s d = 0.27, 95% CI [-0.26,+ 0.70].

Chart, bar chart

Description automatically generated

Figure 3: *Chart shows the distribution of priming effect scores on the stem completion task for the two conditions (wakeful rest vs. control). Priming effect scores represent the number of stems completed with words from the primed list minus the number of stems completed with words from a list despite the participant not having been exposed to that list.*

Because of the floor effects, nearly half of the participants showed negligible priming effects. Logically, if they failed to show a priming effect, there would be no opportunity for these participants to show differential amounts of priming between the wakeful rest and control conditions, and the analysis thus fails to provide a fair test of the hypothesis that there will be larger priming effects in the wakeful rest condition. To address this problem, an unplanned analysis was completed that excluded participants who failed to score higher on the primed items compared to the unprimed items in both the wakeful rest and control conditions. Nineteen participants were retained for a one-factor ANOVA using the priming effect scores. The distribution of these is shown in Figure 4. The priming effect was larger in wakeful rest compared to the control condition, M for wakeful rest = 3.16, SD = 1.83; M for control = 2.05, SD = 0.91, and this difference was significant, F(1,18) = 7.49, p = .014. In terms of effect sizes, partial η2 = 0.29, 95% confidence intervals +.03 to +.50; generalized η2 = 0.13; and Cohen’s d = 0.66, 95% CI [+0.04,+1.00].

Chart

Description automatically generated with medium confidence

Figure 4: *Chart shows the distribution of priming effect scores on the stem completion task for the two conditions (wakeful rest vs. control) for the subsample (n=19) who showed a priming effect in both conditions. Priming effect scores represent the number of stems completed with words from the primed list minus the number of stems completed with words from a list despite the participant not having been exposed to that list.*

**Discussion**

The present study extends previous research on the benefits of wakeful rest for explicit memory by providing evidence that it also benefits priming. Although a few studies have investigated its impact on other forms of implicit learning (Humiston & Walmsley, 2018; Mednick et al., 2009), the present study appears to be the first to examine its impact on priming. It also extends limited previous research on the consolidation of priming effects. Plihal and Born (1999) found that, compared to a wakeful control condition in which participants watched travel videos, a period of REM sleep led to improved priming on a word-stem completion task. Finally, the study complements another study that used relaxation, rather than the standard wakeful rest condition of participants closing their eyes in a quiet room, to enhance explicit memory. In a study otherwise similar to those investigating the impact of wakeful rest on explicit memory, Nava et al. (2004) compared progressive muscle relaxation and a vigilance task. Although both conditions led to equal performance on an immediate recognition test, relaxation resulted in superior performance on a recognition test four weeks later.

A major challenge in investigating implicit learning is how to avoid contamination of task performance by the involvement of explicit memory (Hannula & Greene, 2012). Although Humiston and Walmsley (2018) reported a benefit of wakeful rest for a motor sequencing task in which participants learned to press keys in a particular sequence, it is unclear to what extent explicit learning strategies may have contributed to performance of the task. Mednick et al. (2009) reported benefits for wakeful rest using a contextual cueing task in which participants search for a target letter amongst distractor letters. Some patterns of the spatial arrangement of distractor and target letters are repeated, and learning is shown by increased speed of detection for targets occurring in these patterns. The learning was not contaminated by explicit strategies because participants in the study showed an increase in speed despite being unable on a recognition test to discriminate the spatial arrangements that had been used from ones that had not. In relation to the present study, the stem completion task is a priming task that has been highlighted as being vulnerable to explicit contamination; the participant may realise that the stems can be completed using words previously studied and then use subsequent stems as cues to try to remember the other studied words (Hannula & Greene, 2012). However, there is evidence that the identification task is relatively unaffected by explicit contamination (Perruchet & Baveux, 1989; Ratcliff & McKoon, 1997). Based on reports from their participants that the words flashed before them were either immediately seen or not seen, Perruchet and Baveux (1989) suggested that the task, unlike stem completion, does not involve any extended process of consciously selecting the response from a range of alternatives, and that it is this process that provides the opportunity for explicit recall of items to contaminate performance on implicit tasks.

