Effects of Sleep and Relaxation on Prospective Memory

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Mateja Böhm
aus Köln

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aus dem Institut für Experimentelle Psychologie
der Heinrich-Heine-Universität Düsseldorf

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Berichterstattung:

1. Prof. Ute J. Bayen, Ph.D.

2. Prof. Dr. Reinhard Pietrowsky

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Zusammenfassung

Ereignis-basiertes prospektives Gedächtnis ist die Fähigkeit, Intentionen auszuführen, sobald bestimmte Ereignisse eintreffen (Einstein & McDaniel, 1990). Die erfolgreiche Ausführung dieser Intentionen basiert auf zwei Komponenten: Der prospektiven Komponente (erinnern, *dass* man eine Intention hat) und der retrospektiven Komponente (erinnern, *was* die Intention ist und *wann* sie ausgeführt werden soll). Da das prospektive Gedächtnis im Alltag eine zentrale Rolle spielt, ist es von immenser Bedeutung, Faktoren zu untersuchen, die das prospektive Gedächtnis beeinflussen. Ein wichtiger Einflussfaktor ist Schlaf. Bisherige Studien konnten bereits zeigen, dass Schlaf *zwischen* dem Fassen und Ausführen einer Intention das prospektive Gedächtnis verbessert (z.B. Scullin & McDaniel, 2010), während Schlaf *vor* dem Fassen und Ausführen einer Intention nur in manchen Studien mit dem prospektiven Gedächtnis zusammenhing (z.B. Fabbri, Tonetti, Martoni, & Natale, 2014; aber siehe auch Rendell, Gray, Henry, & Tolan, 2007). Allerdings wurde in all diesen Studien nicht angemessen zwischen der prospektiven und retrospektiven Komponente getrennt, sodass die Bedeutung von Schlaf für die einzelnen Komponenten weiterhin unklar ist. Das Ziel der vorliegenden Arbeit ist es, zu untersuchen, welche der Komponenten des prospektiven Gedächtnisses von Schlaf beeinflusst werden und durch welche Mechanismen dies geschieht. Dazu wurden fünf Experimente durchgeführt. Die Komponenten wurden mithilfe des multinomialen Modells für ereignisbasiertes prospektives Gedächtnis getrennt (Smith & Bayen, 2004).

In Experiment 1 untersuchte ich den Einfluss von Nachtschlaf auf das prospektive Gedächtnis. Es zeigte sich ein positiver Effekt von Schlaf auf die prospektive Komponente. Das Ergebnismuster weist darauf hin, dass dieser Effekt durch aufgefrischte Aufmerksamkeitsressourcen und die Konsolidierung der Assoziation zwischen der Intention und des Ausführungskontexts zustande kam. Ein positiver Effekt von Schlaf auf die retrospektive Komponente wurde möglicherweise durch einen Tageszeiteffekt verdeckt.

In den Experimenten 2 und 3 untersuchte ich den Einfluss von Entspannung auf das prospektive Gedächtnis. Entspannung ähnelt Schlaf dahingehend, dass Entspannung ein Zustand geringer Interferenz ist (vergleiche Schichl, Ziberi, Lahl, & Pietrowsky, 2011) und einen positiven Einfluss auf Aufmerksamkeitsprozesse hat (z.B. Lutz et al., 2009). Somit können diese Mechanismen hinter dem positiven Effekt von Schlaf auf das prospektive Gedächtnis untersucht werden, ohne den Einfluss der aktiven Gedächtniskonsolidierung, die während des Schlafens stattfindet. Entspannung führte zu einer besseren prospektiven Komponente, was vermutlich auf aufgefrischte Aufmerksamkeitsressourcen zurückzuführen ist. Allerdings hatte Entspannung keinen Einfluss auf die retrospektive Komponente. Dies spricht gegen geringe Interferenz als Mechanismus des Effekts von Schlaf auf die retrospektive Komponente.

In den Experimenten 4 und 5 untersuchte ich den Einfluss von Schläfrigkeit und Schlafqualität als Nachwirkungen vorangegangenen, schlechten Schlafs auf das prospektive Gedächtnis. Schläfrigkeit und Schlafqualität alleine zeigten keinen Zusammenhang mit den Komponenten des prospektiven Gedächtnisses. Allerdings war Schläfrigkeit ein Moderator des Zusammenhangs zwischen der prospektiven Komponente und Schlafqualität: Unter hoher Schläfrigkeit hatte schlechte Schlafqualität einen negativeren Einfluss auf die prospektive Komponente als unter niedriger Schläfrigkeit. Dies zeigt, dass Schlaf auch dann einen Einfluss auf das prospektive Gedächtnis haben kann, wenn er vor Fassen und Ausführen der Intention stattfindet.

In der vorliegenden Arbeit konnte ich zeigen, dass Schlaf die prospektive Komponente verbessert. Das Ergebnismuster legt nahe, dass dies durch die Auffrischung von Aufmerksamkeitsressourcen und die Konsolidierung der Assoziation zwischen der Intention und des Ausführungskontexts geschieht. Zudem führt die Konsolidierung der Zielworte während des Schlafs vermutlich zu einer Verbesserung der retrospektiven Komponente. Geringe Interferenz scheint dabei keine Rolle zu spielen. Des Weiteren moderiert Schläfrigkeit den Zusammenhang zwischen Schlafqualität und der prospektiven Komponente. Zusammenfassend lässt sich sagen, dass die vorliegende Arbeit dazu beiträgt, die Effekte von Schlaf auf das prospektive Gedächtnis sowie die zugrundeliegenden Mechanismen zu entschlüsseln. Dies kann als Grundlage für die Prävention von prospektiven Gedächtnisfehlern bei Personen, die an Schlafstörungen leiden, dienen.

Abstract

Event-based prospective memory entails carrying out intentions upon certain events (Einstein & McDaniel, 1990). Successful prospective memory is based on two components: The prospective component (remembering *that* an intention needs to be carried out) and the retrospective component (remembering *what* the intention is and *when* it has to be carried out). Prospective memory is central in everyday life. Thus, it is crucial to identify factors affecting prospective memory. One of these factors is sleep. Previous studies have shown that sleep taking place *between* forming and carrying out an intention improves prospective memory (e.g., Scullin & McDaniel, 2010), while sleep *before* forming and carrying out an intention seemed to affect prospective-memory performance in some studies only (e.g., Fabbri, Tonetti, Martoni, & Natale, 2014; but see Rendell, Gray, Henry, & Tolan, 2007). All of these studies did not distinguish between the prospective and the retrospective components, so that the effect of sleep on the separate components is still unclear. The present work aimed at establishing the effect of sleep on the separate components and the mechanisms at play in five experiments. I disentangled the components of prospective memory using the multinomial model of event-based prospective memory (Smith & Bayen, 2004).

In Experiment 1, I investigated the effect of nighttime sleep on prospective memory. Sleep enhanced the prospective component. The pattern of results suggests that this effect was due to refreshed attentional resources and consolidation of the association between the intention and its appropriate context. A positive effect of sleep on the retrospective component was possibly masked by a time-of-day effect.

In Experiments 2 and 3, I investigated the effects of relaxation on prospective memory. Relaxation is akin to sleep because both entail low interference (cf. Schichl, Ziberi, Lahl, & Pietrowsky, 2011) and have positive effects on attentional resources (e.g. Lutz et al., 2009). This enabled me to investigate these two mechanisms possibly driving the effect of sleep on prospective memory without the influence of active memory consolidation, which takes place during sleep. In both experiments, relaxation improved the prospective component, which may be attributed to refreshed attentional resources. However, relaxation did not affect the retrospective component. This speaks against low interference as a mechanism driving the positive effect of sleep on the retrospective component.

In Experiments 4 and 5, I investigated the influence of sleepiness and sleep quality as consequences of previous poor sleep on prospective memory. Sleepiness and sleep quality per se were not related to the components of prospective memory. However, sleepiness was a moderator of the relationship between sleep quality and the prospective component: Worse sleep quality lead to a more negative

effect on the prospective component in a condition with high sleepiness. This shows that sleep may affect prospective memory, even if it takes place before forming and carrying out an intention.

In the current work, I showed that sleep enhances the prospective component. The pattern of results indicates that refreshed attentional resources and consolidation of the association between the intention and its appropriate context may be the driving mechanisms. Additionally, while consolidation of the prospective-memory target words during sleep seems to improve the retrospective component, low interference does not seem to be a mechanism driving the effect of sleep on the retrospective component. Furthermore, sleepiness is a moderator of the relationship between sleep quality and the prospective component. In conclusion, the present work has contributed greatly to establishing effects of sleep on prospective memory and identifying the mechanisms driving the positive effect of sleep on prospective memory. On this basis, prospective-memory failures in individuals suffering from sleep disorders may be prevented.

1. Introduction[1]

1.1 Prospective Memory

Prospective memory (PM) involves remembering to carry out intentions at the appropriate time (e.g., Einstein & McDaniel, 1990). For instance, a diabetic may have to take insulin upon being served a meal. Successful PM has two components (Einstein & McDaniel, 1990): The *prospective component* involves remembering *that* an intention needs to be carried out and the *retrospective component* involves remembering *what* the intention is and *when* it should be carried out. For instance, a diabetic must not only remember having an additional intention while actively engaging in a conversation at a restaurant (prospective component). He must also remember the content of the intention, this is, take insulin when recognizing that the waiter approaches with the ordered food (retrospective component).

PM is ubiquitous in daily life and important in many jobs and professions such as health care, air traffic control, and office work (e.g., Dismukes, 2012; Grundgeiger, Sanderson, MacDougall, & Venkatesh, 2010; Wilson, Farrell, Visser, & Loft, 2018). Failures in PM occur often and may have severe consequences (Terry, 1988). It is, therefore, important to identify factors affecting PM. Several previous studies demonstrated a positive effect of sleep on PM (Barner, Seibold, Born, & Diekelmann, 2017; Diekelmann, Wilhelm, Wagner, & Born, 2013a, 2013b; Scullin & McDaniel, 2010). The present research aimed at further establishing and investigating sleep as a benefiting factor for PM.

PM tasks can be categorized in event-based and time-based tasks. Event-based PM tasks require carrying out an intention when a certain event occurs, whereas time-based PM tasks require carrying out an intention at a certain point in time or after a certain amount of time has elapsed (Einstein & McDaniel, 1990; Smith, 2008). For example, nurses who measure blood pressure whenever a patient arrives at the hospital perform an event-based PM task, whereas nurses who measure a patient's blood pressure every morning at 8 a.m. perform a time-based PM task. Due to the fundamental differences between both task types, the research presented here is limited to event-based PM.

1.2 Prospective-Memory Paradigm

The type of computerized event-based PM task used in the present research was first introduced by Einstein and McDaniel (1990) and has since been proven useful in myriads of laboratory PM studies (Kliegel, McDaniel, & Einstein, 2008). The task paradigm involves an ongoing task with an embedded

[1] The introduction was partially adopted from Manuscripts 1, 2, and 3 in the Appendix.

PM task. The ongoing task must be interrupted when a target event occurs that signals the necessity to carry out a PM task. This is akin to, for example, a nurse who must interrupt her ongoing administrative work whenever she needs to measure an arriving client's blood pressure. In the following experiments, the ongoing task was a color-matching task, where participants had to indicate whether a word had the same color as one of four previously presented rectangles (c.f. Smith & Bayen, 2004). The embedded PM task was to press a specific key whenever participants encountered one of several previously studied words during the ongoing task. The prospective component of this PM task is to remember that one has to do something in addition to the ongoing task; the retrospective component is to recognize the studied PM target words when they occur during the ongoing task.

The target events in this PM task are nonfocal to the ongoing task because they are defined by different features than those that are relevant for the ongoing task (see McDaniel & Einstein, 2007). Thus, in this task, participants need to shift their attentional focus from the features relevant for the ongoing task to the features relevant for the PM task. For example, in the color-matching task used here, participants must shift attention from the color of the words to their meaning. There is consensus among PM researchers that in nonfocal PM tasks, the prospective component depends on attentional processes (McDaniel & Einstein, 2000; Scullin, McDaniel, & Shelton, 2013; Smith, 2003; for empirical demonstrations, see e.g., Burgess, Quayle, & Frith, 2001; Cona, Scarpazza, Sartori, Moscovitch, & Bisiacchi, 2015; Kuhlmann & Rummel, 2014). In the nonfocal PM task used here, the retrospective component consists of target-word recognition: Participants have to recognize the PM target word presented to them before pressing the PM key. Thus, studies from other cognitive domains, such as attention and recognition memory, may be taken into account when constructing hypotheses separately for both PM components. This is especially so if PM literature on the subject at hand is scarce.

1.3 Disentangling the Prospective and Retrospective Components

The most common measure of PM performance is PM hit rate, which is the proportion of correct responses in PM target trials. This measure confounds the prospective component and the retrospective component, because in order to hit a PM target, participants must remember that they had to do something (prospective component) and must recognize the target word (retrospective component). A PM hit may also result from lucky guessing. Therefore, it is important to obtain separate and unconfounded measures of the prospective and the retrospective components. The multinomial processing tree (MPT) model of event-based PM introduced by Smith and Bayen (2004) provides such measures.

In general, MPT models allow us to estimate the probabilities of latent processes underlying performance from frequencies of participant responses in a particular task. MPT models are frequently used in cognitive psychology (for reviews, see Batchelder & Riefer, 1999, and Erdfelder et al., 2009). The MPT model of event-based PM was designed for ongoing tasks with two response options (e.g., the color-matching task where colors may or may not match) and an embedded PM task (e.g., when participants are required to press a specific key upon encountering target words). Thus, there are three response options: (a) the colors match, (b) the colors do not match, and (c) the word is a PM target. There are four different trial types: (1) target, color match; (2) target, no color match; (3) distractor, color match; (4) distractor, no color match. As any of the three responses can be given on any of the four trial types, there are 12 different response categories. The response frequencies in each category are tallied and analyzed with the model.

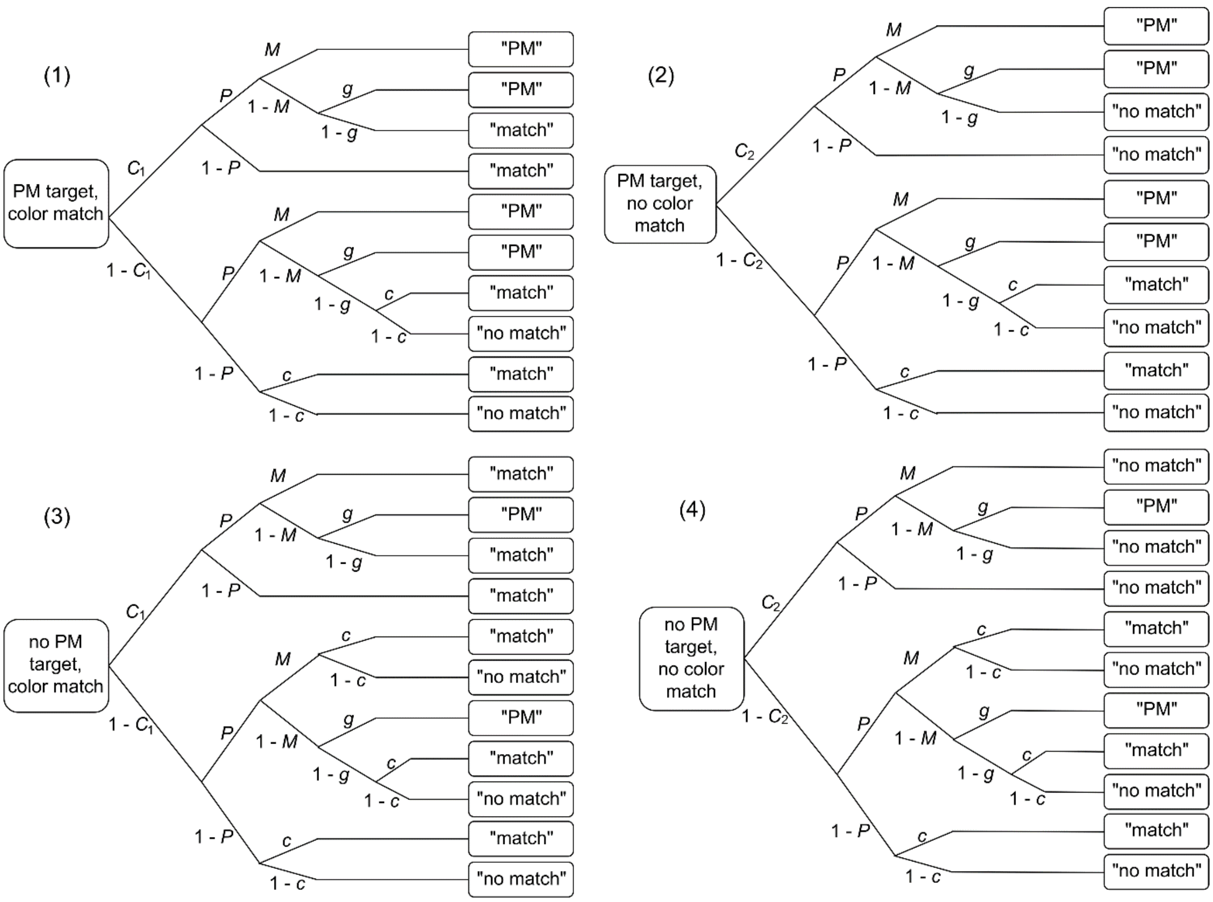

Figure 1.[2] The multinomial processing tree model of event-based prospective memory (PM) by Smith and Bayen (2004). C_1 = probability to detect that the colors match; C_2 = probability to detect that the colors do not match; *P* = prospective component; *M* = retrospective component; *c* = probability to guess that the colors match; *g* = probability to guess that the word is a PM target.

[2] Adapted from “A multinomial model of event-based prospective memory” by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, p. 758. Copyright 2004 by the American Psychological Association.

The MPT model of event-based PM is shown in Figure 1. Each of the trees represents one of the trial types. The first tree represents trials with a target word and a color match. Here, participants detect the color match with probability C_1. They may further remember that they have an intention, with probability *P* (prospective component). With probability *M* (retrospective component), they may correctly recognize the target word as such and thus press the PM key. If they do not recognize the target word, with probability 1 – *M*, they either guess that the word was a target (with probability *g*) or that it was a distractor (with probability 1 – *g*). If, on the other hand, participants do not remember that they have an intention, with probability 1 – *P*, they will answer "match" because they have detected the color match. The lower part of the tree represents cases in which participants do not detect the color match (with probability 1 – C_1). Nevertheless, they may remember that they had an intention with a probability of *P*. If they recognize the target word (*M*), they answer "PM". If alternatively, they do not recognize the word, they could guess that the word is a PM target (with probability *g*) or that it is not (1 – *g*). If they guess that the word is not a target, they must guess that the colors match, with probability *c*, or do not match (1 – *c*). Similarly, if participants do not remember that they had an intention (with probability 1 – *P*), they guess that the colors match, with probability *c*, or do not match (1 – *c*).

The second tree refers to trials with a target word, but without a color match, and is constructed in a similar manner. In this tree, parameter C_2 indicates the probability with which participants detect that the colors do not match and leads to "no match" responses.

The third tree refers to trials without a target word and with a color match and is constructed in a similar manner as the first tree. With probability *M*, participants recognize the word is a distractor. Whenever participants recognize the distractor or guess that the word is a distractor, they answer the color-matching task and do not press the PM key. Therefore, when participants do not detect the color match, but recognize the distractor as such, they guess that the color matches (with probability *c*) or not (1 – *c*).

The fourth tree refers to trials without a target word and without a color match and is similar to the third tree. Here, parameter C_2 represents the probability with which participants detect that the colors do not match.

Due to limited degrees of freedom, parameter restrictions need to be set to obtain an identifiable model. Following the recommendations by Smith and Bayen (2004), I set guessing parameter *c* equal to the actual ratio of color matches and guessing parameter *g* equal to the actual ratio of target words at test, assuming that guessing probabilities matched the actual ratios (probability-matching, e.g., Buchner, Erdfelder, & Vaterrodt-Plünnecke, 1995; Van Zandt, 2000). The MPT model of PM has been shown to be valid in nonfocal PM tasks (Horn, Bayen, Smith, & Boywitt, 2011; Rummel, Boywitt, & Meiser, 2011; Smith & Bayen, 2004) and has been used in a number of previous studies (e.g., Arnold, Bayen, & Böhm, 2014; Arnold, Bayen, & Smith, 2015; Pavawalla, Schmitter-Edgecombe, & Smith, 2012; Schnitzspahn, Horn, Bayen, & Kliegel, 2012; Smith & Bayen, 2005, 2006; Smith, Bayen, & Martin, 2010).

Usually, the observed categorical data is collapsed across participants and group parameters are estimated via maximum-likelihood estimation (Hu & Batchelder, 1994). The model fit can be evaluated using the asymptotically chi-square distributed goodness-of-fit index G^2. I used group-based multinomial analyses in Experiments 1, 2, and 3. In addition, I reparameterized the MPT model of event-based PM according to Knapp and Batchelder (2004) in Experiment 1. The reparameterized model includes reduction rates for parameters *P* and *M*, thereby modelling the changes in parameter estimates between two time points. This modification allowed me to test for interactions by comparing the reduction rates between two groups.

In contrast to these group-based multinomial analyses, the Bayesian hierarchical latent-trait approach (Klauer, 2010) provides model parameters for each participant separately. The latent-trait approach takes correlations between parameters into account and postulates that the individual parameters stem from an overarching multivariate normal distribution. Using the latent-trait approach, the distributions for each parameter at group level and at the individual level, as well as the distribution for each parameter correlation, are estimated. For each of these distributions, a prior distribution is assumed. The data update the prior distribution, so that the posterior distribution is obtained (Bayes' theorem). Samples from these posterior distributions are drawn using the Markov chain Monte Carlo algorithm. These samples provide information about the properties of these distributions (i.e., centrality and variance parameters). The uncertainty expressed by variance parameters is also considered when computing regressions between individual parameter estimates and extraneous variables. I used this approach to compute correlations between sleep-related variables and the prospective and retrospective components in Experiments 4 and 5.

1.4 The Current Work

Although previous studies have shown a sleep benefit for PM, no studies on sleep and PM have conclusively differentiated between the prospective and retrospective components of PM. Hence, the first aim of the present research was to further define the effect of nighttime sleep on PM by determining its effects on the prospective and retrospective components of PM.

The second aim of the present research was to identify the mechanisms driving the beneficial effect of sleep on the components of PM. Knowing these mechanisms may open venues for intervention with individuals who suffer from PM deficits. In retrospective-memory literature, two kinds of sleep functions are discussed (for a review, see Rasch & Born, 2013): Sleep may benefit retrospective memory *actively* via memory consolidation or *passively* by shielding acquired information from interference. However, as outlined above, PM does not only include a retrospective component, but also the prospective component, which is unique to PM. The prospective component may additionally benefit from refreshed attentional resources after sleep episodes because the prospective component is related to attention. Overall, four mechanisms may underlie the effect of sleep on PM: (1) refreshed attentional resources (Kirszenblat & van Swinderen, 2015; Lo et al., 2012), (2) consolidation of the link between the intention and its appropriate context (Scullin & McDaniel, 2010), (3) consolidation of PM target words (Rasch & Born, 2013), and (4) shielding the PM target words from retroactive interference (Wixted, 2004). Apart from mechanism (2), none of the mechanisms have been investigated with regard to their effect on PM. Thus, the present work adds to the existing literature by identifying the mechanisms driving the beneficial effect of sleep on the components of PM.