**Theoretical implications**

Previous explanations of the benefits of wakeful rest on explicit memory are based on a general theory of memory consolidation. The two-stage model proposes that new memories are temporarily stored in the hippocampus and other linked structures in the medial temporal area before being transferred to more permanent storage in neocortical areas (McClelland et al., 1995; Nadel et al., 2012). Sleep is hypothesized to play a major role in this transfer: New memories are covertly reactivated during sleep and, during their transfer to more permanent storage, may be manipulated and transformed as they are integrated with existing memories (Born & Wilhelm, 2012; Elsey et al., 2018; Rasch & Born, 2008). In relation to the benefits of wakeful rest, it has been suggested that wakeful rest functions in the same way as sleep and that, by reducing sensory input and associated coding activity, it provides an opportunity for new memories to be covertly reactivated within the hippocampal system, and transferred to more permanent storage; whereas the control activities interfere with the process (Craig et al., 2016; Dewar, Alber et al., 2012). In support of this, increased activity in the hippocampal system has been detected in states of wakeful rest and it has been suggested that this may represent the reactivation of recent memories for consolidation purposes (Schapiro et al., 2018; Tambini et al., 2010).

Although the standard wakeful rest condition may have its impact through the reduction of sensory input, the theory is not committed to suggesting that such a reduction is a necessary or sufficient condition of facilitating the process of hippocampal consolidation. The core idea is that any post-learning activity that interferes with this process will impair memory for the studied material and that, conversely, any activity that does not interfere will not impair memory. An example of the latter is provided by the studies of Varma and colleagues (2017, 2018) which used the n-back task in the control condition that was compared with wakeful rest. In the n-back task participants are presented with a series of numbers one at a time. For each number, the participant is required to indicate whether it was the same as the number presented ‘n’ steps earlier in the sequence. Previous research has suggested that the hippocampal system is minimally involved in performance of the n-back task (e.g. Esposito et al., 2016). In the studies, the n-back task did not result in a decrement in explicit memory performance compared to a wakeful rest condition. Varma and colleagues concluded that reducing sensory input is not necessary and that, rather, the important factor is that the post-learning activity does not make too many demands on memory systems served by the hippocampal system and thereby create interference in the consolidation process. Evidence that a reduction in sensory input is not a sufficient condition for memory benefits was provided by Varma et al. (2018). A wakeful rest condition in which participants heard auditory cues (e.g. the sound of a playground) designed to elicit autobiographical memories that would be expected to interfere with hippocampal consolidation processes, resulted in worse explicit memory performance than either a standard wakeful rest condition or an n-back condition. Craig et al. (2014) similarly found that cueing autobiographical memories or future imaginings with sounds during the post-learning period resulted in worse performance than a standard wakeful rest condition and equivalent performance to a picture search control task.

The present study also provides some support for the claim that a reduction in sensory input is not necessary to obtain memory benefits. In contrast to most previous studies, wakeful rest in this study involved using a relaxation technique rather than simply closing one’s eyes. Although the relaxation techniques presented a different kind of sensory input to the control condition (i.e. they were primarily auditory, whereas the control condition was primarily visual), the two conditions were not differentiated by any obvious disparity in the amount of sensory input they presented. Yet there was a difference in priming performance between the two conditions, consistent with the claim of that reduction of sensory input in wakeful rest conditions is not a necessary condition of better performance. More compelling evidence of this is provided by the study of Nava et al. (2004) in which participants viewed a series of pictures, and then either listened to a relaxation recording or completed a vigilance task. The vigilance task required participants to listen to the same recording of a progressive muscle relaxation exercise but, instead of following the instructions to relax, participants were required to press a button every time a body part was mentioned. Immediately after, they were given an unexpected recognition test (i.e. the learning was incidental) and then a second recognition test four weeks later. Although there was no difference on the immediate test, those in the relaxation group performed significantly better on the delayed test. The fact that the external sensory input was identical in both conditions rules out an explanation in terms of lower sensory input being a necessary condition of the occurrence of better memory performance following wakeful rest.