In contrast to the effect of sleep during the retention interval on PM, the consequences of insufficient sleep for PM have received little attention. Although some studies examined effects of sleepiness and poor sleep quality on PM (Fabbri, Tonetti, Martoni, & Natale, 2014, 2015; Ohayon & Vecchierini, 2002; Rendell, Gray, Henry, & Tolan, 2007; Rendell, Mazur, & Henry, 2009), the studies confounded the prospective and retrospective components and lead to mixed findings. Thus, the third aim of the research presented here was to investigate whether sleepiness and poor sleep quality impair the components of PM, using reliable methods and Bayesian statistics.

2. Prospective Memory and Nighttime Sleep[3]

Previous studies showing a beneficial effect of sleep on PM (e.g., Diekelmann et al., 2013a) confounded the prospective and retrospective components of PM. Thus, Experiment 1 served to establish effects of nighttime sleep on the different components of PM.

The beneficial effect of nighttime sleep on PM may be ascribed to the four mechanisms outlined in the introduction. Experiment 1 aimed at identifying the mechanisms underlying the effect of sleep on PM. I will now describe how these mechanisms may affect the prospective and retrospective components of PM, before I turn to briefly describing Experiment 1. A detailed report of Experiment 1 is in Manuscript 1.

[3] Section 2 was partially adopted from Manuscript 1 in the Appendix.

The first two mechanisms may affect the prospective component. (1) During nonfocal PM tasks, the prospective component relies on attentional processes. Thus, if sleep refreshes attentional processes, then the prospective component should benefit from sleep. In fact, previous studies have shown that sleep deprivation impairs attention (Alhola & Polo-Kantola, 2007; Kirszenblat & van Swinderen, 2015; Lim & Dinges, 2010; Lo et al., 2012), indicating that the prospective component too should be impaired after prolonged wakefulness.

(2) Scullin and McDaniel (2010) showed that sleep strengthens the association between an intention and its context. For example, if your intention is to buy milk on your way to work, sleep may strengthen the association between your intention (buying milk) and the appropriate context (your way to work). If your intention–context association is strong, you will be more likely to retrieve the intention when you are in the appropriate context (on your way to work). According to Scullin et al. (2013), retrieval of an intention in turn leads to the strategical recruitment of attentional resources in order to monitor for PM target events (i.e., a better prospective component). Hence, stronger intention–context associations following sleep should lead to an enhanced prospective component.

(3) The third mechanism may affect the retrospective component. Sleep benefits retrospective memory including recognition memory by promoting memory consolidation (Rasch & Born, 2013). In particular, future-relevant information (i.e., information that the participant expects to be tested on in the future) benefits from sleep (Wilhelm et al., 2011). For PM tasks, this means that sleep should enhance the memory representation of PM target words. Thus, participants should more easily recognize PM target words during the ongoing task after sleep as compared to wakefulness. That is, the retrospective component should be improved.

(4) The fourth mechanism may likewise affect the retrospective component. By shielding the PM target words from interference, sleep should lead to an improved memory representation of PM target words. This should enhance the retrospective component.

2.1 Experiment 1

The design of Experiment 1 is illustrated in Figure 2. Participants completed one testing session at 8 a.m. and one at 8 p.m. In the first session, participants performed a PM task embedded in an ongoing task. Afterwards, they studied new PM target words and were instructed to carry out the intention during the second session, which took place after a retention interval of approximately 12 hours. For participants in the wake group (n = 31), the first session was in the morning and the second session in the evening, so that they were awake during the retention interval. For the sleep group (n = 31), the

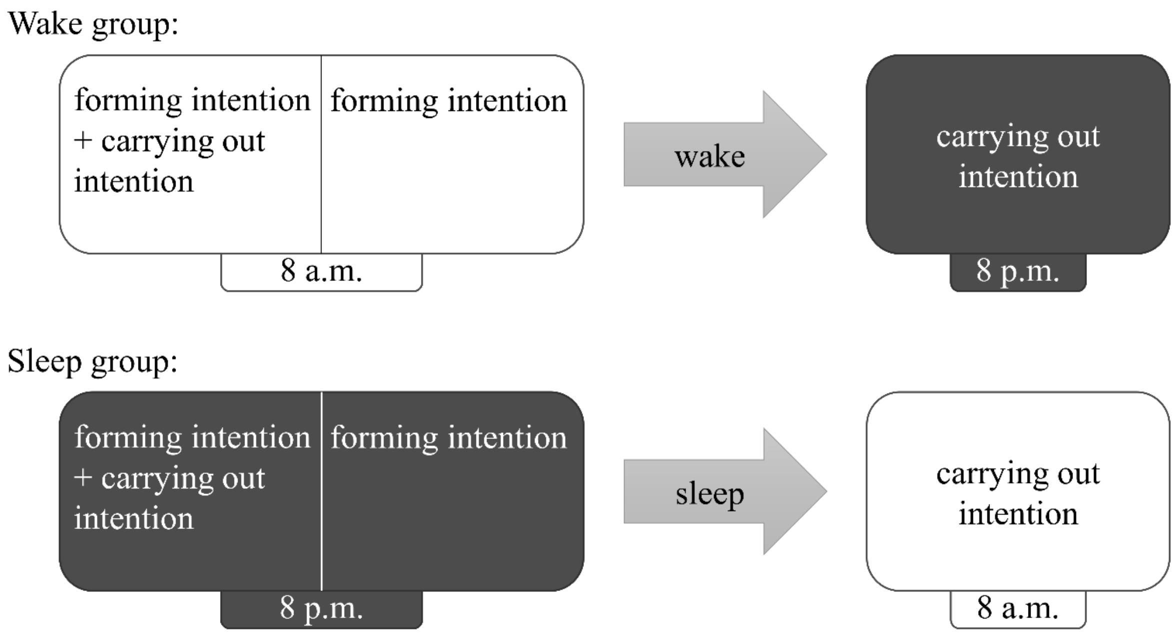

Figure 2. Study design in Experiment 1.

first session was in the evening and the second in the morning, so that they were asleep for (part of) the retention interval. I administered a PM task in the first session to control for time-of-day effects. Including a PM task at the first session further enabled me to derive different hypotheses for each of the postulated mechanisms. Thus, depending on the pattern of results, I could deduce which mechanism drove the beneficial effect of sleep on PM.

I expected a decline in the prospective component from the first to the second session due to the different lengths of the retention intervals. Consolidation of the intention–context association and refreshing of attentional resources should both increase the prospective component after sleep. However, both lead to somewhat different hypotheses. Critically, I expected different types of interaction depending on the mechanisms underlying sleep effects: Intention–context consolidation should lead to an ordinal interaction, whereas refreshed attentional resources should lead to a hybrid interaction. If the intention–context association is consolidated during sleep, this should result in a benefit for the prospective component of the sleep group in the second session only. In the first session, by contrast, the two groups should not differ. This pattern constitutes an ordinal interaction, that is, from the first to the second session, the prospective component declines less in the sleep group as compared to the wake group. If sleep benefits the prospective component via refreshed attentional resources, this mechanism should benefit the prospective component in the morning, regardless of whether sleep took place during the retention interval or not. Thus, in the first session, the wake group should show a higher prospective component than the sleep group. The sleep group, on the other hand, should show a higher prospective component in the second session. As these effects are based on the same mechanism, they should be of the same size at both time points, but in opposite directions. Thus, refreshed attentional resources following sleep would result in a hybrid interaction.

I now turn to predictions for the retrospective component. This component should also decline from the first to the second session due to the longer retention interval. However, in the sleep group, the consolidation of PM target words as well as the protection of the PM target words against interference should counteract this decline. Thus, I predicted an ordinal interaction with similar levels of the retrospective component in the first session, followed by a stronger decline in the wake group than in the sleep group as measured in the second session.

Figure 3 illustrates the results of Experiment 1. Against our expectations, nighttime sleep exclusively improved the prospective component, which is the unique characteristic of PM. In addition, there is a statistical trend indicating a small advantage in the prospective component of the wake group over the sleep group.

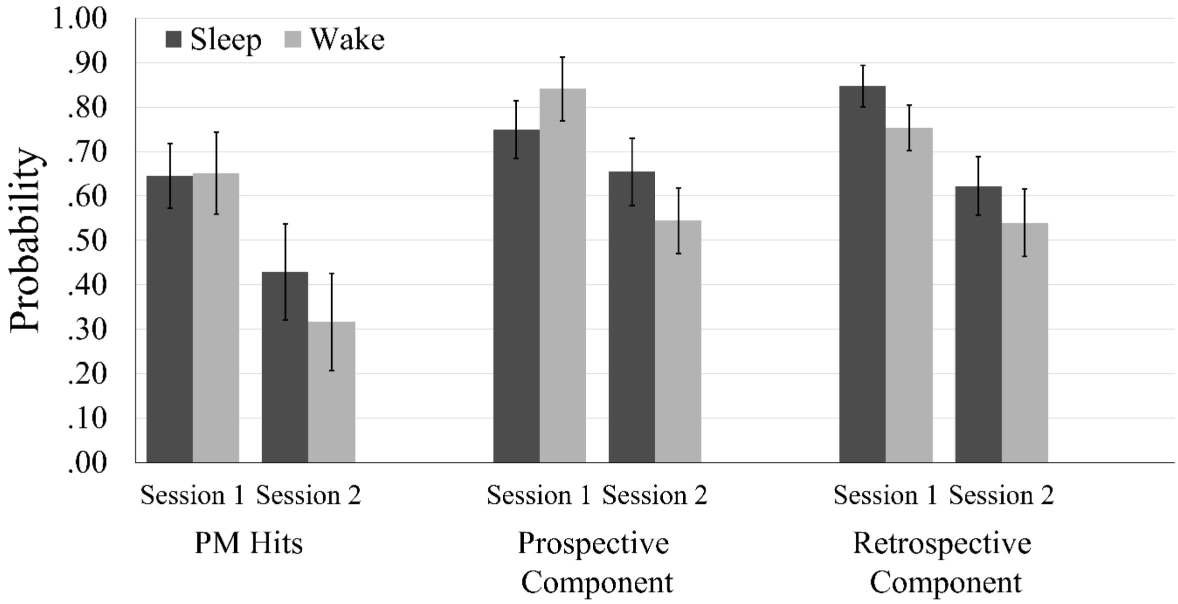

Figure 3. Mean prospective-memory (PM) hit rate and the model estimates of the prospective and the retrospective components of PM for the sleep group and the wake group in the two sessions. Error bars indicate 95% confidence intervals.

2.2 Discussion

The pattern of results regarding the prospective component appears to reflect a combination of two mechanisms: A statistical trend in the first session indicating a small advantage in the prospective component of the wake group over the sleep group suggests a benefit in the wake group from refreshed attentional resources in the morning. In the second session, in turn, the advantage in the prospective component of the sleep group over the wake group was larger than the advantage of the wake group over the sleep group in the first session (i.e., a significant interaction). This pattern of results suggests that in the second session, the sleep group benefitted from both, consolidation during sleep and from refreshed attentional resources. I thus conclude that both mechanisms contributed to the effects of sleep on the prospective component.

An effect of sleep on the retrospective component was possibly masked by a time-of-day effect, leading to better recognition memory in the evening as compared to the morning. Whether the effect of sleep on the retrospective component may be attributed to active consolidation processes or low interference during sleep, is unclear at this point. However, this issue will be addressed in Experiments 2 and 3.

Overall, Experiment 1 is the first study on the effect of sleep on PM to properly disentangle the prospective and retrospective components. The results show that the prospective and the retrospective components of PM benefit from nighttime sleep via different mechanisms. The prospective component benefits from refreshed attentional resources and consolidation of the intention–context association during sleep. The retrospective component is enhanced via consolidation of PM target words or low interference during sleep. These insights may help to understand PM failures in individuals suffering from sleep disorders (e.g., idiopathic REM sleep behavior disorder; Bezdicek et al., 2018).

3. Prospective Memory and Relaxation[4]

In Experiment 1, I investigated the mechanisms driving the beneficial effect of sleep on PM. Interference and refreshed attentional resources are two of the mechanisms, which may underlie this effect of sleep on PM. I investigated whether interference and refreshed attentional resources may account for (part of) the sleep benefit for PM in Experiments 2 and 3 by using a relaxation manipulation.

Relaxation has been argued to be similar to midday sleep in reducing interference from new information (Schichl, Ziberi, Lahl, & Pietrowsky, 2011; Schönauer, Pawlizki, Köck, & Gais, 2014). Thus, relaxation is particularly suitable to investigate the effect of low interference on PM, without the active consolidation processes that come along with sleep. A positive effect of relaxation on PM may thus indicate that low interference also plays a role in the effect of sleep on PM. Critically, relaxation

[4] Section 3 was partially adopted from Manuscript 2 in the Appendix.

should influence the retrospective component by shielding the PM target words from retroactive interference.

Furthermore, relaxation is akin to sleep because attention has been shown to benefit from different types of relaxation (e.g., Ainsworth, Eddershaw, Meron, Baldwin, & Garner, 2013; Legostaev, 1996; Lutz et al., 2009; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). Therefore, by enhancing attentional processes, relaxation should also have a beneficial effect on the prospective component in Experiments 2 and 3. This would also corroborate the findings from Experiment 1.

If relaxation has a beneficial effect on PM, this may also have practical implications: While sleep has been shown to be a means to improve PM, sleep is not a viable option in every situation to promote PM. During breaks, workers may have problems falling asleep, may need to be on stand-by, or the setting does not promote sleep. Relaxation, by contrast, can be easily implemented in many settings and can be easily interrupted when necessary rendering it applicable for clerks, nurses, and pilots, for example. I therefore performed Experiments 2 and 3 to investigate whether relaxation has a positive effect on event-based PM. In the following, I will briefly describe Experiments 2 and 3. A detailed report of Experiments 2 and 3 is in Manuscript 2.

3.1 Experiment 2

In Experiment 2, participants either received relaxation-hypnosis or played a computer game during the retention interval between forming and carrying out the intention. Because relaxation has been shown to benefit attentional processes (Ainsworth et al., 2013), I expected the prospective component to be superior after relaxation-hypnosis.

It is reasonable to assume that relaxation, in addition to positively affecting the prospective component of the task by benefitting attention, may also benefit the retrospective component, as some studies measuring retrospective memory alone found positive effects of relaxation on retrospective memory (Nava, Landau, Brody, Linder, & Schächinger, 2004; Schichl et al., 2011). However, Schönauer et al. (2014) did not find a beneficial effect of meditation on recognition nor recall. Overall, the retrospective component may also be enhanced after relaxation-hypnosis, as relaxation improves retrospective memory in some studies.

In this first experiment of effects of relaxation-hypnosis on event-based PM, I showed that PM performance benefitted from relaxation-hypnosis. Disentangling this effect with the MPT model of event-based PM, I showed that it was due to a benefit to the prospective component of the PM task, not to the retrospective component. These findings indicate that relaxation-hypnosis may improve PM by enhancing attentional processes, thus leading to a better prospective component.

There was no effect on the retrospective component, which consists of target word recognition. As the parameter estimates for the retrospective component of the PM task were close to ceiling, it is possible that a ceiling effect may have obscured beneficial effects of relaxation on the retrospective component, a possibility that will be addressed in Experiment 3.

3.2 Experiment 3

Experiment 3 had two main objectives. First, I sought to replicate the beneficial effects of relaxation-hypnosis on the prospective component of PM. Second, I wanted to know if a ceiling effect possibly obscured effects of relaxation on the retrospective component. To avoid a ceiling effect in Experiment 3, I raised the retrospective-component demands of the task by increasing the number of to-be-remembered PM target words.

I expected that the prospective component would again benefit from relaxation-hypnosis. The retrospective component might also benefit once the ceiling effect was eliminated. In fact, I replicated the results from Experiment 2, showing that PM performance benefits from relaxation-hypnosis. Again, this benefit was driven by an effect of relaxation-hypnosis on the prospective component.

The two groups did not differ regarding the retrospective component, supporting evidence against an effect of relaxation on retrospective memory (Schönauer et al., 2014). The retrospective-component parameter M was not at ceiling in Experiment 3. Thus, after conducting this experiment, I can rule out an effect of relaxation on the retrospective component.

3.3 Discussion

Experiments 2 and 3 provided convincing evidence for a positive influence of relaxation-hypnosis on the prospective component of PM. This effect may be due to refreshed attentional resources after relaxation. Relaxation-hypnosis did not have an effect on the retrospective component, indicating that low interference may not drive the effect of sleep on the retrospective component.

The results suggest that relaxation improves the prospective component of PM by refreshing attentional resources. This indicates that occupational groups for which PM is critical (e.g., nurses, doctors, pilots) may benefit from relaxation exercises during breaks. Thus, future research should investigate whether relaxation is a viable approach toward improving PM in daily life.

4. Prospective Memory, Sleepiness, and Sleep Quality[5]

Experiment 1 and other studies have shown that PM benefits from sleep episodes taking place during the retention interval (Barner et al., 2017; Diekelmann et al., 2013a, 2013b; Scullin & McDaniel, 2010). In contrast, studies regarding the aftermath of poor sleep and its effect on PM are very scarce and have not distinguished between the prospective and retrospective components of PM. Thus, Experiments 4 and 5 aimed at investigating the effect of sleepiness and sleep quality on the prospective and retrospective components of PM. In the following, I will first outline why sleepiness should have an effect on PM, before turning to sleep quality. Afterwards, I will briefly describe Experiments 4 and 5. A detailed report of these Experiments is in Manuscript 3.

It seems reasonable to assume that higher levels of sleepiness should be associated with poorer PM: According to a meta-analysis by Lim and Dinges (2010), sleepiness induced by sleep deprivation impairs sustained attention. In turn, deficits in sustained attention may impair PM in nonfocal PM tasks as well. Two published studies investigated effects of sleepiness on event-based PM and provided some evidence for a detrimental effect of sleepiness on PM (Grundgeiger, Bayen, & Horn, 2014; Ohayon & Vecchierini, 2002). Again, these studies confounded the components of PM. This is problematic because studies from other cognitive domains suggest that sleepiness should have differential effects on the prospective versus retrospective components of PM. Sleepiness and partial sleep restriction (i.e., restricting sleep by several hours for a prolonged period of time) lower attention (Byun, Kim, & Riegel, 2017; Henelius et al., 2014; Kraemer et al., 2000; Lowe, Safati, & Hall, 2017; Maire et al., 2014; Shattuck & Matsangas, 2015). Thus, there is strong evidence for effects of sleepiness on attentional processes, and therefore, the prospective component of PM should also be impaired when a person is sleepy. There seem to be no effects of sleepiness induced by sleep deprivation or partial sleep restriction on recognition memory (Drummond et al., 2000; Lo, Chong, Ganesan, Leong, & Chee, 2016; Stenuit & Kerkhofs, 2008; Swann, Yelland, Redman, & Rajaratnam, 2006). The retrospective component should, therefore, be equally unaffected by sleepiness.

Previous studies suggested that sleep quality may affect PM performance (Fabbri et al., 2014), whereas other studies did not find correlations with either subjective sleep quality (Rendell et al., 2007, 2009), or objective sleep quality (Fabbri et al., 2015). The effect of sleep quality on PM is thus unclear at this point. Results regarding effects of sleep quality on sustained attention are mixed (Benitez & Gunstad, 2012; Byun et al., 2017), indicating that sleep quality may affect the prospective component of PM. The only study in which the effect of young adults' sleep quality on retrospective recognition memory was examined (Gobin, Banks, Fins, & Tartar, 2015) showed no association for

[5] Section 4 was partially adopted from Manuscript 3 in the Appendix.

stimuli with neutral valence. This suggests that sleep quality should not impair the retrospective component.

4.1 Experiment 4

In Experiment 4, I aimed at investigating effects of sleepiness and sleep quality on the components of PM. The PM task was performed by 118 participants. I measured sleepiness and sleep quality via reliable self-assessment questionnaires (Åkerstedt & Gillberg, 1990; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Based on the existing literature, I expected a detrimental effect of sleepiness and sleep quality on PM to be primarily driven by an effect on the prospective component. I computed Bayes Factors to directly compare the evidence for the null versus the alternative hypotheses (which is not possible in classical frequentist statistics). Thus, even if I did not find an influence of sleepiness or sleep quality on components of PM, I could quantify the evidence and assess whether a null effect was attributable to an insufficient number of observations or to the null hypothesis being true. This was of particular importance when establishing the expected null effects on the retrospective component.

Sleepiness and sleep quality predicted neither PM hit rate, nor the prospective or the retrospective component of PM. The Bayes Factors even indicated positive evidence for the null hypothesis, that is, an absence of an effect of sleepiness and sleep quality on the PM components.

For the prospective component, these results are surprising, because according to a meta-analysis of effects of sleepiness on attention (Lim & Dinges, 2010), sleepiness should impair the prospective component. However, the null effect of sleepiness on the retrospective component is in line with other studies that did not find a relationship between sleepiness and recognition memory (Drummond et al., 2000; Lo et al., 2016; Stenuit & Kerkhofs, 2008; Swann et al., 2006).

Sleep quality did not predict PM hit rate, which is not in line with Fabbri et al. (2014), but supports findings from other PM studies (Fabbri et al., 2015; Rendell et al., 2007, 2009). Further, neither PM component was predicted by sleep quality.

However, severe sleepiness or poor sleep quality alone may not be sufficient to impair PM, but some studies indicated that sleep-related variables may interact to have a detrimental effect on PM. Experiment 5 was conducted to solve this issue.

4.2 Experiment 5

In Experiment 5, I used a body-posture manipulation to induce sleepiness. According to the model of sleep and wakefulness by Johns (1993, 1998), a sleep drive and a wake drive determine the level of sleepiness. The stronger the sleep drive is in comparison to the wake drive, the sleepier the individual. Sleep drive can be increased via a manipulation of body posture: Lying in supine posture increases sleepiness and the urge to fall asleep in comparison with sitting upright (Caldwell, Prazinko, & Caldwell, 2003; Caldwell, Prazinko, & Hall, 2000; Cole, 1989; Kräuchi, Cajochen, & Wirz-Justice, 1997; Romeijn et al., 2012; Sharafkhaneh & Hirshkowitz, 2003). Thus, in Experiment 5, participants performed the task in either upright posture (n = 52) or supine posture (n = 53), that is, either sitting or lying down.

PM may be impacted when participants are sleepy *and* have poor sleep quality, as indicated by some previous studies (Fabbri et al., 2014, 2015). Fabbri et al. (2014) found an effect of sleep quality on PM in an extreme-group comparison, where both groups differed on several sleep-related variables. Additionally, Fabbri et al. (2015) showed that sleep quality was related to PM in insomnia patients who also suffered from severe daytime sleepiness. In addition to these studies, a working-memory study supports the hypothesis that sleepiness and sleep quality may interact to affect PM: Muehlhan, Marxen, Landsiedel, Malberg, and Zaunseder (2014) showed a combined effect of sleepiness and sleep quality on reaction times in a working-memory task. Poor sleep quality slowed reaction times – but only for participants who were tested in supine posture and therefore felt sleepier than a comparison group tested in upright posture. Thus, posture-induced sleepiness moderated the relationship between sleep quality and working memory. Because the prospective component of nonfocal PM tasks draws on resource-demanding processes (e.g., Smith, 2003), it is associated with working memory (Arnold et al., 2015; Smith & Bayen, 2005). Thus, I expected that body posture would also moderate the relationship between sleep quality and the prospective component, as it did with working memory.

Although supine posture induced sleepiness in Experiment 5, I did not find differences between upright and supine posture in either PM component. However, there was a moderation: The effect of sleep quality on the prospective component of PM differed depending on body posture. In supine posture, poor sleep quality in the nights before formation and execution of intentions had a more negative effect on the prospective component of a PM task compared to the effect in upright posture.

Posture moderated the relationship between sleep quality and the prospective component of PM. This may indicate that humans are able to compensate for poor sleep quality – but only under conditions that do not induce sleepiness, such as upright posture. Also, sleepiness induced by supine posture alone does not suffice for a detrimental effect on the prospective component of PM. Rather, sleep quality must be considered as well.

4.3 Discussion

Compensation may explain why there were no main effects of sleepiness and sleep quality on the prospective component in Experiments 4 and 5. Drummond, Gillin, and Brown (2001) suggested that brain regions related to attention are activated more strongly after sleep deprivation and thereby reduce detrimental effects of sleep deprivation on attention-switching tasks. The same may hold for PM tasks under sleepiness, leading to a preserved prospective component. I propose that the prospective component is impaired after participants suffered from poor sleep quality only when they encounter conditions that promote sleepiness, because they fail to compensate in such situations. Future studies should be conducted to investigate the recruitment of brain regions for PM tasks under sleepiness-inducing conditions to establish possible mechanisms of compensation.

The retrospective component may be spared by sleepiness and sleep quality because it largely relies on automatic familiarity processes (Mandler, 1980). In fact, Swann et al. (2006) showed that participants rely more heavily on automatic processes after sleep restriction as compared to unimpaired sleep, thus preserving recognition memory.

Although Experiments 4 and 5 show convincingly that sleepiness did not affect the prospective nor retrospective component of PM, this does not mean that sleep-related variables do not have an impact on PM at all. The results show that moderate levels of sleepiness, as commonly found in everyday life, did not impair PM. In general, it is reassuring to know that moderate levels of sleepiness or poor sleep quality by themselves do not compromise PM, as short sleep and poor sleep quality have become more prevalent in modern society (e.g., Kronholm et al., 2008). However, it appears that extreme levels of sleepiness, such as after total sleep deprivation or partial sleep restriction, impair PM (Grundgeiger et al., 2014; Lowe et al., 2017). Thus, in the present experiments, PM may have been spared because sleepiness was only at moderate level.

5. General Discussion

Previous studies, which had shown an effect of sleep on PM, confounded the components of PM. In the present research, I disentangled the components of PM via multinomial modeling. In Experiment 1, I showed an effect of sleep on the prospective component, which is unique to PM. This indicates that the positive effect of sleep on PM is distinct from the beneficial effect of sleep on retrospective memory because it does not solely result from an enhancement in the retrospective component.

The second aim was to establish the mechanisms driving the effect of sleep on PM. I will first summarize the mechanisms improving the prospective component before turning to the retrospective component of PM. The results of Experiment 1 corroborate Scullin and McDaniel's

(2010) conclusion that the prospective component benefits from the consolidation of the link between the intention and its appropriate context. Furthermore, the pattern of results in Experiment 1 suggests that refreshed attentional resources may enhance the prospective component in the morning, thus leading to time-of-day effects in the prospective component. That refreshed attentional resources enhance the prospective component is also supported by the results from Experiments 2 and 3: Relaxation, which has a positive effect on attention (e.g., Lutz et al., 2009), improved the prospective component. In sum, the prospective component seems to benefit from sleep via the following mechanisms: Consolidation of the link between the intention and its contents, and refreshed attentional resources.

The retrospective component did not seem to benefit from sleep in Experiment 1. However, participants showed a better retrospective component in the evening. Thus, the wake group may have benefitted from this time-of-day effect, thereby levelling out the beneficial effect of sleep on the retrospective component in the sleep group. Although it is possible that the retrospective component benefitted from both low interference and consolidation of PM target words in Experiment 1, Experiments 2 and 3 suggest that low interference does not improve the retrospective component. Thus, the retrospective component of PM seems to only benefit from consolidation processes during sleep. Thus, sleep actively enhances the retrospective component of PM via consolidation, instead of benefitting the retrospective component passively via low interference.

While sleep taking place during the retention interval has a positive effect on PM, I showed in Experiments 4 and 5 that naturally occurring levels of sleepiness and poor sleep quality as *consequences* of poor sleep per se do not affect the components of PM. However, sleepiness moderated the relationship between sleep quality and the prospective component: Under high levels of sleepiness, sleep quality had a more negative impact on the ability to remember that something needed to be done. This shows that the relationship between sleep-related variables and the components of PM is very complex. More research is needed to reveal the interplay between sleep-related variables and PM.

Overall, I could show that sleep taking place during the retention interval enhances both the prospective and retrospective components of PM. This happens via different mechanisms for both components: The prospective component benefits from consolidation of the intention–context association and refreshed attentional resources. The retrospective component benefits from target-word consolidation only. In addition, sleep taking place before forming and carrying out an intention impacts PM under certain conditions: When the circumstances promote sleepiness, poor sleep quality has a more negative effect on the prospective component. In contrast, the retrospective component is spared completely.

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Appendix

Manuscript 1 was submitted as:

Böhm, M. F., Bayen, U. J., & Pietrowsky, R. (2018). *Nighttime sleep improves the prospective component of prospective memory.* Manuscript submitted for publication.

The general idea for this project was developed by Ute J. Bayen and Reinhard Pietrowsky. I planned the experiment included in this manuscript, selected the materials, and developed the experimental design with the support of the co-authors. I organized and supervised the data collection. Part of the data were collected by Master student Kerstin Rischert and Bachelor students Michaela Hauch and Jana Wegerhoff. I planned the data analysis with input from the co-authors and performed the data analysis. I interpreted the results in collaboration with the co-authors. I prepared the first draft of this manuscript. The first draft underwent several revisions by Ute J. Bayen and myself. Reinhard Pietrowsky commented on the resulting manuscript. I addressed these comments in a final version, which was approved by all authors.

Manuscript 2 was submitted as:

Böhm, M. F., Bayen, U. J., & Pietrowsky, R. (2018). *Event-based prospective memory benefits from relaxation-hypnosis.* Manuscript submitted for publication.

The studies described in this project were my idea. I planned the two experiments included in this manuscript, selected the materials, and developed the experimental design with the support of the co-authors. I organized and supervised the data collection. Part of the data were collected as part of the Experimentalpraktikum (Module D; group 11) in winter semester 2016/17 and summer semester 2017. I planned the data analysis with input from the co-authors and performed the data analysis. I interpreted the results in collaboration with the co-authors. I prepared the first draft of this manuscript. The first draft underwent several revisions by Ute J. Bayen and myself. Reinhard Pietrowsky commented on the resulting manuscript. I addressed these comments in a final version, which was approved by all authors.

Manuscript 3 was submitted as:

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The studies described in this project were my idea. I planned the two studies included in this manuscript, selected the materials, and developed the study design with the support of Ute J. Bayen. I organized and supervised the data collection. Part of the data were collected as part of the Experimentalpraktikum (Module D) in winter semester 2014/15 (group 6), summer semester 2015 (group 6), and summer semester 2016 (groups 6 and 7). I planned the data analysis with support of

Marie Luisa Schaper. I performed the data analysis. I interpreted the results in collaboration with the co-authors. I prepared the first draft of this manuscript. The first draft underwent several revisions by the co-authors and myself.

Nighttime Sleep Improves the Prospective Component of Prospective Memory

Mateja F. Böhm, Ute J. Bayen, and Reinhard Pietrowsky

Heinrich-Heine-Universität Düsseldorf

Author Note

Mateja F. Böhm, Ute Johanna Bayen, and Reinhard Pietrowsky, Institute for Experimental Psychology, Heinrich-Heine-Universität Düsseldorf, Germany.

This study was presented at the Tagung experimentell arbeitender Psychologen (TeaP) in Marburg, Germany, in March 2018. The data can be accessed in the Open Science Framework at https://osf.io/83bdn/?view_only=f69ccc6d24a84cee8c8b846b7e4bbcda

Correspondence concerning this article should be addressed to Ute Johanna Bayen, Institut für Experimentelle Psychologie, Gebäude 23.02, Universitätsstraße 1, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany. Email: ubayen@hhu.de

Abstract

Studies suggest that sleep benefits prospective memory (PM). Event-based PM involves carrying out intentions when particular events occur. This experiment investigated whether nighttime sleep improves the prospective component of PM (remembering *that* one has an intention), or a retrospective component (remembering *when* to carry it out), or both. In a first session, participants executed a PM task (that was embedded in an ongoing task) 3 minutes after forming an intention and, in a second session, 12 hours after forming an intention. The sessions were separated by either nighttime sleep or daytime wakefulness. Results based on the multinomial model of event-based PM suggest that the prospective component was significantly improved by sleep via several different mechanisms. The retrospective component was affected by time of day, masking a possible sleep effect.

Keywords: prospective memory, intention, sleep, multinomial modeling, time-of-day

Statement of Significance

Sleep serves important functions including consolidation of memories. Additionally, sleep was recently found to also improve prospective memory (PM). PM involves remembering to carry out intentions at appropriate occasions. As PM is important in many areas of life (e.g., healthcare, social relations), sleep may help avoid severe consequences for health and well-being that may result from PM failures. This study is the first to disentangle effects of sleep on different components of PM via mathematical modeling: The prospective component (remembering *that* one has an intention) and the retrospective component (remembering *when* to carry it out). Results suggest that sleep benefits both components of PM via several mechanisms, thus opening venues for intervention with individuals who suffer from PM deficits.

Nighttime Sleep Improves the Prospective Component of Prospective Memory

The role of sleep in the consolidation of memory for past events (*retrospective memory*) has been thoroughly investigated and firmly established.[1] Only recently, however, have researchers shown interest in effects of sleep on *prospective memory* (PM).[2-6] In event-based PM tasks, an intention must be carried out when a certain event occurs. For instance, a diabetic may have to take insulin upon being served a meal. As PM is central in many areas of daily life, PM failures may have serious consequences.[7] To avoid these, it is crucial to further investigate if and how sleep may benefit PM. Studies have shown that PM is enhanced after sleep.[2-4, 6] However, these studies did not conclusively differentiate between different components of PM. An important distinction is the one between prospective and retrospective components of PM tasks.[8] The prospective component involves remembering *that* an intention needs to be carried out, whereas the retrospective component involves remembering *what* needs to be done and *when*. In the current study, we used a formal stochastic model to separate effects of sleep on these different components of PM.

A laboratory event-based PM task is typically embedded in an ongoing task.[8] For instance, in our computer-based experiment, the ongoing task was to indicate via keypress whether or not one of the colors of sequentially presented rectangles matched the color of a subsequent word. The embedded PM task was to press a different key whenever specific previously studied words (*PM targets*) appeared.[9] This PM task is *non-focal* to the ongoing task, because the prospective component of the PM task requires shifting the attentional focus from the characteristics of the ongoing task (i.e., the colors) to the PM task (i.e., the words). Theorists agree that the prospective component of non-focal PM tasks requires attentional processes to monitor the environment for PM targets.[9-11] The retrospective component of the described PM task entails recognizing the PM target words.

In the current study, we wanted to determine whether effects of sleep on PM are attributable to effects on the prospective component, the retrospective component, or both. Sleep improved PM performance in naturalistic and laboratory PM tasks.[2-6] Three mechanisms may underlie the effect of sleep on PM: (1) refreshed attentional resources[12, 13], (2) consolidation of the link between the intention and its appropriate context[6, 11], and (3) consolidation of PM targets.[1] We now describe each of these mechanisms and how they may drive the sleep effect on PM.

The first two mechanisms may affect the prospective component. (1) During nonfocal PM tasks, the prospective component relies on attentional processes. Thus, if sleep refreshes attentional processes, then the prospective component should benefit from sleep.

(2) Sleep strengthens the association between an intention and its context.[6] For example, if your intention is to buy milk on your way to work, sleep may strengthen the association between your intention (buying milk) and the appropriate context (your way to work). If your intention–context association is strong, you will be more likely to retrieve the intention when you are in the appropriate context (on your way to work). The retrieval of an intention in turn leads to the strategical recruitment of attentional resources in order to monitor for PM targets (i.e., a higher prospective component).[11] Hence, stronger intention–context associations following sleep should lead to an enhanced prospective component.

(3) The third mechanism may affect the retrospective component. Sleep benefits retrospective memory including recognition memory by strengthening memory consolidation.[1] In particular, future-relevant information (i.e., information that the participant expects to be tested on in the future) benefits from sleep.[14] For PM tasks, this means that sleep should enhance the memory representation of PM targets. Thus, participants should more easily recognize PM targets during the ongoing task after sleep as compared to wakefulness. That is, the retrospective component should be improved.

Thus, via three different mechanisms, sleep may benefit either or both components of PM, which necessitates the separate measurement of both components. Yet, the impact of sleep on the two components has not been clearly established. The retrospective component was presumably at ceiling in most studies on PM and sleep, and effects of sleep on PM performance were thus ascribed to the prospective component.[3, 4, 6] In an attempt to separate both components, previous research used a modified paradigm in which their measure of the prospective component was, however, confounded with a retrospective component[3]: Participants first studied cue words to criterion (i.e., 90% free recall). Afterwards, they studied a new word with every cue word. The cue words subsequently served as PM targets. Whenever a PM target appeared during the ongoing task, participants were supposed to press the PM key and to recall the second word. The PM hits (i.e., key presses following a PM target) were interpreted as a measure of the prospective component, because the retrospective component was assumed to be at ceiling as participants had studied the words to criterion.[3] This rationale is questionable, however, because (a) the PM targets may become less retrievable over time and (b) the criterion was a free-recall measure, whereas the key press depended on recognition memory. Therefore, PM hits were possibly influenced by retrospective memory and thus not a pure measure of the prospective component of PM. The authors concluded that both the prospective and the retrospective components benefitted from sleep, although the effect on the "prospective component" may have been (at least in part) due to the well-established effect of sleep on retrospective memory.

Multinomial Model of Event-Based Prospective Memory

Overall, the current state of research calls for a clear distinction of effects of sleep on the prospective versus the retrospective component of PM. To separate the two components, we used the multinomial processing tree (MPT) model of event-based PM.[15] In general, MPT models are stochastic models frequently applied in cognitive psychology.[16, 17] Each model is tailored to a specific experimental paradigm. On the basis of categorical data, MPT models estimate the probabilities with which certain underlying cognitive processes take place.

The MPT model of event-based PM provides separate and independent measures of the prospective and the retrospective components of PM. It has been validated for non-focal PM tasks[15,18,19] and applied in a number of studies.[20-26]

The model is depicted in Figure 1. Participants have three response options on each trial: They may indicate that the colors match ("match" response), that the colors do not match ("no match" response), or that the word was a PM target ("PM" response). There are four possible item types during the task: (a) PM target, match, (b) PM target, no match, (c) no PM target, match, and (d) no PM target, no match. As there are three response options for each of the four trial types, parameter estimation is based on 12 response categories.

The first tree in Figure 1 represents color-match trials with PM targets. With probability C_1, participants detect the color match. They may further remember that they had an intention with probability P (prospective component of the PM task). If they additionally recognize the word as a PM target, with probability M, (retrospective recognition component), then they answer "PM" on this trial. If they do not recognize the word as a PM target, with the complementary probability $1 - M$, they guess whether the word is a PM target (with probability g) or not (with probability $1 - g$). Participants then answer "PM" or "match", respectively. If participants detect the color match (with probability C_1), but do not remember that they had an intention (with probability $1 - P$), they answer "match". The lower half of this tree denotes cases in which participants do not detect the color match, which occurs with probability $1 - C_1$. With probability P they have an intact prospective component and with probability M they recognize the PM target, leading to a "PM" response. If participants do not recognize the PM target, with probability $1 - M$, they have to guess if the word was a target. With probability g, they guess that the word is a PM target and answer "PM". With probability $1 - g$, they guess that the word is not a PM target. Because they do not detect the color match, they must guess whether the colors match (with probability c) or not (with probability $1 - c$), answering "match" or "no match", respectively. If participants do not detect the color match (with probability $1 - C_1$) and do not remember that they had an intention (probability $1 - P$), they also guess whether the colors match (c) or not ($1 - c$).

The other trees represent different types of trials, but follow the same logic. The second and fourth trees represent no-match trials with PM targets or distractors, respectively, and include parameter C_2, which represents the probability of detecting that the colors do not match. The third and fourth trees represent trials with distractor items in matching or non-matching color, respectively. In these trees, M is the probability that the participant knows that this is a distractor item. If this is the case, the participant will not give the "PM" response, but will respond "match" or "no match" depending on whether the participant detects or guesses a match or a no-match.

Importantly, the model allows us to disentangle effects of sleep on the prospective component and the retrospective component of PM via the unconfounded model-based measures P and M, respectively.

Time-of-Day Effects

Another possible confound must be considered. When studying effects of nighttime sleep, a sleep group may be tested in the morning and a wake control group in the evening. Effects of sleep may thus be confounded with time-of-day effects.[27] Typically, young adults are late chronotypes.[28] In non-focal PM tasks, the prospective component relies on controlled processes, which should be more effective during their optimal time of day.[29] In fact, young adults performed better on PM tasks when tested during their optimal time (*on-peak*, in the evening) as compared to their non-optimal time (*off-peak*, in the morning).[30] Time-of-day effects were also demonstrated on attention.[31] Some studies showed time-of-day effects on recognition[32, 33], whereas others did not.[34, 35] As time-of-day effects may confound our results masking possible sleep effects, we chose a design that allowed us to test for effects of sleep on PM, while also assessing time-of-day effects. We will describe relevant time-of-day effects when discussing the results.

The Current Study

The design is illustrated in Figure 2. Participants completed one testing session at 8 a.m. and one at 8 p.m. In the first session, participants studied five words and were instructed to press a specific key whenever these words appeared during the ongoing task, which started after a retention interval of 3 minutes. Afterwards, participants studied five new words, and were instructed to carry out the intention during the second session, which took place after a retention interval of approximately 12 hours. For participants in the wake group, the first session was in the morning and the second session in the evening, so that they were awake during the retention interval. For the sleep group, the first session was in the evening and the second in the morning, so that they were asleep for (part of) the retention interval. We administered a PM task in the first session to control for time-of-day effects. We further measured possible differences in chronotype (i.e., morning or evening type) by administering the Morningness-Eveningness Questionnaire (MEQ).[36]

Hypotheses. We will first derive hypotheses regarding the prospective and the retrospective components, then regarding the overall PM performance that arises from these components. We expected a decline in the prospective component from the first to the second session due to the different lengths of the retention intervals. Consolidation of the intention–context association and refreshing of attentional resources should both increase the prospective component. However, both lead to somewhat different hypotheses. If the intention–context association is consolidated during sleep, this should result in a benefit for the prospective component of the sleep group in the second session only. In the first session, by contrast, the two groups should not differ. This pattern constitutes an *ordinal* interaction, that is, from the first to the second session, the prospective component declines less in the sleep group as compared to the wake group.

If sleep benefits the prospective component via refreshed attentional resources, this mechanism should benefit the prospective component in the morning, regardless of whether sleep took place during the retention interval or not. Thus, in the first session, the wake group should show a higher prospective component than the sleep group. The sleep group, on the other hand, should show a higher prospective component in the second session. As these effects are based on the same mechanism, they should be of the same size at both time points, but in opposite directions. Thus, refreshed attentional resources following sleep would result in a *hybrid* interaction. That is, both groups would show a decline in the prospective component from the first to the second session, but the direction of the effects changes. Critically, we expected different types of interaction depending on the mechanisms underlying sleep effects: Intention–context consolidation should lead to an ordinal interaction, whereas refreshed attentional resources should lead to a hybrid interaction.

We now turn to predictions for the retrospective component. This component should also decline from the first to the second session due to the longer retention interval. However, in the sleep group, the consolidation of PM targets should counteract this decline. Thus, we predicted an ordinal interaction with similar levels of the retrospective component in the first session, followed by a stronger decline in the wake group than in the sleep group as measured in the second session.

With regard to hypotheses on overall PM performance measured as PM hit rate (i.e., the proportion of PM targets upon which the participant pressed the PM key): PM performance arises from an interplay of the underlying prospective and retrospective components. Both the prospective and the retrospective components are positively related to overall PM performance. As both the prospective and the retrospective components are expected to decline with the length of the retention interval, PM hit rate should also decline from the first to the second session due to the increased retention interval.

As explained above, consolidation of the context–intention association and consolidation of PM targets would lead to ordinal interaction effects on the prospective and the retrospective component, respectively. This interaction would be reflected in PM hit rate, such that the decline in PM hit rate across sessions would be less pronounced in the sleep group compared to the wake group. If, on the other hand, attentional resources are refreshed during sleep, then this should benefit the prospective component in the morning, thereby benefitting PM hit rates in the morning in both groups. Thus, if sleep exerts effects through all three theoretical mechanisms, we expect the benefit of the wake group over the sleep group during the first session to be smaller than the benefit of the sleep group over the wake group during the second session, because the wake group only benefits from refreshed attentional resources in the first session, whereas the sleep group benefits from both refreshed attentional resources and consolidation processes in the second session. This pattern constitutes a hybrid interaction effect on PM hit rate, with a lesser decline in PM hit rate from the first to the second session in the sleep group compared to the wake group. Overall, we expected PM hit rate to benefit from sleep, thereby replicating previous findings.[2-4, 6]

Because the context should act as a reminder of an associated intention, consolidation of the intention–context association during sleep should also lead to a lower number of participants in the sleep group who never pressed the PM key during the second session (compared to the second session of the wake group).

Method

Design

The design is illustrated in Figure 2. The wake group completed the first session in the morning, and the second session in the evening. The sleep group completed the first session in the evening, and the second session in the morning. The design was thus a mixed 2 × 2 design with group (wake vs. sleep) as between-subjects factor and session (first vs. second) as within-subjects factor.

Participants

The study was conducted in accordance with the ethical principles stated in the Declaration of Helsinki. Participants were students recruited on campus and via social media. They were compensated with course credit or money. They fulfilled the following inclusion criteria to ensure that they showed normal sleep behavior and were able to perceive and understand all stimulus materials: (a) German native speaker, (b) aged between 18 and 30 years, (c) no achromatopsia, (d) did not travel to a time zone differing more than 3 hours from Central European Time in the last four weeks, (e) no shift work in the last four weeks, (f) not taking sleep medication on a regular basis, (g) no sleep disorders and nightly awakenings, (h) good neurological and psychological health, (i) no alcohol dependency, (j) no consumption of recreational drugs on a regular basis, (k) not pregnant, and (l) no participation in previous PM studies. Furthermore, participants had a regular sleep schedule, that is, on weekdays they got up after 5:30 a.m. and before 12 a.m. on a regular basis. On weekdays, they regularly went to bed before 2 a.m. On weekends, they got up before 1 p.m. and went to bed before 4 a.m. on a regular basis. Additionally, we selected participants who would be able to get at least 7 hours of sleep between sessions in case they were assigned to the sleep group (taking the commute to the laboratory into account). Also, participants had to be willing to participate in both the sleep and the wake group to avoid selective dropouts. Participants were instructed to refrain from alcohol for 24 hours and from recreational drugs for 48 hours prior to and for the duration of the study.

To find an interaction in the prospective and retrospective components with a small effect size of ω = .024 and a power of .80, 31 participants per group were needed with each participant completing 110 trials per session. For the repeated-measures ANOVA of PM hit rate, a total sample size of 62 meant that a small-to-medium effect of $f = .18$ could be found with a power of .80 and an alpha-level of .05. Sixty-four students participated. Data from two participants were lost due to technical error. One participant in the wake group was replaced because he did not return for the second session. The final sample size was thus 62 (31 in each group). The participants of the final sample were aged between 18 and 29 years (*Mean* = 22.74, 95% CI [22.04, 23.45]). Six participants in the sleep group and five in the wake group were male, the others female.