On the other hand, it is difficult to account for the present findings (or, indeed, those of Nava et al., 2004) in terms of the explanation offered by Varma and colleagues of their own findings. They suggested that the n-back task prevents interference with the consolidation process because the task requires close attention to external stimuli and thereby prevents off-task mental activities such as mind-wandering and autobiographical thinking that do interfere with consolidation. Applying this to the present findings, the suggestion would be that the relaxation techniques required closer attention to external stimuli than the control task and were therefore better at preventing interference from mental activities such as autobiographical thinking. This seems an unlikely explanation. The control task in the present study was more attentionally-demanding, particularly for the participants involved, and seems more, not less, likely to have suppressed off-task thinking.

If the benefits of relaxation in the present study are not to be explained in terms of reductions in sensory input or off-task thinking, how are we to account for them? A major issue of uncertainty is whether the two conditions (wakeful rest and control) acted differentially on consolidation processes in the hippocampal system, or on other storage processes outside the hippocampal system that contribute to priming performance. The neural basis of priming is unclear. Evidence, primarily from studies using PET, suggests that the initial exposure to the stimuli is associated with increased blood flow in posterior neocortical areas associated with perception and recognition, but that there is a reduction in blood flow in these areas on the post-exposure priming task (Schacter & Buckner, 1998; Yasuno et al., 2000). This has been interpreted as indicating that less activation of the neural representations of the stimuli is required during the priming task because the prior exposure has left them in a partly activated state (e.g. Schacter & Buckner, 1998; Yasuno et al., 2000). There is also evidence of activation of the hippocampal system during priming tasks, but what role this plays in the effectiveness of priming performance and whether it relates to consolidation processes remains unclear (Hannula & Greene, 2012; Schacter & Buckner, 1998).

If wakeful rest in the present study had a beneficial effect on hippocampal consolidation processes, one potential mechanism for this effect is that the relaxation condition, rather than minimising interference in consolidation, directly boosts those processes. Resting states in general are associated with a range of neurophysiological indicators that have been linked with consolidation. These include decreased acetylcholine (Marrosu et al., 1995), slow oscillatory EEG rhythms (Brokaw et al., 2016), and enhanced activity of the parasympathetic nervous system (Clark et al., 1999). It may be that relaxation was more effective than the control task in the present study because it boosted neurophysiological processes that underpin hippocampal consolidation processes.

Another possibility is that the impact of the experimental manipulations was not on hippocampal consolidation processes, but on activation levels in neocortical areas involved in perception and recognition. Interference effects in priming have been found in several experimental paradigms, such as the negative priming paradigm in which presented stimuli include a target for a response and a distracter that has to be ignored; when the distracter becomes the target for the response in later trials, responses to the distracter are slower than to control stimuli (Mayr & Buchner, 2007). Although other theories have been offered, inhibition accounts of these interference effects are widely advocated (Bajo et al., 2006; Mayr & Buchner, 2007; Taubenfeld et al., 2019). These suggest that the interference arises because the experimental manipulation inhibits activity levels that normally contribute to the priming effect. For example, in the case of negative priming, the suggestion is that ignoring the distracter involves inhibiting levels of activity in its neocortical representation so that responses are slowed when it subsequently becomes the distracter (Mayr & Buchner, 2007). In line with these other inhibitory accounts, it could be speculated that the control task in the present study resulted in poorer priming performance because it inhibited the activity levels of the representations of the stimuli in neocortical areas to a greater extent than the wakeful rest condition. Specifically, attention to the control task may have suppressed the ongoing level of activation in neocortical representations of the stimuli, meaning that they were less likely subsequently to influence responding on the priming tasks.