Material and Procedure

An online screening questionnaire ensured that participants fulfilled the inclusion criteria. The questionnaire included 45 questions of various formats. Respondents who fulfilled all inclusion criteria were assigned to one of the groups, alternating between sleep and wake groups.

For the seven nights prior to their first session, participants filled in the Consensus Sleep Diary-Core[37] (translated to German using back-translation) at home every morning. This sleep diary renders scores for sleep quality and sleep efficiency (i.e., the ratio of minutes in bed that were spent asleep).

Session 1. Within each group, up to four participants were tested simultaneously. Upon arrival at the laboratory for the first session, participants gave informed consent and turned in their sleep diary. They were seated in individual computer booths and put on ear-muffs. Participants then indicated their current sleepiness on a computerized version of the Karolinska Sleepiness Scale (KSS)[38], which is a 9-point Likert Scale ranging from 1 (*extremely alert*) to 9 (*extremely sleepy – fighting sleep*).

Then, participants read the instructions for the ongoing color-matching task, which required them to indicate whether the color of a word matched that of four previously presented rectangles. The possible colors were red, blue, green, yellow, and white. Each rectangle was presented for 500 ms with inter-stimulus intervals of 250 ms. The colors were presented equally often during the color-matching task. Color matches and non-matches occurred equally often. Participants used the *v* key and the *m* key for self-paced *match* and *no-match* responses (approximately counterbalanced). They performed six practice trials of the ongoing task followed by PM instructions. They were asked to press the space bar instead of the *match* or *no-match* key whenever they encountered one of five target words. They were told that they could press the space bar even after pressing the *match* or *no-match* key. Then, the five PM target words were presented in consecutive random order in black on white background in Arial 24 font for five seconds each.

Overall, we chose 220 words from a database, that offers information regarding concreteness, arousal, and valence.[39] Frequency, word length, and number of syllables were taken from the dlex database.[40] These words were divided into four lists of 55 words each. Of these 55 words, 5 were chosen as PM target words. The lists did not differ from each other regarding concreteness, arousal, valence, frequency, word length, and number of syllables. Also, target words and distractors did not differ regarding these characteristics. Each word was presented twice, leading to 110 trials per list. Half of the participants of each group received lists A and B (counterbalanced in the first or second session), and the other half received lists C and D (also counterbalanced).

During the 3-minute retention interval following target word presentation, participants solved simple mathematical problems (e.g., 7 + 3 + 8) and were given performance feedback. Afterwards, participants completed 110 trials of the color-matching task, 10 of which included PM target words. PM target words occurred on every 9th to 13th trial, on average on every 11th trial. In order to allow belated PM responses even to the last PM target word, we added one trial at the end. If participants pressed the space bar on this trial, this was counted as a belated PM response. If not, this trial was removed from analyses. After the task, participants were told that they would study five new words, upon which they should press the space bar when encountering them during the ongoing color-matching task in the second session. The five target words from the second list were then presented consecutively in the same manner as before. Participants again solved mathematical problems for 3 minutes to avoid rehearsal of the target words.

Afterwards, participants were compensated for their participation in the first session. Participants in the wake group were asked to refrain from napping during the day. Participants in the sleep group spent the night at home and once more filled in the Consensus Sleep Diary-Core at home in the morning.

Session 2. Participants returned for the second session after a retention interval of approximately 12 hours. Participants again completed the ongoing task with the embedded PM task, which proceeded exactly like the tasks in the first session. However, the PM target words were now taken from the second list. After completion of the tasks, participants were asked to indicate whether they knew that they were supposed to do a second task in addition to the ongoing task. They were further asked which key they had to press when they encountered the previously studied words during the ongoing color-matching task.

Participants then completed a 21-item questionnaire to double check for inclusion criteria and to ask about target rehearsal during the retention interval. Furthermore, they completed the MEQ, which indicates whether participants are morning types, evening types, or intermediate types. Finally, participants were debriefed and compensated.

Statistical Analyses and Results

With the exception of the multinomial modeling, we conducted all analyses with IBM SPSS Statistics 24. We set $\alpha = .05$.

Checks of Randomization and Manipulation

Sleep Diary. We conducted the following analyses to ensure that the two groups were comparable regarding their natural sleep characteristics and that the sleep group's experimental night neither differed from the nights of the previous week nor from the wake group's night before their first session. Table 1 shows the descriptive data for the checks of randomization and manipulation.

First, a between-subjects MANOVA did not yield group differences in sleep quality, total sleep time, and sleep efficiency, Pillai's trace = .09, $F(3, 58) = 1.99$, $p = .125$, $\eta_p^2 = .09$. Second, a repeated-measures MANOVA yielded differences between the sleep group's experimental night and their usual sleep regarding sleep quality, total sleep time, and efficiency, Pillai's trace = .55, $F(3, 27) = 10.80$, $p < .001$, $\eta_p^2 = .55$ (We had to exclude one participant from this analysis because of missing data). This difference was due to less total sleep time during the experimental night as compared to the sleep group's usual sleep pattern, $F(1, 29) = 21.72$, $p < .001$, $\eta_p^2 = .43$. Third, a between-subjects MANOVA did not yield differences between the sleep group's experimental night and the wake group's night before their first session regarding sleep quality, total sleep time, and efficiency, Pillai's trace = .13, $F(3, 56) = 2.71$, $p = .054$, $\eta_p^2 = .13$.

Overall, these analyses show that the two groups were comparable in their natural sleep characteristics. Furthermore, the experimental night was successful with high sleep efficiency and good sleep quality.

Morningness-Eveningness Questionnaire. The two groups did not differ in MEQ total scores, $t(60) = - 1.50$, $p = .140$ (two-tailed), $d = .38$, which identified them as intermediate types (i.e., neither morning type nor evening type) on average.

Karolinska Sleepiness Scale. The two groups did not differ in sleepiness as captured by the KSS ratings given at the beginning of the first session, $t(60) = 0.78$, $p = .436$ (two-tailed), $d = .20$.

Rehearsal. The two groups did not differ in proportion of participants rehearsing target words, $z = 1.82$, $p = .069$ (two-tailed), $d = .48$, with 27 participants rehearsing in the sleep group and 21 in the wake group. A between-subjects MANOVA did not yield group differences regarding the number of times nor the number of minutes participants rehearsed, Pillai's trace = .01, $F(2, 58) = 0.22$, $p = .803$ (two-tailed), $\eta_p^2 = .01$.

Ongoing-Task Performance

Ongoing-task performance was measured as percent correct on ongoing-task trials. A mixed-factorial ANOVA with session (first, second) as within-subjects factor and group (sleep, wake) as between-subjects factor revealed a significant main effect of session, $F(1, 60) = 7.30$, $p = .009$, $\eta_p^2 = .108$. Participants showed a practice effect, performing better in the second session (*Mean* = .87, 95% CI [.85, .89]) than the first (*Mean* = .84, 95% CI [.82, .87]). The main effect of group was not significant, $F(1, 60) = 2.17$, $p = .146$, $\eta_p^2 = .035$, with the wake group (*Mean* = .84, 95% CI [.82, .87]) and the sleep group (*Mean* = .87, 95% CI [.85, .89]) showing similar performance. The interaction was also not significant, $F(1, 60) = 0.37$, $p = .543$, $\eta_p^2 = .006$, with both groups showing similar performance in the first ($Mean_{sleep}$ = .86, 95% CI_{sleep} [.82, .89]; $Mean_{wake}$ = .83, 95% CI_{wake} [.80, .86]) and the second session ($Mean_{sleep}$ = .89, 95% CI_{sleep} [.86, .92]; $Mean_{wake}$ = .85, 95% CI_{wake} [.82, .89]).

PM Hit Rate

A mixed-measures ANOVA with session (first, second) as within-subjects factor and group (sleep, wake) as between-subjects factor showed a significant main effect of session, $F(1, 60) = 35.05$, $p < .001$, $\eta_p^2 = .369$, on PM hit rate (i.e., proportion of PM targets correctly responded to). As shown in Figure 3, PM hit rate declined from the first session with a short retention interval to the second session with a long retention interval, as expected. The main effect of group was not significant, $F(1, 60) = 1.21$, $p = .275$, $\eta_p^2 = .020$, neither was the interaction, $F(1, 60) = 1.64$, $p = .205$, $\eta_p^2 = .027$.

The number of participants who never pressed the PM key did not differ between groups, neither in the first session ($n_{sleep} = 0$; $n_{wake} = 1$), $z = 1.01$, $p = .313$ (two-tailed), $d = .26$, nor in the second session ($n_{sleep} = 4$; $n_{wake} = 6$), $z = 0.69$, $p = .490$ (two-tailed), $d = .18$.

Multinomial-Modeling Results

The PM hit rate confounds the prospective and retrospective components, thus we used the MPT model of event-based PM[15] to disentangle both components. To render the MPT model identifiable, we imposed restrictions based on probability-matching on the guessing parameters assuming that participants matched the actual probabilities in the task (*probability matching*[15, 41]). We set parameter *c* equal to .50 as that is the probability with which colors matched during the ongoing task. Furthermore, we set parameter *g* equal to .09 as that is the probability with which PM targets occurred during the ongoing task.

As explained in the introduction, we expected interactions of group and time of measurement on model parameters. Within the MPT modeling approach, interactions can be tested by reparameterizing the model.[42] The reparameterized model includes reduction rates for parameters *P* and *M.* We refer to these reduction rates as β_P and β_M, respectively. The smaller the reduction rate the larger the decline from the first to the second session.

We conducted the MPT modeling with the multiTree program.[43] Parameters were estimated via maximum-likelihood estimation[44] based on the aggregated response frequencies shown in Table S1. The asymptotically chi-square distributed goodness-of-fit index G^2 indicated that the joint MPT model fit the data, $G^2(16) = 25.50$, $p = .061$. Technical details of model fitting and parameter comparisons are explained elsewhere.[15, 44]

Prospective component. The parameter estimates are in Figure 3. We compared the two groups in the first session to determine if time-of day effects may have possibly confounded effects of sleep. The two groups did not differ regarding the prospective component in the first session, $\Delta G^2(1) = 3.47$, $p = .062$. Comparing the two groups in the second session rendered a significant effect, $\Delta G^2(1) = 4.07$, $p = .044$, with the sleep group having a higher probability to remember *that* they needed to perform a PM task.

Analyses using the reparameterized model showed an interaction of group and session on the prospective component, $\Delta G^2(1) = 7.38$, $p = .007$, with the wake group showing a higher reduction rate ($\beta_P = .65$, 95% CI [.54, .75]) than the sleep group ($\beta_P = .87$,95% CI [.75, 1.00]). This indicates that the prospective component decreased significantly more during wakefulness than during sleep.

Retrospective component. The parameter estimates are in Figure 3. In the first session, the two groups differed regarding the retrospective component, $\Delta G^2(1) = 6.92$, $p = .009$, with the sleep group having a higher probability of discriminating target and distractor items. Thus, participants had a better retrospective component in the evening. In the second session, the two groups did not differ regarding the retrospective component, $\Delta G^2(1) = 2.60$, $p = .107$.

Analyses using the reparameterized model showed no effect of interaction of group and session on the retrospective component, $\Delta G^2(1) = 0.06$, $p = .805$, with the wake group showing a comparable reduction rate ($\beta_M = .72$, 95% CI [.60, .83]) as the sleep group ($\beta_M = .73$, 95% CI [.65, .82]). This shows that the retrospective component did not decrease differentially during sleep and wakefulness.

Ongoing-Task Parameters C_1 and C_2. In the first session, the two groups differed regarding parameters C_1, $\Delta G^2(1) = 20.42$, $p < .001$, and C_2, $\Delta G^2(1) = 7.99$, $p = .005$. The sleep group had higher estimates of C_1 (*Mean* = .58, 95% CI [.54, .62]) than the wake group (*Mean* = .44, 95% CI [.39, .48]). The estimates of C_2, however, were higher in the wake group (*Mean* = .88, 95% CI [.86, .90]) than the sleep group (*Mean* = .83, 95% CI [.80, .85]). In the second session, the sleep group had a higher parameter C_1 (*Mean* = .67, 95% CI [.63, .71]) than the wake group (*Mean* = .57, 95% CI [.53, .61]), $\Delta G^2(1) = 14.14$, $p < .001$. The two groups did not differ regarding parameter C_2 in the second session ($Mean_{sleep}$ = .86, 95% CI_{sleep} [.83, .88], $Mean_{wake}$ = .84, 95% CI_{wake} [.82, .87]), $\Delta G^2(1) = 0.73$, $p = .393$. Thus, the sleep group seemed to have a persisting advantage in parameter C_1 over the wake group, that is, the probability to detect color matches was consistently higher in the sleep group. The wake group had a higher probability to detect that colors did not match in the first session only.

Discussion

We investigated effects of nighttime sleep on prospective memory to determine whether sleep benefits the prospective, or the retrospective, or both components of PM and to discern the mechanisms that may drive effects. To this end, we had participants perform PM tasks either before and after a full night's sleep or before and after a day of wakefulness. We disentangled the prospective and the retrospective components of PM via an MPT model. Nighttime sleep exclusively improved the prospective component, which is the unique characteristic of PM. Thus, the effect of sleep on PM in previous studies does not simply arise from the established effect of sleep on retrospective memory. We will first discuss the results for the prospective component, then for the retrospective component, and then discuss how both contribute to the results for overall PM performance.

In both groups, the prospective component decreased from the first to the second session as the length of the retention interval increased. However, the decrease in the prospective component was more pronounced in the wake group than in the sleep group. The two groups did not differ during the first session, but did so during the second session. As explained in the introduction, the strengthening of the intention–context association by sleep results in an ordinal interaction of sleep group and session. Attentional resources refreshed by sleep, on the other hand, result in a hybrid interaction. The pattern of results appears to reflect a combination of both mechanisms: A statistical trend ($p = .062$) in the first session indicating a small advantage in the prospective component of the wake group over the sleep group suggests a benefit in the wake group from refreshed attentional resources in the morning. In the second session, in turn, the advantage in the prospective component of the sleep group over the wake group was larger than the advantage of the wake group over the sleep group in the first session (i.e., a significant interaction). This result pattern suggests that in the second session, the sleep group benefitted from both, consolidation during sleep and from refreshed attentional resources. We thus conclude that both mechanisms contributed to the effects of sleep on the prospective component.

The retrospective component in the first session was better in the evening than in the morning, although the average score on the MEQ chronotype measure was in the intermediate range. Possibly, 8 p.m. was not too late for good recognition memory in intermediate chronotypes, whereas 8 a.m. was too early for intermediate chronotypes. The time-of-day effect on retrospective recognition is in line with some previous results[32], but contradicts other studies that found the opposite effect[33] or no time-of-day effect on recognition.[34, 35] More research is needed on time-of-day effects on recognition. A possible time-of-day effect on the retrospective component should be considered when designing PM studies.

We did not find a difference in the retrospective component in the second session. One possible explanation is that learning and carrying out the intention did not take place in the same session this time – thus, the sleep group may have benefitted from being closer to peak during encoding of the second intention, whereas the wake group may have benefitted from being closer to peak while carrying out the second intention, thus levelling out possible time-of-day effects in the second session. A second possible explanation is that the retrospective component did benefit from consolidation during sleep in the sleep group, thus levelling out the time-of-day benefit in the wake group in the second session. We believe the second explanation is more likely as the sleep effect on retrospective memory is well established[1], and future-relevant information is selectively consolidated during sleep[14], which should benefit consolidation of the PM target words during sleep.

We neither found effects of sleep nor of time of day on PM hit rate. This stands in contrast to prior evidence of sleep improving overall PM.[2-4, 6] During the first session, the prospective and the retrospective components had opposite effects (albeit this effect is not significant in the prospective component) so that their effects on PM hits traded off, explaining the null finding in PM hit rate. Thus, if we had not separated both components, we would have missed the time-of-day effect on the retrospective component and the sleep effect on the prospective component. This highlights the importance of distinguishing between the prospective and the retrospective components in sleep studies on PM.

Limitations of the study include reliance on self-report data (sleep-diary) to show that participants in the sleep group experienced acceptable sleep quality and sleep efficiency during the experimental night. Future studies may employ actigraphy or polysomnographic recordings. Furthermore, the results regarding the retrospective component of PM need to be confirmed. To this end, more studies investigating time-of-day effects on the retrospective component need to be conducted, as well as sleep studies using different study designs to avoid time-of-day effects (e.g., studying midday napping) and to yield conclusive evidence regarding sleep effects on the retrospective component.

In sum, we showed conclusively that nighttime sleep benefits the prospective component of PM, which is the component that is unique to PM: After sleep compared to wakefulness, participants were more likely to remember that they needed to perform an intention. The result pattern is compatible with the ideas that intention-context associations are strengthened by sleep[6], and that attentional resources are refreshed. An effect of sleep on the retrospective component was possibly masked by a time-of-day effect, leading to better recognition memory in the evening as compared to the morning.

List of Abbreviations

ANOVA

Analysis of Variance

CI

Confidence Interval

KSS

Karolinska Sleepiness Scale

MANOVA

Multivariate Analysis of Variance

MEQ

Morningness-Eveningness Questionnaire

MPT model

Multinomial Processing Tree model

PM

Prospective memory

Disclosure Statement

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Table 1

Measure	Sleep Group	Wake Group
One-week sleep efficiency	83.51 [81.04, 85.98]	85.46 [82.98, 87.94]
One-week sleep quality[a]	2.80 [2.61, 2.98]	2.71 [2.51, 2.92]
One-week total sleep time[b]	7.68 [7.32, 8.04]	7.50 [7.25, 7.75]
One-night sleep efficiency[c]	84.79 [81.76, 87.81]	87.76 [84.15, 91.38]
One-night sleep quality[a, c]	2.57 [2.31, 2.82]	2.77 [2.42, 3.12]
One-night total sleep time	6.89 [6.56, 7.22]	6.24 [5.50, 6.97]
MEQ	49.74 [47.46, 52.02]	52.52 [49.49, 55.54]
KSS	4.39 [3.80, 4.98]	4.03 [3.32, 4.74]
Number of rehearsals	2.52 [1.99, 3.04]	3.13 [1.31, 4.95]
Rehearsal duration in min.	3.97 [2.48, 5.46]	4.42 [1.09, 7.74]

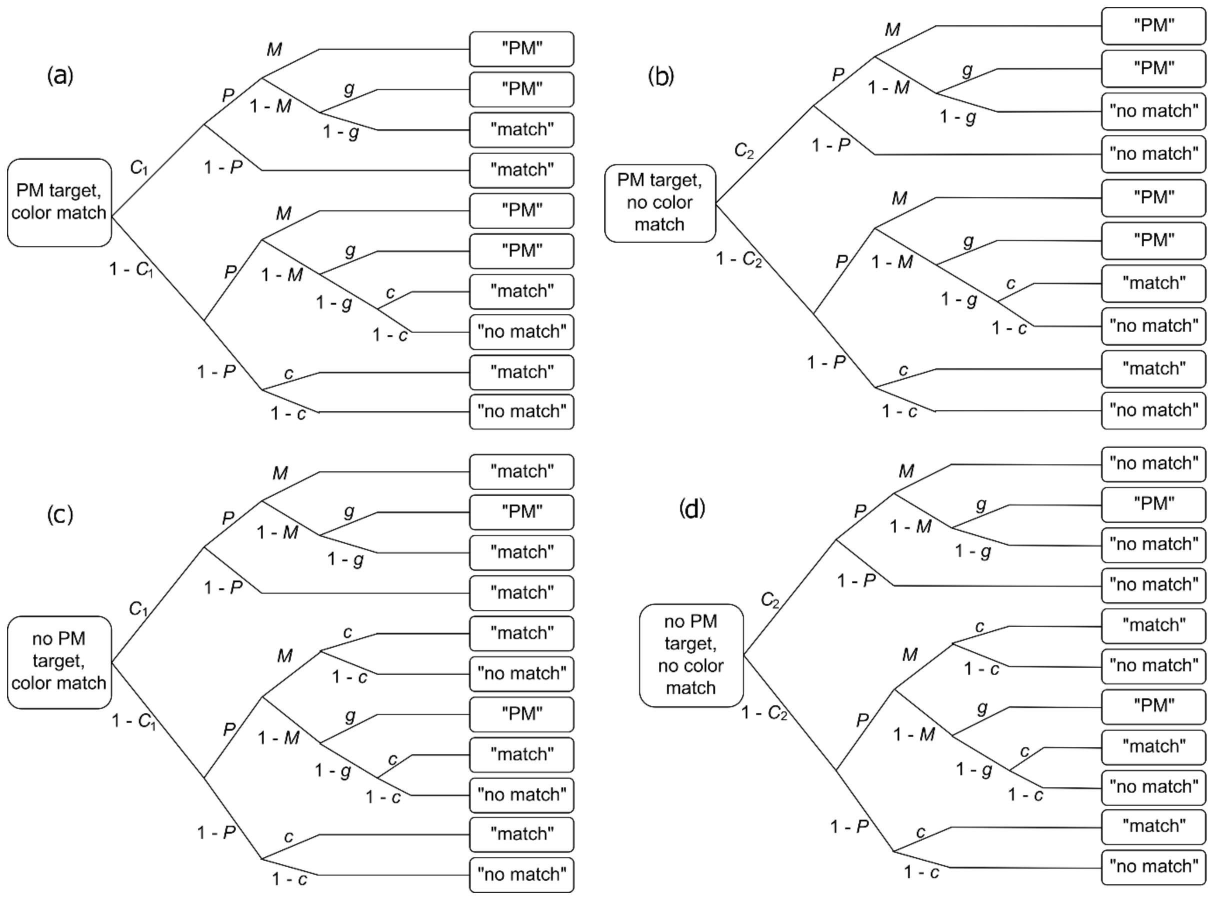
Means and 95% Confidence Intervals of the Control Measures for the Sleep Group and the Wake Group. Confidence intervals are in brackets. MEQ = Morningness-Eveningness Questionnaire. KSS = Karolinska Sleepiness Scale. [a]higher values indicate better sleep quality. [b]per night. [c]night before the second session (sleep group) or night before the first session (wake group).

Figure Captions

Figure 1. The multinomial model of event-based prospective memory (PM). P = prospective component, M = retrospective component, g = probability to guess that the word is a PM target, C_1 = probability to detect a color match, C_2 = probability to detect that colors do not match, c = probability to guess that colors match. Adapted from "A multinomial model of event-based prospective memory" by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, p. 758. Copyright 2004 by the American Psychological Association.

Figure 2. Study design.

Figure 3. Mean prospective-memory (PM) hit rate and the model estimates of the prospective and the retrospective components of PM for the sleep group and the wake group in the two sessions. Error bars indicate 95% confidence intervals.


(a)
PM target, color match
C_1
$1 - C_1$
P
1 - P
M
1 - M
g
1 - g
c
1 - c
"PM"
"PM"
"match"
"match"
"PM"
"PM"
"match"
"no match"
"match"
"no match"
(b)
PM target, no color match
C_2
$1 - C_2$
"PM"
"PM"
"no match"
"no match"
"PM"
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(c)
no PM target, color match
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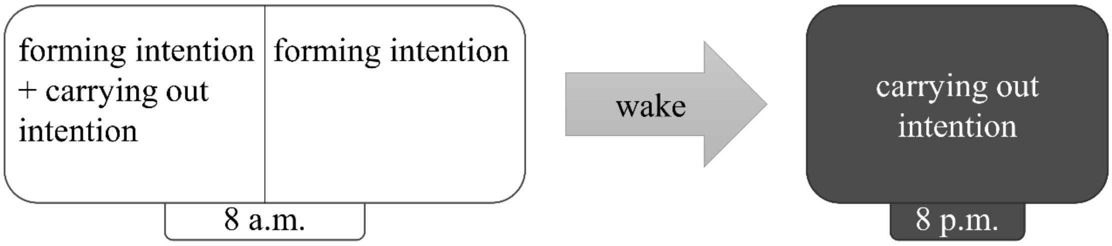
Wake group:



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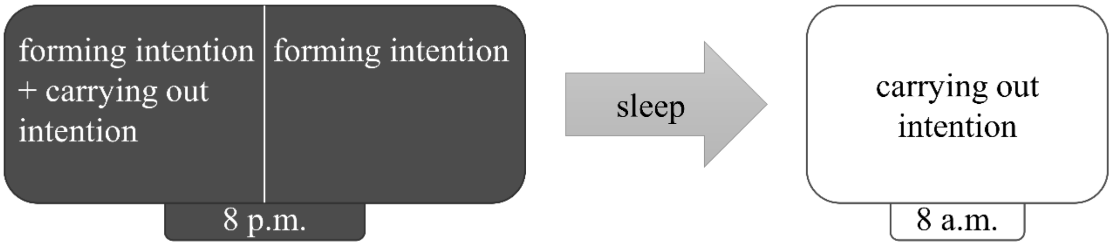

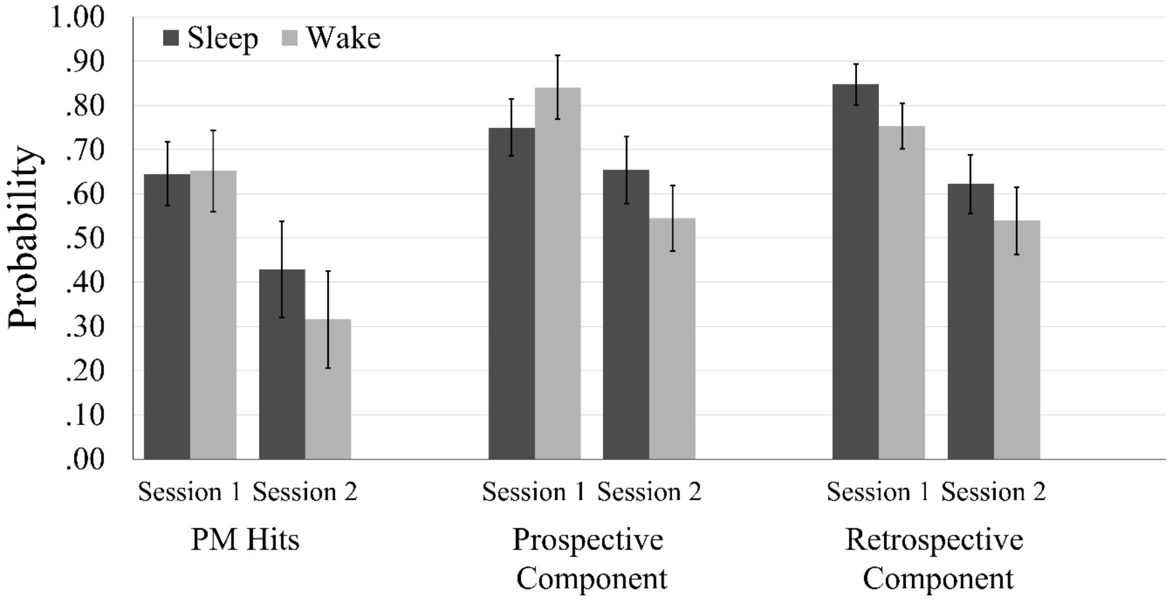
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Retrospective Component

Event-Based Prospective Memory Benefits from Relaxation-Hypnosis

Mateja F. Böhm, Ute J. Bayen, and Reinhard Pietrowsky

Heinrich-Heine-Universität Düsseldorf

Author Note

Mateja F. Böhm, Ute Johanna Bayen, and Reinhard Pietrowsky, Institute for Experimental Psychology, Heinrich-Heine-Universität Düsseldorf, Germany.

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Correspondence concerning this article should be addressed to Ute Johanna Bayen, Institut für Experimentelle Psychologie, Gebäude 23.02, Universitätsstraße 1, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany. Email: ubayen@hhu.de

Abstract

Event-based prospective memory (PM) involves remembering and performing intentions when a particular event occurs. The authors investigated effects of relaxation-hypnosis on event-based PM in two experiments. PM consists of a prospective component (remembering *that* something needs to be done), which relies on preparatory attention, and a retrospective-memory component (remembering *what* needs to be done and *when*). Previous studies found beneficial effects of relaxation on attention and retrospective memory. Therefore, we expected a beneficial effect of relaxation-hypnosis on the prospective and retrospective components of PM and applied the multinomial model of event-based PM (Smith & Bayen, 2004) to separately measure the two components. In two experiments, participants were instructed to perform a computerized PM task, then either listened to a relaxation-hypnosis CD or played a computer-game before performing the PM task. Relaxation-hypnosis had a positive effect on PM performance due to a beneficial effect on the prospective component, but not the retrospective component.

Keywords: prospective memory, intentions, relaxation, hypnosis, multinomial modeling

Event-Based Prospective Memory Benefits from Relaxation-Hypnosis

Prospective memory (PM) involves remembering to carry out an intention in the future, for instance, taking medication at the appropriate point in time. Event-based PM tasks require carrying out an intention when a certain event occurs, whereas time-based PM tasks require carrying out an intention at a certain point in time or after a certain amount of time has elapsed. For example, nurses who measure blood pressure whenever a patient arrives at the hospital perform an event-based PM task, whereas nurses who measure a patient's blood pressure every morning at 8 a.m. perform a time-based PM task.

PM is ubiquitous in everyday life and stressful jobs, such as nursing and aviation (Dismukes, 2007). Failures in PM occur often and can have severe consequences (Terry, 1988). It is, therefore, important to find ways to improve PM.

Sleep has been shown to improve PM (e.g., Scullin & McDaniel, 2010). However, sleep is not a viable option in every situation. During breaks, workers may have problems falling asleep, may need to be on stand-by, or the setting does not promote sleep. Relaxation, by contrast, can be easily implemented in many settings and can be easily interrupted when necessary rendering it applicable for clerks, nurses, and pilots, for example. Relaxation has been argued to be similar to midday sleep in reducing interference from new information (Schichl, Ziberi, Lahl, & Pietrowsky, 2011; Schönauer, Pawlizki, Köck, & Gais, 2014), and it enhances a variety of cognitive abilities (for a review, see Chiesa, Calati, & Serretti, 2011). We therefore performed the (to our knowledge) first experiments to investigate whether relaxation has a positive effect on event-based PM as well.

In the laboratory, event-based PM is typically studied by embedding a PM task in an ongoing task (Einstein & McDaniel, 1990). First, participants are instructed to perform the ongoing task. The ongoing task we used in the present experiments was a color-matching task, in which participants indicated whether the color of a word matched one of four previously presented rectangles (cf. Smith & Bayen, 2004, 2006). Participants then received PM task instructions. They were instructed to press a specific key whenever one of several PM target words appeared during the color-matching task. The presentation of these words was followed by a retention interval in which participants either relaxed or played a computer game. Thereafter, participants performed the ongoing task with the embedded PM task.

The described ongoing color-matching task is non-focal to the PM task as it does not draw the focus of attention to the defining features of the PM targets (McDaniel & Einstein, 2007). We chose a non-focal task, because there is consensus among theorists of PM that in non-focal tasks, remembering that one has to do something requires resource-demanding attentional processes (Smith, 2003; McDaniel & Einstein, 2000). Attention has been shown to benefit from relaxation. Legostaev (1996) found a positive effect of autogenic training on attention. Similarly, Ainsworth, Eddershaw, Meron, Baldwin, and Garner (2013) showed that meditation selectively enhanced executive attention. Furthermore, meditation had a positive effect on sustained attention (Lutz et al., 2009; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010). Therefore, by enhancing attentional processes, relaxation should also have a beneficial effect on remembering to do something in our PM task.

However, remembering to do something is not the only component of a PM task. In event-based PM tasks, participants must also remember the events upon which they are supposed to perform the PM task. In our paradigm, they must remember the PM target words. Einstein and McDaniel (1990) refer to this latter task component as a retrospective component of a PM task, whereas remembering that something needs to be done is the prospective component. It is reasonable to assume that relaxation, in addition to positively affecting the prospective component of the task by benefitting attention, may also benefit the retrospective component, as some studies measuring retrospective memory alone found effects. Schichl et al. (2011) reported better free recall of word lists after relaxation. Nava, Landau, Brody, Linder, and Schächinger (2004) reported better recognition of visual material four weeks after a relaxation intervention, but not immediately after relaxation. Schönauer et al. (2014) did not find a beneficial effect of meditation on recognition nor recall.

Although the effect of relaxation on retrospective memory has not been found consistently, increased rehearsal in the relaxation group may lead to a better retrospective component. Hicks, Marsh, and Russel (2000) suggested that rehearsal may benefit PM, and Mahy, Schnitzspahn, Hering, Pagobo, and Kliegel (2017) indeed found PM to be increased after a delay filled with a low-paced task that gave participants more opportunity to rehearse. In line with this, Einstein, McDaniel, Williford, Pagan, and Dismukes (2003) found that low-demanding tasks offered more time for rehearsal, thus leading to better PM. As relaxation is a low-demanding task as well, rehearsal may yield a positive effect on the retrospective component of PM in participants who relaxed and may thus confound effects of relaxation. We therefore asked participants how often and for how long they had rehearsed the target words during the retention interval.

The most common measure of PM performance is PM hit rate, which is the proportion of correct responses in PM target trials. This measure confounds the prospective component and the retrospective component, because in order to give the PM response upon presentation of a PM target, participants must both remember that they must do something and recognize the target. To obtain pure measures of the prospective component and the retrospective recognition component of PM, we separated the two components with the multinomial model of event-based PM (Smith & Bayen, 2004). The model is described in detail in the Data-Analyses-and-Results section. This model has been thoroughly validated for non-focal tasks (Horn, Bayen, Smith, & Boywitt, 2011; Rummel, Boywitt, & Meiser, 2011; Smith & Bayen, 2004) and frequently been applied (e.g., Arnold, Bayen, & Böhm, 2015; Arnold, Bayen, &

Smith, 2015; Pavawalla, Schmitter-Edgecombe, & Smith, 2012; Schnitzspahn, Horn, Bayen, & Kliegel, 2012; Smith & Bayen, 2005, 2006; Smith, Bayen, & Martin, 2010).

We expected relaxation to show an overall positive effect on event-based PM that may be based on the attention-demanding prospective component, the retrospective component, or both. Ihle et al. (2014) did not find an effect of relaxation on PM, which may, however, have been due to the short amount of time (10 min) participants relaxed in their study. Also, they investigated time-based PM, whereas we investigate event-based PM, which is a different type of task.

There are several relaxation techniques, such as relaxation-hypnosis, autogenic training, progressive muscle relaxation, meditation, and yoga. In our experiments, we had participants engage in relaxation-hypnosis because it is applicable with participants who are inexperienced in relaxation techniques (Schichl et al., 2011). We chose a computer game as control activity because computer games have been used in previous studies of relaxation (e.g., Schichl et al., 2011). Thus, in our experiments, participants either received relaxation-hypnosis or played a computer game during the retention interval between forming and carrying out the intention.

We expected the prospective component to be superior after relaxation-hypnosis, because attentional processes benefit from relaxation. The retrospective component may also be enhanced after relaxation, as relaxation improves retrospective memory in some studies. As the prospective component and the retrospective component may both be enhanced after relaxation-hypnosis, we also expected PM performance as measured by PM hit rate to be higher in the relaxation group compared to the computer-game group.

Experiment 1

Method

Participants and Design. Participants were recruited on the university campus or online and received academic credit or monetary compensation. Inclusion criteria were: (a) between 18 and 30 years old, (b) German native speaker, (c) no dyschromatopsia, (d) no history of psychological or neurological disorders, (e) no sleep disorders or consumption of sleep-inducing drugs, (f), no shiftworker, (g) nonsmoker, (h) no history of alcohol or drug addiction, (i) no consumption of any medication or drugs 24 hours prior to the study. (j) Furthermore, participants did not regularly get up before 5 a.m. or after 12 a.m. on weekdays or after 12 a.m. on weekends. They did not regularly go to sleep after 2 a.m. on weekdays or after 4 a.m. on weekends.

An a-priori power analysis conducted with multiTree (Moshagen, 2010) for the multinomial modeling showed that 28 participants in each group were needed to obtain a power of .80 to find an effect of $\omega = .036$ (which corresponds to a 15% difference between the parameter estimates) in the prospective component, given that each participant completed 110 trials of the combined color-matching and PM task.

Overall, 66 participants were randomly assigned to the relaxation-hypnosis or computer-game groups. Five participants had to be excluded because of technical problems (3) or errors in experimental procedure (2). One participant was excluded because she indicated that she could not see everything properly during the experiment. Another participant was excluded because she never pressed the designated key when target words occurred and could not indicate which key she had to press when prompted after the task. Thus, there were 59 participants in the final sample (average age 21.34 years, 95% CI [20.65, 22.02]) of which 30 were in the relaxation-hypnosis group and 29 in the computer-game group. Five participants of each group were male, the others female. The groups did not differ regarding previous experience with relaxation techniques, with six participants in the relaxation-hypnosis group and ten participants in the computer-game group indicating that they had experience, $z = 1.25$, $p = .211$, $r = .16$.

Procedure and Material. We screened with an online questionnaire for the inclusion criteria and invited qualifying respondents to individual testing sessions. After consent, the participant put on earmuffs and the computer-based experiment started. The 19-inch displays had a resolution of 1280 × 1024 pixels and a color depth of 32-bit color.

Participants first read the instructions for the ongoing color-matching task described below and completed six practice trials. Then, they learned about the PM task and were instructed to press the space bar whenever one of five target words appeared during the color-matching task. They were told that in each trial they could press the space bar even after accidentally giving the answer to the color-matching task. Afterwards, five target words were presented sequentially in black on white background for 5 seconds each, in Arial 24-point font size. Next, the one-hour retention interval started.

Computer game. Twenty-nine participants played a platform game consisting of several levels for one hour (Bleszinski, 1997).

Relaxation-hypnosis. Thirty participants engaged in relaxation-hypnosis using an audio CD (Hartmann, 2009). The CD started with relaxation exercises (6 min), continued with a guided visualization (16 min), and ended with a guided hypnosis (26 min). In total, the CD was 48 minutes long. Participants played the computer game for the remaining 12 minutes such that arousal levels would be equal across groups at the time of test.

Color-matching and PM tasks. After the retention interval, participants completed 110 trials of the color-matching task with the embedded PM task. For the color-matching task, participants saw a sequence of four rectangles of different colors (blue, green, red, yellow, or white) on a black background (with equal frequency of colors across participants).

Each rectangle was 166 × 120 pixels in size and presented for 500 ms with an inter-stimulus interval of 250 ms. After the fourth rectangle, a word was presented in Arial 24-point font size, and participants indicated whether the color of the word matched one of the rectangles or not by pressing the *v* or *m* key (approximately counterbalanced within groups) on the keyboard. Responses were self-paced. There were 50% match trials and 50% non-match trials, in random order.

We chose 165 words from the database by Lahl, Göritz, Pietrowsky, and Rosenberg (2009) and added information regarding frequency, word length, and number of syllables from the dlex database (Heister et al., 2011). To avoid material effects, we divided the words into three lists with 55 words each. The lists did not differ in concreteness, arousal, valence, frequency, word length, nor number of syllables. Five words per list were chosen as target words. The target words did not differ from the distractors regarding the previously named criteria. Each participant saw only one of the lists, which were approximately counterbalanced across participants within a group.

Each word of the lists was presented twice, leading to 110 trials comprised of 10 target trials and 100 distractor trials. Target trials occurred on every 9th to 13th trial (on every 11th trial on average). To allow for a delayed answer on the last target trial, one additional trial was added at the end of the task. If the space bar was pressed during this trial, this was counted as a delayed PM response to the previous trial. Otherwise, the additional trial was not analyzed.

Questionnaires. After completing the color-matching and PM tasks, participants first indicated if they had engaged in rehearsal of the target words during the retention interval. If they affirmed this, they were asked to indicate how often and for how long they had rehearsed. Next, participants freely recalled the target words and wrote them down. Afterwards, the Posthypnotic Inquiry Scale of the Hypnotic State Assessment Questionnaire

(HSAQ; Kronenberger, LaClave, & Morrow, 2002) was administered. We had translated this questionnaire to German using back translation. We adjusted the questions for the computer-game group in which participants were asked about their sensations during the computer game. We added two questions asking whether participants had felt relaxed or excited during the retention interval. Afterwards, participants filled in a demographics questionnaire so we could double check whether they fulfilled the inclusion criteria.

Finally, participants were debriefed and compensated. Sessions took about 1.5 hours.

Data Analyses and Results [1]

Manipulation Check. On a scale from 6 to 12, lower HSAQ scores indicate a stronger feeling of relaxation. The relaxation-hypnosis group was more relaxed (*Mean* = 7.93, 95% CI [7.43, 8.42]) during the retention interval than the computer-game group (*Mean* = 9.04, 95% CI [8.59, 9.48]), $t(54) = -3.38$, $p = .001$, $d = 0.91$.[2] Also, 27 out of 30 participants in the relaxation-hypnosis group indicated that they had felt relaxed during the retention interval in comparison to 7 out of 29 participants in the computer-game group, $z = 5.12$, $p < .001$, $r = .67$. Similarly, 3 out of 30 participants in the relaxation-hypnosis group indicated that they had felt excited during the retention interval in comparison to 20 out of 29 participants in the computer-game group, $z = 4.64$, $p < .001$, $r = .60$. Hence, the manipulation was successful.

Ongoing-Task Performance. The rate of correct responses on the color-matching task trials was .84 in both groups (95% $CI_{Relaxation}$ [.81, .87]; 95% CI_{Game} [.81, .87]), $t(57) = -0.13$, $p = .899$, $d < 0.01$.

PM-Task Performance. As shown in Figure 1, the relaxation-hypnosis group had a higher PM hit rate (i.e., proportion of PM target items correctly responded to) than the computer-game group, $t(47.12) = 2.58$, $p = .013$, $d = 0.70$.

PM hit rate measures a conglomerate of prospective and retrospective task components. To disentangle these, we used a formal stochastic model that we will present in turn.

Multinomial Model of Event-Based PM. Multinomial processing tree (MPT) models are widely used in cognitive psychology (for reviews, see Batchelder, 2017; Erdfelder et al., 2009). Based on categorical data from experimental studies, these models estimate the probabilities with which latent cognitive processes or states occur. The MPT model of event-based PM (Smith & Bayen, 2004) allows us to disentangle the prospective and retrospective components of laboratory PM tasks and can thus give us insights into possible effects of relaxation-hypnosis on both components.

The model has been designed for PM tasks that are embedded in ongoing tasks with two response options such as the color-matching task used in our experiments. The model is shown in Figure 2. It consists of four trees, each representing a different item type: (1) the word is a PM target and the colors match, (2) the word is a PM target and the colors do not match, (3) the word is not a PM target and the colors match, (4) the word is not a PM target and the colors do not match. The branches of each tree lead to one of the three response options: the colors match ("match"), the colors do not match ("no match"), or the word is a PM target ("PM"). The four trial types crossed with the three response options result in 12 response categories.

The first tree refers to trials with a PM target in matching color. With probability C_1, participants detect the color match. If they do, they either remember that they have to carry out an intention with probability P or, with the complementary probability $1 - P$, do not remember that they need to perform the PM task. In the latter case they respond "match". If they remember that they need to perform the PM task, recognizing the PM target (with probability M) leads to a "PM" response. However, if they do not recognize the PM target, with probability $1 - M$, participants may guess that the word is a target with probability g and answer "PM". Alternatively, they guess that the word was not a target word with probability $1 - g$ and answer "match" as they correctly detected the color match. If the color match of this item is not detected (with probability $1 - C_1$), participants may still remember that they need to carry out an intention with probability P. Again, if they do so, they need to recognize the target word to answer "PM", which occurs with probability M. If they do not correctly recognize the target word, with probability $1 - M$, participants must guess whether there is a color match or not as they did not detect the color match. With probability c participants guess that the colors matched and answer "match", whereas they guess that the colors did not match with probability $1 - c$ and answer "no match". If participants do not detect the color match (with probability $1 - C_1$) and do not remember that they need to carry out an intention (with probability $1 - P$), they must guess whether a color match occurred (with probability c) or not (with probability $1 - c$).

The second tree refers to trials that include a target word without color match. In this tree, parameter C_2 represents the probability of detecting that the colors do not match. Participants answer "no match" whenever they detect that the colors do not match and do not perform the PM task.

The third tree refers to trials with a distractor item in a matching color. In trees referring to distractor items, M is the probability that the distractor is correctly identified as such. On trials where participants correctly identify the distractor and detect the color match, they will respond "match". Similarly, on trials where the color match is not detected and participants identify the distractor, they must guess whether the colors matched, with probability c, or that the colors did not match with probability $1 - c$, leading to "match" or "no match" responses, respectively.

The fourth tree refers to trials with a distractor word without color match. This tree includes parameter C_2, the probability to detect a color non-match.

To obtain a mathematically identifiable model, we set several parameter restrictions as suggested by Smith and Bayen (2004). That is, we set parameter c to .50 assuming that when guessing a color match, participants matched the relative frequency with which color matches occurred during the experiment (*probability matching*; e.g. Van Zandt, 2000). Also, we set parameter g to .09, matching the relative frequency with which PM targets occurred.

Multinomial-Modeling Results. The frequencies of responses in the 12 response categories, aggregated over participants, are available in Table A1. They were used for the estimation of the MPT model parameters.[3]

To test the assumptions of the model, we performed goodness-of-fit tests. For these, we set α to .01 because the power to reject the model due to a small effect of $\omega = .1$ with $\alpha = .05$, 4 degrees of freedom and 3,190 observations (29 participants × 110 trials) would have been approximately .998. The model fit the data of both the relaxation-hypnosis group, $G^2(4) = 11.71$, $p = .020$, $\omega = .06$, and the computer-game group, $G^2(4) = 4.21$, $p = .378$, $\omega = .04$.

The parameter estimates for parameter P (prospective component) and parameter M (retrospective component) for both groups are shown in Figure 1. For tests of group differences between parameters, we set α to .05. The relaxation-hypnosis group had a better prospective component P than the computer-game group, $\Delta G^2(1) = 20.60$, $p < .001$. The two groups did not differ significantly regarding the retrospective component M, $\Delta G^2(1) = 3.04$, $p = .081$.

There were no group differences in the ongoing-task parameters. The probability of detecting a color match, C_1, was .55 (95% CI [.51, .60]) in the relaxation-hypnosis group and .56 (95% CI [.52, .61]) in the computer-game group, $\Delta G^2(1) = 0.12$, $p = .729$. The probability of detecting that the colors did not match, C_2, was .81 (95% CI [.78, .84]) in the relaxation-hypnosis group and .79 (95% CI [.76, .82]) in the computer-game group, $\Delta G^2(1) = 0.65$, p = .420.