This raises the question of why the control task had a greater inhibitory impact. Compared to the relaxation techniques, the control task required a higher level of attention and concentration. Specifically, it required a high level of selective attention to particular aspects of the sensory input. Selective attention appears to involve the inhibition of neural processing that is not relevant to the task currently being focused on, through complex networks of inhibitory neurons, emanating from frontal regions (Knudsen, 2018; Salo et al., 2017). Perhaps activation of the neocortical representations of the primed stimuli was suppressed as part of this inhibition of task-irrelevant brain activity.

One might speculate that these inhibitory attentional networks may also be involved in the suppression of consolidation processes in the hippocampus. In this case, the benefits of wakeful rest for explicit memory relative to a control task will depend on the degree of attentional demands made by the control task. Consistent with this, Collins and Walmsley (2020) compared standard wakeful rest and breath-focused mindful meditation. Participants who reported spending more time focused on the meditation were more likely to show a deficit in subsequent explicit memory performance in the meditation condition relative to the wakeful rest condition, whereas those who spent less time focused on the meditation showed an advantage in the meditation condition. Collins and Walmsley argued that this suggests that the engagement of frontal executive systems in focusing attention on tasks may interfere with hippocampal consolidation processes. The suggestion would seem to be contradicted by the studies of Varma et al. (2017, 2018) in which the n-back test, which also makes attentional demands, did not impair performance relative to standard wakeful rest. However, these studies involved university students and the n-back level used was not particularly demanding (n=2 or n=3). It could be that the control task placed insufficient attentional demands on the participants and therefore inhibition of other neural activities was not required. Some studies have compared the benefits of wakeful rest for neurologically intact participants and those with cognitive impairments due to conditions such as dementia (Dewar et al., 2009; Dewar, Pesallaccia, et al., 2012) and reported that the benefit is significantly greater for the cognitively impaired groups. This might reflect a reduced ability in these groups to maintain parallel neural processing and therefore a lower threshold for inhibiting consolidation activities.

In summary, the present findings are consistent with the suggestion that reducing sensory input is not necessary to obtain benefits from what the participant does in the period between exposure and retrieval test. However, the mechanisms underlying the benefits of relaxation on priming in the present study are unclear. The suggestion that it acted to suppress autobiographical and other thinking that interfered with hippocampal processes involved in consolidation (the explanation used by Varma to explain the impact of their n-back task) seems implausible because the control task was more likely to have suppressed such thinking compared to relaxation. It could be that relaxation proactively boosts these consolidation processes, rather than simply suppressing interference. Alternatively, it may be that the benefits of relaxation on priming are unrelated to the hippocampal system, and the attentional demands of the control task may have led to inhibition of the activity in neocortical representations that underpins priming. The study was not designed to test any of these different hypotheses about the mechanism of effect and further work is needed to establish how priming benefits from wakeful rest.

**Practical implications**

The findings also have implications for memory rehabilitation. Acquired memory impairments are typically characterised by difficulties with explicit memory, and implicit memory abilities are often relatively spared (Schacter & Buckner, 1998). It is important, therefore, to find ways of enabling those with typical memory impairments to make best use of their implicit memory as a way of compensating for the deficits in their explicit memory (Riley & Venn, 2015; Wilson & Fish, 2018).