Recall of Target Words. In the final recall test, the relaxation-hypnosis group remembered significantly more target words (*Mean* = 4.60, 95% CI [4.33, 4.87]) than the computer-game group (*Mean* = 3.86, 95% CI [3.47, 4.25]), $t(50.22) = 3.18$, $p = .002$, d = 0.84.

Rehearsal of Target Words. The proportion of participants reporting rehearsal of the target words during the retention interval did not differ between groups, $z = 1.77$, $p = .077$, r = .23, with 29 out of 30 participants rehearsing in the relaxation-hypnosis group and 24 out of 29 participants in the computer-game group.[4] The two groups did not differ regarding the reported average amount of time they spent rehearsing the target words (relaxation 4.67 min, 95% CI [2.62, 6.72]; game 3.97 min, 95% CI [0.49, 7.46]), $t(57) = 0.36$, $p = .723$, $d = 0.11$), nor the number of occasions on which they rehearsed (relaxation 7.80 times, 95% CI [4.34, 11.26]; game 6.81 times, 95% CI [-0.09, 13.71]), $t(57) = 0.27$, $p = .792$, $d = 0.08$. Thus, the results are not confounded by rehearsal.

Discussion

In this first experiment of effects of relaxation-hypnosis on event-based PM, we showed that PM performance benefitted from relaxation-hypnosis. That is, the PM hit rate was higher in the relaxation-hypnosis group than in the comparison group which played a computer game. Disentangling this effect with the MPT model of event-based PM, we showed that it was due to a benefit to the prospective component of the PM task, not to the retrospective component. This indicates that participants in the relaxation-hypnosis group had a higher probability to remember that they had to carry out an intention as compared to the computer-game group.

The positive effect of relaxation-hypnosis on the prospective component is in line with studies showing a positive effect of relaxation on attentional processes, because the prospective component in a non-focal PM task like the one employed in our study relies on attentional processes. Our findings indicate that relaxation-hypnosis may improve PM by refreshing attentional resources, thus leading to a better prospective component.

There was no effect on the retrospective component, which consists of target word recognition. However, after relaxation-hypnosis, we did find better memory for target words in the final free recall, similar to Schichl et al. (2011), who also measured free recall of words after relaxation. Thus, the effect of relaxation may be stronger on recall than on recognition. As the two groups did not differ in their reported rehearsal, differences in rehearsal are excluded as an explanation for differences in recall. Rather, this effect may be due to lower retrospective interference in the relaxation-hypnosis group, that is, less encoding of new, conflicting information (Wixted, 2004). As the parameter estimates for the retrospective recognition component of the PM task were close to ceiling, it is possible that a ceiling effect may have obscured beneficial effects of relaxation on the retrospective recognition component, a possibility that will be addressed in Experiment 2.

Another drawback of Experiment 1 was that we captured the success of the relaxation manipulation via subjective measures only and in hindsight. A more reliable way to monitor the success of the manipulation would be to do so during the retention interval and by using objective measures in addition to subjective ones. We performed Experiment 2 to address these issues.

Experiment 2

Experiment 2 had three objectives. First, we sought to replicate the beneficial effects of hypnosis-relaxation on the prospective component of PM. Second, we wanted to know if a ceiling effect possibly obscured effects of relaxation on the retrospective component. To avoid a ceiling effect in Experiment 2, we raised the retrospective-component demands of the task by increasing the number of to-be-remembered PM target words from 5 to 8.

Third, to improve the manipulation check, we administered the State-Trait Anxiety Inventory X1 (STAI-X1; Laux, Glanzmann, Schaffner, & Spielberger, 1981) to monitor the course of relaxation during the retention interval. The STAI-X1 measures anxiety at a certain point in time. In addition, to obtain objective measures of relaxation, we measured blood pressure and heart rate at three time points during the retention interval, as these are measures which have been shown to indicate relaxation (e.g., Ko & Lin, 2012). Overall, these measures should detect subjective and objective relaxation *during* the retention interval.

We expected that the prospective component would again benefit from relaxation-hypnosis. The retrospective component might also benefit once the ceiling effect was eliminated.

Method

Participants and Design. The form of recruitment and the inclusion criteria were the same as in Experiment 1. While the number of PM target words increased from 5 to 8, the number of PM target trials decreased from 10 to 8. To obtain equally reliable MPT modeling results as in Experiment 1, we raised the number of participants from 30 to 36 per group such that the absolute frequency of PM target trials in the sample was the same as in Experiment 1.

Overall, 83 participants were randomly assigned to the relaxation-hypnosis or computer-game groups. Four participants had to be excluded because they could not see or hear everything well during the experiment (1), failed to understand the PM instructions (1), or fell asleep during relaxation (2). Another six participants had to be excluded because of technical problems (2), noise (1), or experimenter error (3).

Thus, the final sample consisted of 73 participants (average age 22.27 years, 95% CI [21.64, 22.91]) of which 36 were in the relaxation-hypnosis group (10 male, 26 female) and

37 in the computer-game group (8 male, 29 female). There was no group difference regarding previous experience with relaxation techniques, with 10 experienced participants in the relaxation-hypnosis group and 16 in the computer-game group, $z = 1.38$, $p = .168$, $r = .16$.

Procedure and Material. We only made small adjustments to the materials and procedure used in Experiment 1 and will describe the changes in turn.

Color-matching and PM tasks. We selected 360 words following the same procedure as in Experiment 1. The words were divided into three lists with 120 words each, of which 8 words served as targets and 112 words as distractors. Overall, participants completed 120 trials, during which each word was presented once, and target trials occurred on every 12th to 15th trial (on every 13th trial on average). Since the last trial was never a PM target trial, no additional trial had to be added as in Experiment 1.

Blood pressure and heart rate. We measured blood pressure and heart rate using the Omron RS2, which is a digital blood-pressure monitor with a cuff that is placed around the wrist for measurement. We took these measurements at three time points: at the beginning of the retention interval, during the retention interval (i.e., after an additional 48 min of relaxing/playing the computer game), and at the end of the retention interval (i.e., after an additional 6 min of playing the computer game).

STAI-X1. The STAI-X1 consists of 20 statements (e.g. “I feel secure”), which are rated on a 4-point Likert-scale ranging from 1 (*not at all*) to 4 (*very*). Thus, the total scores on this questionnaire range between 20 and 80 points. Higher scores indicate greater anxiety.

Participants completed the STAI-X1 twice. On both occasions, the STAI-XI immediately followed the measurements of blood pressure and heart rate. The measurement of blood pressure, heart rate, and STAI-X1 took a total of about six minutes. Thus, the retention interval amounted to 1 hour in both experiments.

Data Analyses and Results

Manipulation Check. The relaxation-hypnosis group had lower HSAQ scores (*Mean* = 7.74, 95% CI [7.27, 8.22]) than the computer-game group (*Mean* = 8.78, 95% CI [8.35, 9.22]), $t(69.25) = 3.28$, $p = .002$, $d = 0.77$. With 32 participants in the relaxation-hypnosis group and 17 participants in the computer-game group indicating that they had felt relaxed during the retention interval, the proportion in the relaxation-hypnosis group was larger, $z = 4.14$, $p < .001$, $r = .49$. Accordingly, with 4 participants in the relaxation-hypnosis group and 21 participants in the computer-game group indicating that they had felt excited during the retention interval, the proportion in the computer-game group was larger, $z = 4.04$, $p < .001$, $r = .47$.

The two groups also differed regarding their STAI-X1 scores, $F(1, 71) = 9.09$, $p = .004$, $\eta_p^2 = .113$, with overall higher scores in the computer-game group (*Mean* = 36.93, 95% CI [34.84, 39.03]) than the relaxation-hypnosis group (*Mean* = 32.42, 95% CI [30.29, 34.54]). The group × time point interaction was significant, $F(1, 71) = 29.60$, $p < .001$, $\eta_p^2 = .294$. Follow-up tests indicated that as expected the STAI-X1 scores before the retention interval did not differ between the computer-game group (*Mean* = 35.24, 95% CI [33.03, 37.45]) and the relaxation-hypnosis group (*Mean* = 34.44, 95% CI [32.20, 36.68]), $t(71) = 0.51$, $p = .614$, $d = 0.12$. After the retention interval, the computer-game group had significantly higher scores (*Mean* = 38.62, 95% CI [36.22, 41.02]) than the relaxation-hypnosis group (*Mean* = 30.39, 95% CI [27.96, 32.82]), $t(71) = 4.81$, $p < .001$, $d = 1.13$. All subjective measures thus indicated the success of the manipulation.

Next we analyzed whether the objective measures pulse and mean arterial blood pressure (MAP, calculated from the systolic and diastolic blood pressure) decreased due to relaxation-hypnosis. A mixed MANOVA did not yield a significant interaction between time point and group, $\Lambda = .91$, $F(4, 68) = 1.68$, $p = .165$, $\eta_p^2 = .09$. The main effect of group was also not significant, $\Lambda = .97$, $F(2, 70) = 1.00$, $p = .372$, $\eta_p^2 = .03$ indicating that the effect of the manipulation did not show in the objective measures. Merely the main effect of time point was significant, $\Lambda = .68$, $F(4, 68) = 8.13$, $p < .001$, $\eta_p^2 = .32$. A detailed description of the effect of time point as well as the descriptive data are available in the supplement. Overall, the subjective measures indicated a successful manipulation, whereas the objective measures did not.

Ongoing-Task Performance. Participants in the relaxation-hypnosis group performed better in the ongoing task (*Mean* = .88, 95% CI [.86, .90]) than the computer-game group (*Mean* = .82, 95% CI [.79, .86]), $t(71) = 2.87$, $p = .005$, $d = 0.68$.

PM-Task Performance. As shown in Figure 3, participants in the relaxation-hypnosis group performed better in the PM task than the computer-game group, $t(71) = 2.53$, $p = .014$, $d = 0.58$.

Multinomial-Modeling Results[5]. The response frequencies used for the estimation of the MPT model parameters are available in Table A1. As in Experiment 1, we set α to .01. The model fit the data of both the relaxation-hypnosis group, $G^2(4) = 7.55$, $p = .109$, $\omega = .04$, and the computer-game group, $G^2(4) = 2.21$, $p = .697$, $\omega = .03$.

Figure 3 shows the parameter estimates for parameter *P* (prospective component) and parameter *M* (retrospective component) for both groups. As in Experiment 1, we set α to .05 for tests of group differences between parameters. The relaxation-hypnosis group had a significantly higher prospective component than the computer-game group, $\Delta G^2(1) = 29.22$, $p < .001$. The two groups did not differ regarding the retrospective component, $\Delta G^2(1) = 0.47$, $p = .492$.

C_1 (the ability to detect color matches) was higher in the relaxation-hypnosis group ($C_1 = .66$, 95% CI [.63, .69]) than the computer-game group ($C_1 = .51$, 95% CI [.48, .55]), $\Delta G^2(1) = 34.73$, $p < .001$. C_2 (the ability to detect color non-matches) was also higher in the relaxation-hypnosis group (C_2 = .86, 95% CI [.84, .88]) than the computer-game group (C_2 = .78, 95% CI [.75, .80]), $\Delta G^2(1) = 21.95$, $p < .001$.

Recall of Target Words. In the final recall test, the two groups did not differ regarding the mean number of correctly recalled words, $t(71) = 0.90$, $p = .370$, $d = 0.17$, with the relaxation-hypnosis group remembering 4.92 words out of 8 (95% CI [4.24, 5.60]) and the computer-game group 4.49 words (95% CI [3.80, 5.17]).

Rehearsal of Target Words. The proportion of participants rehearsing did again not differ between the two groups, $z = 1.87$, $p = .061$, $r = .22$, with 31 participants rehearsing the words in the relaxation-hypnosis group and 25 participants in the computer-game group.[3] The two groups did not differ regarding time spent rehearsing (relaxation 2.94 min, 95% CI [1.76, 4.12]; game 2.21 min, 95% CI [1.25, 3.17]), $t(71) = 0.97$, $p = .334$, $d = 0.23$. Also, they did not differ regarding the number of occasions on which they rehearsed (relaxation 3.54 times, 95% CI [2.52, 4.56]; game 2.49 times, 95% CI [1.31, 3.66]), $t(71) = 1.37$, $p = .174$, $d = 0.32$. Thus, rehearsal can be ruled out as a confounding variable in Experiment 2 as well.

Discussion

In Experiment 2, we replicated the results from Experiment 1, showing that PM performance benefits from relaxation-hypnosis. Again, the PM hit rate was higher in the relaxation-hypnosis group than the computer-game group, which was driven by an effect on the prospective component: The relaxation-hypnosis group had a higher probability of remembering that they needed to fulfil an intention.

The two groups did not differ regarding the retrospective component, supporting evidence against an effect of relaxation-hypnosis on retrospective memory (Schönauer et al., 2014). Retrospective-memory parameter *M* was not at ceiling in Experiment 2. Thus, after conducting this experiment, we can rule out an effect of relaxation on the retrospective component.

In addition to the PM advantage, the relaxation-hypnosis group also performed better on the ongoing task. It has been shown that relaxation decreases stress (Chiesa & Serretti, 2009), lowers cortisol levels (Dawson, Hamson-Utley, Hansen, & Olpin, 2014), and relieves anxiety (Bell, 2015). Thus, as indicated by the STAI-X1, the relaxation-hypnosis group experienced the test situation in the laboratory as less stressful, which may have led to better PM and color-matching task performance. This challenges studies that could not show an effect of stress on event-based PM (Möschl, Walser, Plessow, Goschke, & Fischer, 2017; Walser, Fischer, Goschke, Kirschbaum, & Plessow, 2013).

Although the relaxation-hypnosis group felt subjectively more relaxed after the retention interval than the computer-game group, this did not show in the objective measures. Possibly, heart rate and blood pressure should be measured continuously throughout the retention interval, that is, during relaxation in the relaxation-hypnosis group. Nava et al. (2004) and Christoph, Luborsky, Kron, and Fishman (1978) found an effect of relaxation on heart rate measured continuously.

General Discussion

Experiments 1 and 2 provided convincing evidence for a positive influence of relaxation-hypnosis on the prospective component of PM. Relaxation-hypnosis did not have an effect on the retrospective component.

Previous studies manipulated retention intervals by varying their length and rehearsal opportunities (Hicks et al., 2000; Mahy et al., 2017). We showed that the quality of tasks during the retention interval also influences PM, independent of length and rehearsal. Thus, researchers may pay more attention to the distractor task chosen for retention intervals when planning future studies.

We could show that people with low experience in relaxation-techniques can benefit from relaxation, and that being subjectively relaxed suffices to elicit a positive effect of relaxation on PM. Possible follow-up studies should determine whether different types of relaxation techniques influence PM differentially. For instance, it has been shown that distinct relaxation techniques have different impacts on memory and anxiety (Subramanya & Telles, 2009; Tang et al., 2007). Additionally, it would be interesting to determine how long relaxation must be to have an effect on PM. Ihle et al. (2014) did not find an effect after 10 minutes of relaxation, but used a time-based task. It would also be of interest to know for how long the beneficial effect endures after cessation of relaxation.

Our results suggest that relaxation improves the prospective component of PM by refreshing attentional resources. This indicates that occupational groups for which PM is critical (e.g., nurses, doctors, pilots) may benefit from relaxation exercises during breaks. Thus, future research should investigate whether relaxation is a viable approach toward improving PM in daily life.

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Footnotes

[1] Bayesian *t* tests and their respective Bayesian factors as computed using JASP (JASP Team, 2017) support the same hypotheses as the frequentist statistics reported here.

[2] All *t* tests and *z* tests reported in this paper are two-tailed.

[3] We also performed hierarchical latent-trait MPT model analyses (Klauer, 2010) with TreeBUGS (Heck, Arnold, & Arnold, 2018) which provide individual parameter estimates. However, with only 110 observations per participant, these analyses had low reliabilities, and we therefore report the results of conventional MPT modeling of aggregate data. The parameter estimates obtained via conventional MPT modeling lie within the 95% confidence intervals of the hierarchical MPT model estimates.

[4] When we included only those participants who engaged in rehearsal, the results from all analyses remained the same regarding direction and significance.

[5] Again, we performed hierarchical latent-trait MPT model analyses to obtain individual parameter estimates. With 120 observations per participant, these analyses still had low reliabilities. Thus, we report the results of conventional MPT modeling of aggregate data. The 95% confidence intervals of the hierarchical MPT model estimates overlap with the confidence intervals of the conventional MPT modeling.

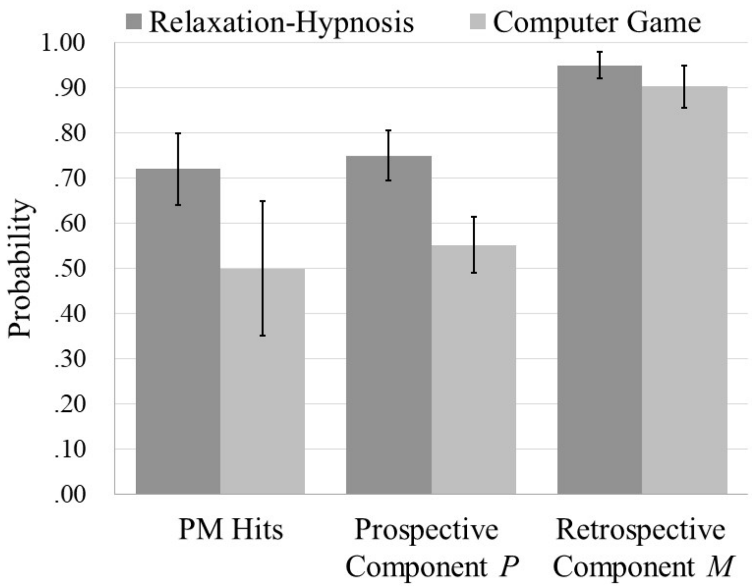

Figure 1. Mean prospective-memory (PM) hit rate and estimates of parameters *P* (prospective component) and *M* (retrospective component) for the relaxation-hypnosis and computer-game groups in Experiment 1. Error bars indicate 95% confidence intervals.

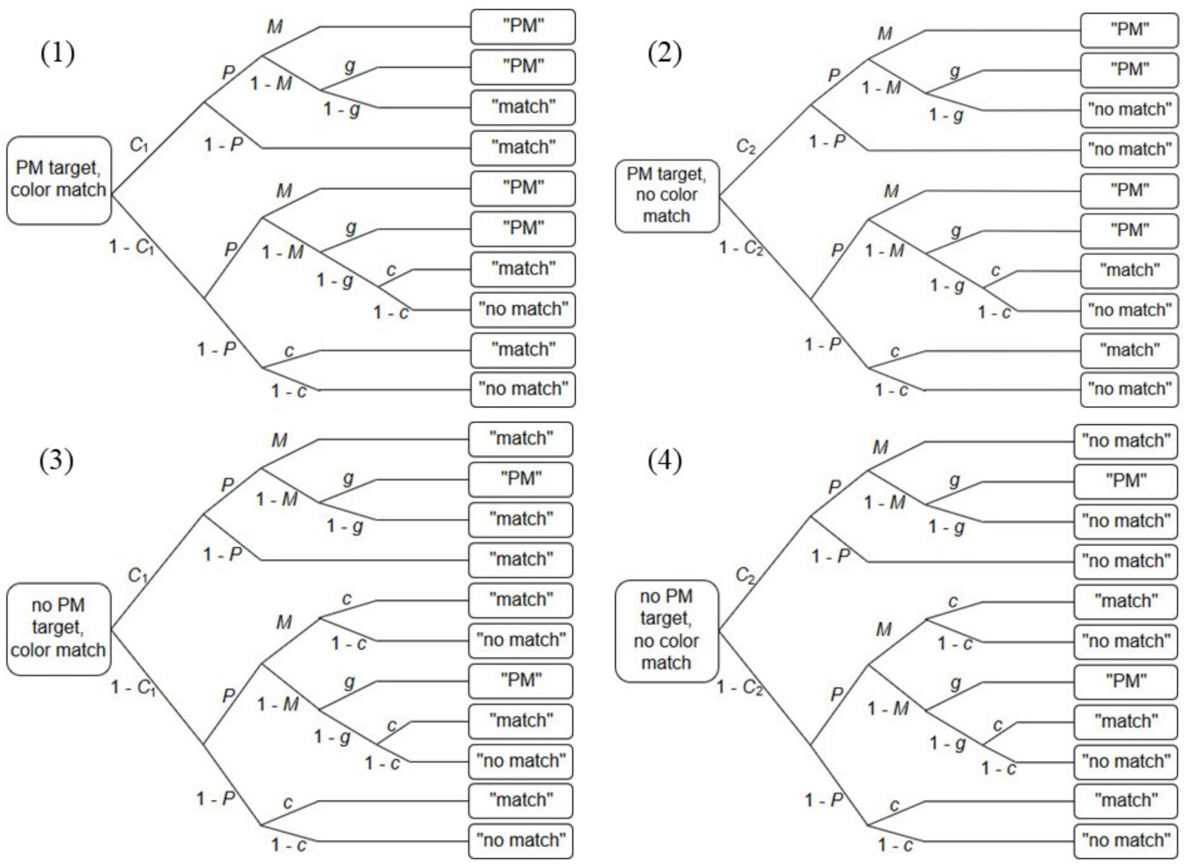

Figure 2. The multinomial processing tree model of event-based prospective memory (PM) by Smith and Bayen (2004). C_1 = probability to detect a color match, C_2 = probability to detect that colors do not match, *P* = prospective component, *M* = retrospective component, *g* = probability to guess that word is a PM target, *c* = probability to guess that colors match. Adapted from "A multinomial model of event-based prospective memory" by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, p. 758. Copyright 2004 by the American Psychological Association.

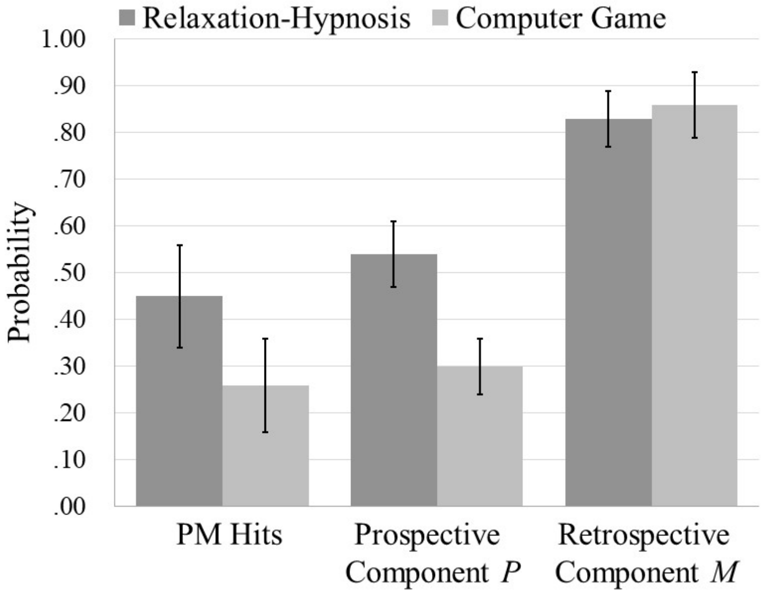

Figure 3. Mean prospective-memory (PM) hit rate and estimates of parameters *P* (prospective component) and *M* (retrospective component) for the relaxation-hypnosis and computer-game groups in Experiment 2. Error bars indicate 95% confidence intervals.

Appendix

Table A1

Response Frequencies for Experiments 1 and 2

Group	Item type	Response type		
		"PM"	"match"	"no match"
Experiment 1, relaxation-hypnosis	PM target, CM	103	33	14
	PM target, no CM	112	6	32
	No PM target, CM	1	1168	331
	No PM target, no CM	9	139	1352
Experiment 1, computer game	PM target, CM	71	61	13
	PM target, no CM	75	9	61
	No PM target, CM	10	1123	317
	No PM target, no CM	4	148	1298
Experiment 2, relaxation-hypnosis	PM target, CM	67	70	7
	PM target, no CM	63	4	77
	No PM target, CM	17	1652	347
	No PM target, no CM	9	144	1863
Experiment 2, computer game	PM target, CM	40	85	23
	PM target, no CM	37	16	95
	No PM target, CM	5	1560	507
	No PM target, no CM	7	228	1837

Note. PM = prospective memory. CM = color match.

Do Body Posture, Sleepiness, and Sleep Quality Affect Prospective Memory?

Mateja F. Böhm, Ute J. Bayen, and Marie Luisa Schaper

Heinrich-Heine-Universität Düsseldorf

Author Note

Mateja F. Böhm, Ute Johanna Bayen, and Marie Luisa Schaper, Institute for Experimental Psychology, Heinrich-Heine-Universität Düsseldorf, Germany.

Preliminary results were presented at the 6th International Conference on Memory (ICOM) in Budapest, Hungary, in July of 2016. Data can be accessed via the Open Science Framework at https://osf.io/z3yk7/?view_only=fadf9f8c54e44534a67ec75ad8f22a28

Correspondence concerning this article should be addressed to Ute Johanna Bayen, Institut für Experimentelle Psychologie, Gebäude 23.02, Universitätsstraße 1, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany. Email: ubayen@hhu.de

Abstract

Frequent changes in working postures are a preventive measure against back pain. Dynamic workstations allow working in upright (sitting, standing) or supine posture (lying down). However, supine posture induces sleepiness and may thus affect work performance. We investigated how sleepiness affects work-related cognition, specifically event-based prospective memory (PM). Event-based PM involves carrying out intentions when specific events occur. It consists of a prospective component (remembering *that* something must be done) and a retrospective component (remembering *what* must be done and *when*). Because sleepiness has been shown to affect attention, we expected an effect of posture on the prospective component in an attention-demanding nonfocal PM task. In two experiments, we investigated effects of sleepiness and sleep quality on both PM components. We separated the prospective and retrospective components via Bayesian multinomial processing-tree modeling and found conclusive evidence that neither component was related to sleep quality or sleepiness in upright posture. In Experiment 2, posture moderated the effect of sleep quality on the prospective component: In supine posture (i.e., with stronger sleepiness), poor sleep quality had a more negative effect on the prospective component than in upright posture. Explanations for these findings and implications for the use of dynamic workstations are discussed.

Keywords: prospective memory, body posture, sleepiness, sleep quality, multinomial modeling

Do Body Posture, Sleepiness, and Sleep Quality Affect Prospective Memory?

Low back pain is a common ailment (e.g., Schmidt et al., 2007) and may be prevented and relieved by regularly changing working postures (e.g., Bridger, 2009) such as sitting, standing, or lying down. However, supine posture may induce sleepiness (e.g., Caldwell, Prazinko, & Caldwell, 2003) and thus decrease work performance by impairing cognitive functioning. One important work-related area of cognitive functioning is prospective memory (PM), which involves remembering to carry out intentions at the appropriate time (e.g., Einstein & McDaniel, 1990). In the present study, we investigated whether subjective sleepiness affects PM (Experiment 1) and compared effects of upright versus supine posture on sleepiness and PM (Experiment 2).

Low back pain has a one-year-prevalence of about 50 - 75 % (e.g., Schmidt et al., 2007; Yiengprugsawan et al., 2017). It is one of the leading causes of work absence thereby resulting in substantial economic costs (Maniadakis & Gray, 2000; Olafsson, Jonsson, Fritzell, Hägg, & Borgström, 2018; Stewart, Ricci, Chee, Morganstein, & Lipton, 2003; van Tulder, Koes, & Bouter, 1995). To reduce these costs and maintain quality of life for individuals (e.g., Hagen, Svensen, Eriksen, Ihlebaek, & Ursin, 2006), preventive measures against low back pain are paramount. Low back pain has been ascribed to prolonged, static sitting (Andersson, 1981; Reinecke, Hazard, & Coleman, 1994; van Deursen et al., 1999). Height-adjustable tables that allow office workers to alternate between sitting and standing positions have been on the market for more than 25 years (U.S. Patent No. 5,174,223, 1992). Recently, dynamic workstations have been introduced that additionally allow workers to alternate between upright postures and reclined or supine postures during desk and computer work (U.S. Patent No. 8,939,500, 2015). In such dynamic workstations, the computer screen and desktop automatically move with the seat's position so that working in different postures is possible without meticulous adjustment of the whole workstation for each change of posture. However, reclined and supine postures may differ from upright (i.e., sitting and standing) postures in that they induce sleepiness (Caldwell et al., 2003; Caldwell, Prazinko, & Hall, 2000; Cole, 1989; Kräuchi, Cajochen, & Wirz-Justice, 1985; Romeijn et al., 2012; Sharafkhaneh & Hirshkowitz, 2003). Thus, they may impair work performance as sleepiness may negatively affect cognitive processes (e.g., Lowe, Safati, & Hall, 2017). It is therefore crucial to examine effects of sleepiness on work-related cognitive functions to evaluate the usefulness of dynamic workstations in the workplace.

In our research, we first investigated possible effects of sleepiness on PM in common upright sitting posture in Experiment 1. In Experiment 2, we replicated the findings from Experiment 1 and additionally compared upright with supine postures, because levels of sleepiness induced by supine posture may differ from naturally occurring sleepiness in upright posture. In the following, we will first introduce the reader to PM and its component processes, then describe a computerized PM task paradigm that resembles computer tasks in the workplace and allows us to measure components underlying PM performance. After that, we will review the literature on effects of sleepiness on PM.

Event-based PM involves remembering to perform a previously planned action when a specific event occurs. For example, someone may have to interrupt his computer work when a colleague arrives in order to give her a message. Event-based PM is ubiquitous in daily life and important in many jobs and professions such as health care, air traffic control, and office work (e.g., Dismukes, 2012; Grundgeiger, Sanderson, MacDougall, & Venkatesh, 2010; Wilson, Farrell, Visser, & Loft, 2018). Due to the digital revolution, vastly increasing numbers of work places involve long hours of sitting at computers (Statistisches Bundesamt, 2009). PM tasks are ubiquitous in such a setting. For instance, people working at a computer need to remember to add an attachment to an e-mail before sending it.

Successful event-based PM has two components (Einstein & McDaniel, 1990). The *prospective component* involves remembering *that* an intention needs to be carried out and the *retrospective component* involves remembering *what* the intention is and *when* it should be carried out. For instance, an office assistant must not only remember having an additional intention while checking his e-mails (prospective component). He must also remember to forward emails to his boss when recognizing that they regard certain topics that the boss had previously specified (retrospective component).

As dynamic workstations are meant to prevent and relieve low back pain in office workers whose jobs typically involve long hours of computer work, we chose a computerized PM task for our experiments that is similar to the types of tasks performed in typical office work, and that at the same time allowed us to yield valid measures of the prospective and retrospective task components via mathematical modeling. We thereby aimed to achieve a balance between real-life relevance and experimental rigor. The type of computerized event-based PM task we used was first introduced by Einstein and McDaniel (1990) and has since been proven useful in myriads of PM studies (Kliegel, McDaniel, & Einstein, 2008). The task paradigm involves an ongoing task with an embedded PM task. The ongoing task must be interrupted when a target event occurs that signals the necessity to carry out a PM task. This is akin to, for example, an office assistant who must interrupt his ongoing computer work whenever emails from certain clients arrive (and ignore emails from other people). In the current study, the ongoing task was a color-matching task, where participants had to indicate whether a word had the same color as one of four previously presented rectangles (c.f. Smith & Bayen, 2004). The embedded PM task was to press a specific key whenever participants encountered one of several previously studied words during the ongoing task. The prospective component of this PM task is to remember that one has to do something in addition to the ongoing task; the retrospective component is to recognize the studied PM target words when they occur during the task.

Prospective Memory and Sleepiness

As said, a concern about dynamic workstations is that reclined or supine body posture may negatively affect work performance by inducing sleepiness. Although several previous studies demonstrated a positive effect of sleep on PM (Barner, Seibold, Born, & Diekelmann, 2017; Böhm, Bayen, & Pietrowsky, 2018, under review; Diekelmann, Wilhelm, Wagner, & Born, 2013a, 2013b; Scullin & McDaniel, 2010), possible effects of sleepiness on PM have mostly been neglected. It seems reasonable to assume that higher levels of sleepiness should be associated with poorer PM: According to a meta-analysis by Lim and Dinges (2010), sleepiness induced by sleep deprivation impairs sustained attention. In turn, deficits in sustained attention may impair a variety of cognitive tasks. PM relies on sustained attention (e.g., Burgess, Quayle, & Frith, 2001), which suggests that sleepiness should impair PM as well. To our knowledge, only two published studies investigated effects of sleepiness on event-based PM. A quasi-experimental questionnaire study by Ohayon and Vecchierini (2002) suggested that self-reported daytime sleepiness may predict PM difficulties in older adults, but was overall inconclusive. In a sample of young healthy adults, Grundgeiger, Bayen, and Horn (2014) showed that one night of total sleep deprivation resulted in increased sleepiness and impaired PM. Thus, there is some evidence for a detrimental effect of sleepiness on PM.

Although evidence regarding effects of sleepiness on PM is thus scarce, studies from other cognitive domains suggest that sleepiness should have differential effects on the prospective versus retrospective components of PM. There is consensus among PM researchers that in *nonfocal* PM tasks, the prospective component depends on attentional processes (McDaniel & Einstein, 2000; Scullin, McDaniel, & Shelton, 2013; Smith, 2003; for empirical demonstrations, see e.g., Burgess et al., 2001; Cona, Scarpazza, Sartori, Moscovitch, & Bisiacchi, 2015; Kuhlmann & Rummel, 2014). PM target events that are nonfocal to the ongoing task are defined by different features as those that are relevant for the ongoing task (see McDaniel & Einstein, 2007). Thus, in such tasks, participants need to shift their attentional focus from the features relevant for the ongoing task to the features relevant for the PM task. For example, in the color-matching task described above, participants must shift attention from the color of the words to their meaning. Therefore, if sleepiness impairs attention, it should also impair the prospective component of PM. Sleepiness indeed lowers attention (Byun, Kim, & Riegel, 2017; Henelius et al., 2014; Kraemer et al., 2000; Maire et al., 2014; Shattuck & Matsangas, 2015), and partial sleep restriction (i.e., restricting sleep by several hours for a prolonged period of time) impairs sustained attention (for a meta-analysis, see Lowe et al., 2017). Thus, there is strong evidence for effects of sleepiness on attentional processes, and therefore, the prospective component of PM should also be impaired when a person is sleepy.

The retrospective component of PM in the described task entails episodic recognition memory for PM target words. That is, in the example above, the office assistant must remember which messages he must forward to his boss immediately. Therefore, if sleepiness impairs recognition memory, it should also impair the retrospective component of PM. There seem to be no effects of sleepiness induced by sleep deprivation or partial sleep restriction on recognition memory (Drummond et al., 2000; Lo, Chong, Ganesan, Leong, & Chee, 2016; Stenuit & Kerkhofs, 2008; Swann, Yelland, Redman, & Rajaratnam, 2006). The retrospective component of our PM task should, therefore, be equally unaffected by sleepiness, and possible effects of sleepiness on PM performance should be due to its prospective, not its retrospective component.

We included sleep quality as a covariate, because it has been shown to relate to sleepiness (Åkerstedt, Axelsson, Lekander, Orsini, & Kecklund, 2013). Poor sleep quality may thus result in sleepiness-related impairments in cognitive functions. Previous studies suggested that sleep quality may affect PM performance (Fabbri, Tonetti, Martoni, & Natale, 2014), whereas other studies neither found correlations with subjective sleep quality (Rendell, Gray, Henry, & Tolan, 2007; Rendell, Mazur, & Henry, 2009), nor with objective sleep quality (Fabbri, Tonetti, Martoni, & Natale, 2015). The effect of sleep quality on PM is thus unclear at this point. Results regarding effects of sleep quality on sustained attention are mixed (Benitez & Gunstad, 2012; Byun et al., 2017; Popp et al., 2015) indicating that sleep quality may affect the prospective component of PM. The only study in which the effect of young adults' sleep quality on retrospective recognition memory was examined (Gobin, Banks, Fins, & Tartar, 2015) showed no association for stimuli with neutral valence. This suggests that sleep quality should not impair the retrospective component of our PM task. Because of possible effects of sleep quality on at least the prospective component of PM, we deemed it important to take sleep quality into account when determining effects of sleepiness on PM.

The following experiments are the first to test the possible effects of dynamic workstations on cognitive functioning by investigating the effects of sleepiness and sleep quality on the separate PM components. The literature reviewed above suggests that if sleepiness and low sleep quality have detrimental effects on PM, these should be driven by deficits in the prospective component, but not the retrospective component. We thus had different hypotheses for the two components of PM, necessitating separate and unconfounded measurement of each component. To render our hypotheses testable, we used (a) the multinomial processing tree (MPT) model of PM (Smith & Bayen, 2004), which allowed us to obtain separate measures of the prospective and the retrospective component (for a detailed model description, see the Results section of Experiment 1), and (b) Bayesian statistics. Using the Bayesian framework, we can directly compare the evidence for the null versus the alternative hypotheses (which is not possible in classical frequentist statistics). Thus, even if we do not find an influence of sleepiness or sleep quality on components of PM, we can quantify our evidence and assess whether a null effect is attributable to an insufficient number of observations or to the null hypothesis being true. This is of particular importance when establishing the expected null effects on the retrospective component. Bayesian statistics thus render null results interpretable, thereby strengthening the argument for or against the use of dynamic workstations.

Experiment 1

In Experiment 1, we aimed at investigating effects of sleepiness on components of PM in conventional upright posture. All participants performed a computerized nonfocal PM task while sitting at a computer. We measured sleepiness with the Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990) and sleep quality with the Pittsburgh Sleep Quality Index (PSQI; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). PM performance is commonly measured as PM hit rate, which is the ratio of PM target items upon which participants correctly pressed the PM key. Because prospective and retrospective components jointly lead to PM hits, we used the MPT model of event-based PM (Smith & Bayen, 2004) to measure the effect of sleepiness on both components separately and without confounds (for details of the modeling, see the Results section of Experiment 1). Based on the existing literature, we expected a detrimental effect of sleepiness and sleep quality on PM to be primarily driven by an effect on the prospective component.

We expected the prospective component of PM to be worse when participants were sleepy, as previous studies showed that sleepiness impaired attentional processes (e.g., Henelius et al., 2014). Sleep quality may also, if anything, negatively affect the prospective component, but the current literature as outlined above does not allow for a clear prediction. We did not expect an effect of sleepiness nor sleep quality on the retrospective component of PM, as suggested by previous studies, which did not find an effect on recognition (e.g., Drummond et al., 2000; Gobin et al., 2015; Lo et al., 2016).

Method

Participants. To determine sample sizes, we used the same power considerations in both experiments. An a priori power analysis showed that 104 participants were required to obtain a power of .80 to find a small-to-medium overall effect of $f^2 = .11$ in a regression on PM hit rate with $\alpha = .05$ and three predictors (sleepiness before and after the experiment, and sleep quality). To forestall possible drop-outs, we recruited 118 participants (87 female, 31 male; mean age = 21.42 years, 95% CI [20.87, 21.97]), who were German native speakers, between 17 and 30 years old, did not report achromatopsia (because of the color-matching task), and were of good mental and physical health. Additionally, they fulfilled the following inclusion criteria to ensure normal sleep behavior and normal cognitive functioning: (a) no sleep disorders, (b) no shift work in the past 3 months, (c) no more than four alcoholic beverages the night before, (d) not under the influence of pharmaceutical or recreational drugs that could impair attention, (e) non-smokers, as smoking has a detrimental effect on sleep (Cohrs et al., 2014; Jaehne et al., 2012), and (f) no previous participation in PM studies. Participants were recruited on the university campus or via online social networks and received monetary reimbursement or course credit. The Research Ethics Committee of the College of Mathematics and Natural Sciences at the Heinrich-Heine-Universität Düsseldorf declared this study exempt from ethics review.

Procedure, measures, and materials. Participants gave written consent after arriving at the laboratory and were tested in groups of up to four in individual computer booths. The experiment was computer-based except for the paper-pencil questionnaires presented at the end. At the beginning of the experiment, participants rated their current level of sleepiness on a computer-based version of the KSS (Åkerstedt & Gillberg, 1990), which is a 9-point Likert Scale ranging from 1 (*extremely alert*) to 9 (*extremely sleepy – fighting sleep*). The KSS correlates with objective EEG and EOG measures of sleepiness and is a valid and reliable tool for measuring sleepiness (Åkerstedt & Gillberg, 1990; Kaida et al., 2006). Then, the PM task was administered as described in the following.

Ongoing color-matching task and prospective-memory task. As the ongoing task, we used a color-matching task (e.g., Smith & Bayen, 2004), in which participants indicated whether the color of a word matched that of one of four previously presented rectangles. Participants were instructed to press the *v* or *m* key to indicate whether or not the colors matched (with the assignment counterbalanced across participants). Rectangles and words were presented in red, blue, white, green, and yellow on black background. The colors were presented equally often during the color-matching task. Color matches and non-matches occurred equally often and in random order. The words were written in Arial 24 and the rectangles were 120 × 166 pixel in size. Rectangles were presented for 500ms each with inter-stimulus intervals of 250ms. Words were presented until a response was made. Participants performed six practice ongoing-task trials.

Next, participants performed three blocks of a PM task embedded in the ongoing task. Three blocks were necessary to obtain a sufficient number of PM trials per person for MPT modeling without increasing the proportion of PM trials during the ongoing task (cf., Arnold, Bayen, & Böhm, 2014). Participants received instructions to perform a PM task in addition to the color-matching task. They were instructed to press F1 whenever they encountered one of five previously studied PM target words. They were also told that if they accidentally performed the color-matching task on a PM target trial, they could still press the PM key during the rectangle presentation of the next trial. Then, five PM target words were presented in random order for 5s each, black on white background in Arial 24.

We selected 165 words from the database by Lahl, Göritz, Pietrowsky, and Rosenberg (2009) for the color-matching and PM tasks. We divided the words into three lists of 55 words each. From each list, we chose five words as PM target words such that the lists as well as targets and distractors did not differ regarding valence, arousal, and concreteness (according to Lahl et al., 2009) as well as length, number of syllables, and frequency (according to the dlex database, Heister et al., 2011). One list was presented per block (in counterbalanced order), and each word was presented twice.

After presentation of the target words, participants had to solve simple addition problems of the form a + b + c for 3 min as a distractor task. Then, they performed 110 color-matching task trials, 10 of which included PM target words. Target trials occurred on every 10th trial on average, varying between the 8^{th} and 12^{th} trial.

At the beginning of each of the three consecutive test blocks, the PM-task instructions were given and participants studied five new PM target words followed by the 3 min distractor task. After completing all three blocks, participants indicated which key they were supposed to press upon encountering a PM target word. They were also asked whether they had remembered to press this key anytime during the experiment. Finally, participants filled in the computer-based KSS for a second time.

Paper-pencil questionnaires. Then, participants filled in a questionnaire to assess demographics and check the inclusion criteria. Next, they filled in a self-drafted questionnaire about caffeine consumption, and the Fagerström-Test for nicotine dependency (Bleich, Havemann-Reinecke, & Kornhuber, 2002).[1]

Afterwards, they filled in the German version of the PSQI (translated by Riemann & Backhaus, 1996), which captures subjective sleep quality during the previous two weeks in

10 questions, which can be subsumed in 7 components: (1) subjective sleep quality, (2) sleep latency, (3) sleep duration, (4) habitual sleep efficiency (i.e., the amount of time participants spent asleep in relation to the amount of time spent in bed), (5) sleep disturbances, (6) use of sleep medication, and (7) daytime dysfunctions. The component scores are summed up to a global PSQI score that ranges from 0 to 21, with higher values indicating poorer sleep quality. To discriminate between good and bad sleepers, a cut-off value of > 6 has been suggested for the German version of the test (Backhaus, Junghanns, Broocks, Riemann, & Hohagen, 2002), resulting in a sensitivity of 93.4% and a specificity of 100%. Buysse et al. (1989) showed that the PSQI is valid, internally consistent, and highly reliable (Cronbach's $\alpha = .83$).

Next, participants filled in the morningness-eveningness questionnaire (Horne & Östberg, 1976) and a sleep diary for the previous night[1]. Finally, participants were debriefed and compensated.

Results

To test the predictions that sleepiness and sleep quality should affect overall PM performance, we first computed linear regressions on PM hit rate with PSQI and KSS scores as predictors. Afterwards, we disentangled the prospective and retrospective components via MPT modeling using the Bayesian-hierarchical latent-trait approach (Klauer, 2010).

In addition to null-hypothesis significance testing, we used Bayesian statistics to weigh the null and alternative hypotheses against each other. In Bayesian statistics, the Bayes factor (BF) indicates the likelihood with which the data are obtained under one hypothesis as compared to the other hypothesis. For instance, a BF_{10} of 3.2 indicates that the data are 3.2 times more likely under the alternative hypothesis as compared to the null hypothesis. Critically, the index of the *BF* indicates whether the null hypothesis is compared to the alternative hypothesis (01) or vice versa (10; e.g., Rouder, Morey, & Pratte, 2017). According to Raftery (1995, p. 139), a *BF* between 1 and 3 can be interpreted as "weak evidence," a *BF* between 3 and 20 as "positive evidence," a *BF* between 20 and 150 as "strong evidence," and a *BF* larger than 150 as "very strong evidence" for one of the hypotheses. Except for the hierarchical Bayesian analyses, we used JASP (Marsman & Wagenmakers, 2016) to conduct the Bayesian analyses in both experiments.

Prospective-memory performance. We measured overall PM performance as PM hit rate, that is, the rate of target words that correctly received a PM response. If the PM key was pressed during presentation of the rectangles of the next trial following a PM target word, this was counted as a correct response (cf. Einstein & McDaniel, 1990).

We regressed PM hit rate (*Mean* = .69, 95% CI [.65, .73]) on sleepiness ratings before and after the PM task (KSS_{before}: *Mean* = 3.84, 95% CI [3.59, 4.09]; KSS_{after}: *Mean* = 5.09, 95% CI [4.76, 5.43]), and on sleep quality (PSQI: *Mean* = 5.72, 95% CI [5.27, 6.17]) by entering the predictors simultaneously. The predictors did not explain variance in PM hit rate, $R^2 = .06$, $F(3, 117) = 2.40$, $p = .071$, $BF_{01} = 2.89$, with weak evidence for the null hypothesis.

Multinomial model of event-based prospective memory. To hit a PM target, participants must remember that they had to do something (prospective component) and must recognize the target word (retrospective component). A PM hit may also result from lucky guessing. Therefore, it is important to obtain separate and unconfounded measures of the prospective and the retrospective components. The MPT model of event-based PM introduced by Smith and Bayen (2004) provides such measures and thus enabled us to determine whether sleepiness and sleep quality predicted the prospective or retrospective component, or both.