Indeed, there is evidence suggesting that, in some circumstances, those with more severe memory impairments should actively avoid using explicit memory at the encoding and retrieval stages. This suggestion seems counterintuitive. According to some general theories of memory, an act of implicit memory (i.e. no intention to retrieve) can, by definition, only involve implicit processes, but an act of explicit memory (i.e. intentional retrieval) typically involves both implicit and explicit processes (e.g. Moscovitch, 2008; Yonelinas & Jacoby, 2012). This would seem to imply that those with explicit impairments should always try to remember (i.e. use their explicit memory) because, even if this is impaired, using residual explicit memory in conjunction with intact implicit memory would still be more effective than using intact implicit memory alone. However, this implication is not valid if, as the evidence suggests (e.g. Borragan et al., 2016; Gagne & Cohen, 2016), explicit encoding and retrieval strategies can interfere with implicit memory. Reliance on implicit memory alone may lead to better performance than explicit memory when the benefits of involving explicit memory are outweighed by the interference costs arising from its impact on implicit memory (Riley & Venn, 2015). This is most likely to occur when the explicit impairments are more severe because the benefits associated with the involvement of explicit memory are likely to be relatively low. To test this hypothesis, Riley and Venn (2015) compared encoding and retrieval instructions designed to encourage reliance on implicit memory alone, with encoding and retrieval instructions designed to encourage the use of explicit memory. Those with more moderate memory and executive impairments performed better under explicit instructions on both an immediate and a delayed (one week) retrieval test. Those with more severe impairments also performed better under explicit instructions on the immediate test, but performed better under implicit instructions on the delayed test. If it is the case that those with more severe impairments should avoid explicit memory in some circumstances, knowing how best to facilitate implicit memory becomes even more important for this group.

Given the evidence of the benefits of wakeful rest on priming for people with acquired memory impairments in the present study, further investigation of its practical relevance is warranted. Priming effects in this study were assessed after a relatively brief period. The impact of wakeful rest on longer term priming needs to be evaluated because the benefits would be of less practical interest if these are very short-lived. It would also be useful to explore whether the benefits of wakeful rest that have been observed for other forms of implicit learning (Humiston & Walmsley, 2018; Mednick et al., 2009) also occur for people with acquired memory impairments.

**Limitations**

An alternative explanation of the findings is that the impact of wakeful rest was on retrieval rather than the storage/consolidation. It could be that participants were more relaxed when completing the priming tasks following the wakeful rest condition compared to the control condition because the effects of taking part in the relaxation exercise persisted through to the completion of the priming tasks, and that being more relaxed at the point of retrieval enhanced priming performance. However, this seems an improbable explanation. Even though it always followed the stem completion task, the identification task also showed a significant advantage for the wakeful rest condition. It seems unlikely that the effects of a relatively brief use of a relaxation technique persisted through performance of the stem completion task (which required active attention to the task of digesting instructions and completing three practice items and 20 word stems over a period of several minutes), and then had a significant impact on retrieval in the identification task.

Other procedural limitations include the restricted evaluation of the effectiveness of the experimental manipulations in inducing relaxation and heightened attention, and the use of different relaxation techniques. Heart rate was the only evaluation made of whether the participant was in a relaxed or aroused state. Other methods could have been used, but using equipment on the body of people who have been through the trauma of a brain injury can be disconcerting for them, and heart rate was chosen because it could be monitored in an unobtrusive way using a commercially available activity wristwatch. Using different relaxation techniques could have affected underlying memory processes in different ways – for example, relaxing music may have provided more opportunity for off-task mind-wandering and autobiographical thinking than progressive muscle relaxation. However, using the same technique for all participants ran the risk of not ensuring that all participants were effectively relaxed. People vary considerably in how well they respond to different relaxation techniques and some people can even find some techniques unsettling rather than relaxing (Manzoni et al., 2008). This was confirmed by the heart rate data and informal feedback from participants in the first session when they chose a technique. Some participants did not like using some of the techniques and showed no reduction in heart rate in response. Furthermore, subsidiary analysis showed no impact of the different techniques on priming performance, although the low statistical power of the analysis should be noted.

**Acknowledgements**

Thanks to Barbara Hagger who assisted with the data collection, and to Headway for facilitating the research

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

**Open practices statement**

The experiment reported in this article was not formally preregistered. A copy of the data file is available at: https://data.mendeley.com/datasets/3hrsn38jvy/1

Requests for materials can be sent via email to the lead author at g.a.riley@bham.ac.uk

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