In general, MPT models allow us to estimate the probabilities of latent processes underlying performance from frequencies of participant responses in a particular task. They are frequently used in cognitive psychology (for reviews, see Batchelder & Riefer, 1999, and

Erdfelder et al., 2009). The MPT model of event-based PM was designed for ongoing tasks with two response options (e.g., the color-matching task where colors may or may not match) and an embedded PM task (e.g., when participants are required to press a specific key upon encountering target words). Thus, there are three response options: (a) the colors match, (b) the colors do not match, and (c) the word is a PM target. There are four different trial types: (1) target, color match; (2) target, color non-match; (3) distractor, color match; (4) distractor, color non-match. As any of the three responses can be given on any of the four trial types, there are 12 different response categories. The response frequencies in each category are tallied and analyzed with the model.

The MPT model of event-based PM is shown in Figure 1. Each of the trees represents one of the trial types. The first tree represents trials with a target word and a color match. Here, participants detect the color match with probability C_1. They may further remember that they have an intention, with probability P (prospective component). With probability M (retrospective component), they may correctly recognize the target word as such and thus push the PM key. If they do not recognize the target word, with probability $1 – M$, they either guess that the word was a target (with probability g) or that it was a distractor (with probability $1 – g$). If, on the other hand, participants do not remember that they have an intention, with probability $1 – P$, they will answer “match” because they have detected the color match. The lower part of the tree represents cases in which participants do not detect the color match (with probability $1 – C_1$). Nevertheless, they may remember that they had an intention with a probability of P. If they recognize the target word (M), they answer “PM”. If alternatively, they do not recognize the word, they guess that the word is a PM target (with probability g) or that it is not ($1 – g$). If they guess that the word is not a target, they must guess that the colors match, with probability of c, or do not match ($1 – c$) because they do not detect the color match. Similarly, if participants do not remember that they had an intention (with probability $1 - P$), they guess that the colors match, with probability c, or do not match ($1 - c$).

The second tree refers to trials with a target word, but without a color match, and is constructed in a similar manner. In this tree, parameter C_2 indicates the probability with which participants detect that the colors do not match and leads to “no match” responses.

The third tree refers to trials without a target word and with a color match and is constructed in a similar manner as the first tree. With probability M, participants recognize the distractor as such. Whenever participants recognize the distractor or guess that the word is a distractor, they answer the color-matching task and do not press the PM key. Therefore, when participants do not detect the color match, but recognize the distractor as such, they guess that the color matches (with probability c) or not ($1 - c$).

The fourth tree refers to trials without a target word and without a color match and is similar to the third tree. Here, parameter C_2 represents the probability with which participants detect that the colors do not match.

Due to limited degrees of freedom, parameter restrictions need to be set to obtain an identifiable model. Following the recommendations by Smith and Bayen (2004), we set guessing parameter c to .50 (the actual ratio of color matches) and guessing parameter g to .09 (the actual ratio of target words at test), assuming that guessing probabilities matched the actual ratios (probability-matching, e.g., Van Zandt, 2000). The MPT model of PM has been shown to be valid (Horn, Bayen, Smith, & Boywitt, 2011; Rummel, Boywitt, & Meiser, 2011; Smith & Bayen, 2004) and has been used in a number of previous studies (e.g., Arnold et al., 2014; Böhm et al., 2018, under review; Pavawalla, Schmitter-Edgecombe, & Smith, 2012; Schnitzspahn, Horn, Bayen, & Kliegel, 2012; Smith & Bayen, 2005, 2006; Smith, Bayen, & Martin, 2010).

The response frequencies obtained in Experiments 1 and 2, summed over participants, are listed in Appendix A. From the individual frequencies, we estimated model parameters for each participant for the prospective component (*P*), the retrospective component (*M*) and color-matching ability (C_1 and C_2) with the Bayesian hierarchical latent-trait approach (Klauer, 2010). This approach enabled us to compute regressions with sleepiness and sleep quality explaining variance in individual parameters. The latent-trait approach takes correlations between parameters into account and postulates that the individual parameters stem from an overarching multivariate normal distribution. Using the latent-trait approach, the distributions for each parameter at group level as well as at the individual level, and the distribution for each parameter correlation are estimated. For each of these distributions, a prior distribution is assumed. The data update the prior distribution, so that the posterior distribution is obtained (Bayes' theorem). Samples from these posterior distributions are drawn using the Markov chain Monte Carlo algorithm. These samples provide information about the properties of these distributions. We obtained centrality and variance parameters of the posterior distributions and report group parameter estimates and 95% Bayesian Credibility Intervals (BCI, in brackets), which indicate the range in which the true value of the parameter lies with 95% confidence. The uncertainty expressed by BCIs is also considered when computing regressions between individual parameter estimates and extraneous variables (such as sleepiness and sleep quality). Using this type of analysis, interactions between predictors cannot be taken into account because setting a prior for this interaction is an unresolved issue.

For our hierarchical MPT analyses, we used TreeBUGS (Heck, Arnold, & Arnold, 2018), which uses the Gibbs sampler JAGS (Plummer, 2013) to sample posterior distributions. We conducted 1,000,000 iterations, implemented a burn-in period of 500,000 samples and retained every 100th sample. Good convergence was given for every parameter, with the Gelman-Rubin statistic $\hat{R}$ < 1.05 (Gelman & Rubin, 1992).

Modeling results. Table 1 shows the group parameter estimates and 95% BCIs. To test whether parameters *P* and *M* were associated with sleepiness and sleep quality, we conducted regression analyses within the hierarchical model described above. The KSS_{before}, KSS_{after} (as measures of sleepiness), and the PSQI (as measure of sleep quality) total scores were used to predict parameters *P* and *M*. Neither sleepiness before, nor after the PM task, nor sleep quality reliably predicted the prospective component *P*. Similarly, neither sleepiness before, nor after the PM task, nor sleep quality predicted the retrospective component *M*. Table 2 shows the regression weights, BCIs and BFs_{01}[2]. All BFs indicate positive evidence for the null-hypothesis, that is, with reasonable certainty, the sleep-related variables were not associated with the PM components.

Discussion

In Experiment 1, sleepiness and sleep quality predicted neither PM hit rate, nor the prospective or the retrospective component of PM. The BFs even indicated positive evidence for the null hypothesis, that is, an absence of an effect of sleepiness and sleep quality on the PM components. For the prospective component, these results are surprising, because according to a meta-analysis of effects of sleepiness on attention (Lim & Dinges, 2010), sleepiness should impair the prospective component (e.g., Henelius et al., 2014). However, the null effect of sleepiness on the retrospective-memory component is in line with other studies that did not find a relationship between sleepiness and recognition memory (Drummond et al., 2000; Lo et al., 2016; Stenuit & Kerkhofs, 2008; Swann et al., 2006). Sleep quality did not predict PM hit rate, which is not in line with Fabbri et al. (2014), but supports findings from other PM studies (Fabbri et al., 2015; Rendell et al., 2007, 2009). Further, neither PM component was predicted by sleep quality.

In terms of work performance, it is reassuring that sleepiness and sleep quality do not influence PM in upright posture. However, if offices are equipped with dynamic workstations, workers may adopt more reclined or even supine postures during work. As supine posture has been shown to induce sleepiness (e.g., Caldwell et al., 2003) and may thereby intensify already existing sleepiness, we investigated the effect of supine posture on PM in Experiment 2. We chose to test participants in supine rather than reclined posture, because supine is the most extreme possible setting in dynamic workstations, thus maximizing statistical power by enhancing the expected effect on sleepiness.

Experiment 2

In Experiment 2, we manipulated body posture. According to the model of sleep and wakefulness by Johns (1993, 1998), a sleep drive and a wake drive determine the level of sleepiness. The stronger the sleep drive is in comparison to the wake drive, the sleepier the individual. Sleep drive can be increased via a manipulation of body posture: Lying in supine posture increases sleepiness and the urge to fall asleep in comparison with sitting upright (e.g., Caldwell et al., 2003). Thus, in Experiment 2, participants performed the task in either upright or supine posture, that is, either sitting or lying down.

Regarding the prospective component of PM, there are two possible outcomes that we deemed possible given the results of Experiment 1. The first possibility is that, as suggested by Experiment 1, sleepiness does not affect the prospective component. In this case, Experiment 2 should not show a difference between upright and supine posture. The alternative possibility is that supine posture elicits stronger levels of sleepiness thus affecting the prospective component. In this case, we should find a lower prospective component in the supine-posture group than in the upright-posture group. We did not expect an influence of sleepiness on the retrospective component, because previous studies did not show an effect of sleepiness on recognition memory (Drummond et al., 2000; Lo et al., 2016; Stenuit &

Kerkhofs, 2008; Swann et al., 2006), and Experiment 1 supported this conclusion for the retrospective component of PM.

Severe sleepiness or poor sleep quality alone may not be sufficient to impair PM, but some studies indicated that sleep-related variables may interact to have a detrimental effect on PM. Fabbri et al. (2014) found an effect of sleep quality on PM in an extreme-group comparison, where both groups differed on several sleep-related variables. Additionally, Fabbri et al. (2015) showed that sleep quality was related to PM in insomnia patients who also suffered from severe daytime sleepiness. Thus, PM may be impacted when participants are sleepy *and* have poor sleep quality. In Experiment 2, the experimental manipulation of body posture enabled us to determine, via hierarchical MPT modeling, whether posture-induced sleepiness and sleep quality have a combined effect on components of PM. In addition to the studies by Fabbri et al. (2014, 2015), a working-memory study supports the hypothesis that sleepiness and sleep quality may interact to affect PM: Muehlhan, Marxen, Landsiedel, Malberg, and Zaunseder (2014) showed a combined effect of sleepiness and sleep quality on reaction times in a working-memory task. Poor sleep quality slowed reaction times – but only for participants who were tested in supine posture and therefore felt sleepier than a comparison group tested in upright posture. Thus, posture-induced sleepiness moderated the relationship between sleep quality and working memory. Because the prospective component of non-focal PM tasks draws on resource-demanding processes (e.g., Smith, 2003), it is associated with working memory (Arnold, Bayen, & Smith, 2015; Smith & Bayen, 2005). Thus, we expected that body posture would also moderate the relationship between sleep quality and the prospective component, as it did with working memory. That is, a negative relationship between sleep quality and the prospective component should be more pronounced under strong levels of sleepiness induced by supine posture.

Method

Design and participants. The power considerations were the same as for Experiment 1. In Experiment 2, the three predictors used in the regression on PM hit rate were body posture, sleep quality, and the interaction of body posture and sleep quality.

Of a total of 105 students (81 female, 24 male; mean age = 22.36 years, 95% CI [21.80, 22.92]), 52 were randomly assigned to the upright group and 53 to the supine group. Participant recruitment and compensation were the same as in Experiment 1. Inclusion criteria were the same as those in Experiment 1 with two additional criteria: (a) Individuals with visual impairment could only participate with a correction device that allowed flawless presentation via the head-mounted display used in Experiment 2 (i.e., contact lenses were allowed, but glasses were not). (b) Participants did not suffer from clinically relevant daytime sleepiness (i.e., Epworth Sleepiness Scale total score < 11; Johns, 2000), as we wanted to investigate normal levels of sleepiness.

Procedure, measures, and materials. Prior to Experiment 2, participants completed an online screening questionnaire inquiring the inclusion criteria. If they fulfilled all criteria, they could sign up to participate. Participants gave written consent after arriving at the laboratory and were tested individually. To double-check for inclusion criteria, participants were administered the Ishihara test of color vision (Ishihara, 1972), a demographic questionnaire, and several sleep-related paper-pencil questionnaires in the following order: the KSS, the Epworth Sleepiness Scale (ESS; Johns, 1991; translated by Bloch, Schoch, Zhang, & Russi, 1999), and the PSQI. The ESS consists of eight items that regard the probability to fall asleep in certain situations (e.g., while watching TV) on a 4-point Likert Scale from 0 to 3. High total sum scores indicate high levels of daytime sleepiness.

Experimental set-up and technical equipment. During the computer-based experiment, the upright group sat in a chair, while the supine group lay down face up on a bed free of covers or pillows. Aside from that, the procedure was the same in both groups. An RB-740 response pad (cedrus Corporation) with one horizontal row of seven keys was placed in the participant's lap. Fingers were placed on the left (3rd) and right (5th) keys, which they would need for the following tasks. Participants wore a Sony HMZ-T2 head-mounted display, which had a resolution of 1,920 × 1,080 pixels and two light-emitting diode displays, one for each eye. The head-mounted display was used to standardize the distance between eyes and screen for both groups and was adjusted until participants could clearly see the text presented to them. Only indirect, dim light was allowed in the room to avoid light reflections on the lenses. Participants were asked to read a short text aloud to verify that they could see everything presented on the display. Then, the experiment started.

Ongoing color-matching task and prospective-memory task. Only slight changes were made to the procedure and materials of the color-matching task and the PM task used in Experiment 1. The words were presented in Arial 28 to facilitate the perception of blue words presented on a black background via the head-mounted display. As the distractor task, participants indicated via key press whether simple addition problems of the form a + b + c = d were correct or not. The middle (4th) key served as PM key. These two changes were introduced because we used a response pad instead of a keyboard in Experiment 2.

Psychomotor Vigilance Task. For the next 10 min., participants performed the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985), a task commonly used to measure sustained attention under sleep deprivation and severe sleepiness (Van Dongen, Maislin, Mullington, & Dinges, 2003). Participants monitored a white screen and were required to press the middle key as fast as possible whenever a black counter (Arial, 24) appeared on the screen. As soon as participants pressed the key, the counter stopped and showed the reaction time in milliseconds. The counter appeared every 2 to 10 seconds at random intervals. If the participants did not react for 10 seconds, the words "no reaction" appeared on screen for 1 second. If the participants pressed the middle key although the counter was not present, the words “false alarm” appeared for 1 second.

Afterwards, the participants removed the head-mounted display, and filled in the KSS for a second time. Finally, they were debriefed and compensated.

Results

We will present results in the following order. We first determined the success of the randomization. We then determined the effects of the experimental manipulation of posture on sleepiness followed by a comparison of both posture groups regarding ongoing-task performance and PM hit rate. Afterwards, we disentangled the prospective and retrospective components of PM via MPT modeling using the Bayesian-hierarchical latent-trait approach (Klauer, 2010) as in Experiment 1.

Randomization check. Table 3 shows the descriptive data for randomization checks. At the outset, the two groups did not differ regarding daytime sleepiness as measured with the ESS, $t(102) = 1.05$, $p = .295$, $d = .21$, $BF_{01} = 2.95$ indicating successful randomization.

The two groups also did not differ regarding sleep quality, $t(102.35) = 1.71$, $p = .089$, $d = 0.34$, $BF_{01} = 1.31$. The mean PSQI scores of the supine group and the upright group were lower than the cut-off value of 6 for poor sleep quality, supine: $t(52) = -4.35$, $p < .001$, $d = 0.60$, $BF_{01} = 678{,}295$; upright: $t(51) = -6.40$, $p < .001$, $d = 0.89$, $BF_{-0} = 561{,}505$. Thus, both groups can be characterized as good sleepers.

Effects of posture on sleepiness and vigilance. Table 3 shows the descriptive data obtained with the KSS and the PVT. We analyzed whether supine posture resulted in increased sleepiness as measured with the KSS. An ANOVA[3] with posture (upright vs. supine) as between-subjects factor and time of measurement (before vs. after the experiment) as within-subjects factor yielded no main effect of posture, $F(1, 101) = 1.26$, $p = .264$, $\eta_p^2 = .01$, $BF_{\text{Inclusion}}$[4] $= 0.40$, but a main effect of time, $F(1, 101)$[4]$= 48.38$, $p < .001$, $\eta_p^2 = .32$,

$BF_{\text{Inclusion}} = 1.96*10^7$, and an interaction, $F(1, 101) = 5.56$, $p = .020$, $\eta_p^2 = .05$, $BF_{\text{Inclusion}} =$ 2.41. Participants were less sleepy before the session than afterwards. As expected, this increase was more pronounced in the supine group. Supine posture thus induced sleepiness.

Then, we analyzed the effects of posture on vigilance as measured with the PVT. A MANOVA showed no significant effect of posture on lapses, false alarms, nor logarithmized[5] reaction times in the PVT, $\Lambda = .96$, $F(3, 101) = 1.36$, $p = .259$, $\eta_p^2 = .04$. Since JASP cannot compute *BF* for MANOVAs, we report test statistics separately for the measures included in the MANOVA in the following. The *BF* indicated no group differences regarding false alarms, $BF_{01} = 4.09$, and logarithmized reaction times, $BF_{01} = 2.67$, but could not be computed for lapses due to their rare occurrence (two in the supine-posture group overall). Supine posture thus induced sleepiness when measured by the subjective KSS, but this effect did not show in the behavioral PVT measures.

Color-matching-task performance. The posture groups did not differ in rate of correct responses in the color-matching task ($M_{\text{upright}} = .86$, $SD_{\text{upright}} = .09$; $M_{\text{supine}} = .84$, $SD_{\text{supine}} = .10$), $t(103) = 1.07$, $p = .287$, $d = 0.21$, $BF_{01} = 2.91$.

Prospective-memory performance. The posture groups did not differ in PM hit rate ($M_{\text{upright}} = .68$, $SD_{\text{upright}} = .19$; $M_{\text{supine}} = .66$, $SD_{\text{supine}} = .22$), $t(103) = 0.54$, $p = .592$, $d = 0.10$, $BF_{01} = 4.26$. To test the moderator hypothesis that sleep quality correlates with PM hit rate in the supine group only, we computed a regression to predict PM hit rate. The predictors were posture (supine vs. upright), PSQI score, and the interaction between posture and PSQI. If the interaction was a significant predictor of PM hit rate, this would indicate that the relationship between PM hit rate and sleep quality varied between posture groups. However, the regression model did not explain variance in PM hit rate, $R^2_{\text{corr}} < .01$, $F(3, 104) = 1.14$, $p =$ $.335$, $BF_{01} = 10.34$. The interaction did not predict PM hit rate, $\beta = -.17$, $t(100) = -1.71$, $p =$

.090, BF_{01} = 1.36. Thus, the relationship between PM hit rate and sleep quality did not differ depending on posture.

Modeling results. We computed a model for each group separately. Table 1 shows the parameter estimates and 95% BCIs of the overall group parameters. We used the PSQI total score to predict parameters *P* and *M* in both posture groups separately. The settings for the estimation process were identical to Experiment 1.

The posture groups did not differ regarding the prospective component *P* as indicated by the 95% BCI [in brackets], which included zero, ΔP = − .03, [−.13, .07]. The two groups did not differ regarding the retrospective component *M* either, ΔM = .06, [−.004, .12].

To examine moderator effects of body posture on the relationship between sleep quality and the prospective and retrospective components of PM, we estimated regression slopes between the PSQI and parameters *P* and *M*, respectively, separately for each posture group. In the upright group, the regression weight of sleep quality predicting the prospective component *P* did not differ from zero, *b* = .08 [−.06, .23], $BF_{01}{}^2$ = 5.34, with the *BF* indicating positive evidence for the null hypothesis, that is, no relationship between sleep quality and the prospective component *P*. In the supine group, the regression weight of sleep quality predicting the prospective component *P* was not different from zero either, *b* = −.13 [−.27, .01], $BF_{01}{}^2$ = 1.62, with the *BF* favoring the null hypothesis, albeit yielding only weak evidence. However, these regression weights differed from each other, Δb = .20, [.01, .40]. This means that sleep quality predicted the prospective component in different ways, depending on posture. Although the regression weights were not different from zero, the weight tended to be negative in the supine-posture group and close to zero/positive in the upright group. In supine posture, participants with better sleep quality (i.e., lower values on the PSQI) tended to have a higher probability to remember that they needed to fulfill an intention. In the upright group, if anything, participants with better sleep quality tended to have a lower probability to remember that they needed to fulfill an intention.

Regarding the retrospective component, the regression weight of sleep quality predicting parameter *M* was neither different from zero in the upright group, $b = .03$ [−.10, .15], $BF_{01}{}^2 = 9.54$, nor in the supine group, $b = .04$ [−.08, .15], $BF_{01}{}^2 = 8.90$, with both BFs yielding positive evidence for the null hypothesis. The regression weights did not differ from each other, $\Delta b = -.01$, [−.18, .16].

Overall, the posture groups did not differ regarding either component of PM. However, the relationship between sleep quality and the prospective component *P* varied depending on posture. Thus, body posture was a moderator of this relationship.

Discussion

In Experiment 2, we aimed at determining effects of sleepiness induced by supine posture on PM. To this end, we experimentally placed participants in either upright or supine posture during an event-based PM task and measured current sleepiness as well as subjective sleep quality the night before. Supine posture induced sleepiness. Body posture moderated the effect of sleep quality on the probability of remembering that something needed to be done: In supine posture, poor sleep quality in the nights before formation and execution of intentions had a more negative effect on the prospective component of a PM task compared to the effect in upright posture.

Furthermore, we replicated the unexpected null results from Experiment 1. That is, the Bayes Factors showed convincing evidence against effects of sleepiness and of sleep quality on PM and its components in upright posture. We, therefore, conclude that neither sleepiness nor sleep quality alone affected PM or its components in upright posture.

As working memory and the prospective component of PM are positively related (Arnold et al., 2015), our results regarding the prospective component are in line with findings by Muehlhan et al. (2014) who found an effect of sleep quality on working memory in supine posture only. Corresponding with Muehlhan et al.'s results regarding working memory, the upright and supine groups did not differ in the prospective component. However, posture moderated the relationship between sleep quality and the prospective component of PM. This may indicate that humans are able to compensate for poor sleep quality – but only under conditions that do not induce sleepiness, such as upright posture. Also, sleepiness induced by supine posture alone does not suffice for a detrimental effect on the prospective component of PM. Rather, sleep quality must be considered as well.

The vigilance measure PVT, was not affected by posture. Commonly, the PVT is used to assess sustained attention. The lack of an effects of body posture on the PVT in Experiment 2 may explain why posture overall did not impair the prospective component of PM: The prospective component should only be affected if the underlying attentional processes suffered from sleepiness induced by supine posture.

The null effect of posture on the retrospective component of PM adds to the studies that did not find effects of sleepiness on recognition memory (Drummond et al., 2000; Lo et al., 2016; Stenuit & Kerkhofs, 2008; Swann et al., 2006).

As a side note, the findings of Experiment 2 also have implications for fMRI studies. Researchers conducting fMRI need to take participants' sleep quality into account because it may affect the results obtained from participants lying in a scanner in supine position. Particular caution must be applied in fMRI studies when comparing healthy controls and participants with health issues that affect sleep quality (e.g., depression, O'Leary, Small, Panaite, Bylsma, & Rottenberg, 2017).

General Discussion

Motivated by questions about possible effects of supine posture in dynamic workstations on cognitive performance, we conducted two experiments to investigate effects of sleepiness and sleep quality on PM and its components in upright and supine postures. We aimed at obtaining a clear pattern of results by applying Bayesian statistics, which enabled us to compare the evidence obtained for the null versus the alternative hypothesis. In Experiment 1, we obtained positive evidence for the null hypothesis, that is, sleepiness and sleep quality did not affect the components of PM in upright posture. In Experiment 2, we did not find differences between upright and sleepiness-inducing supine posture, and additionally showed a moderation: The effect of sleep quality on the prospective component of PM differed depending on body posture. We will first discuss theoretical aspects of our study, before we turn to the applied implications of the current findings with regard to the use of dynamic workstations.

In both experiments, sleepiness did not have a main effect on the prospective component of PM, which contrasts with other studies demonstrating effects of sleepiness on PM (Grundgeiger et al., 2014; Ohayon & Vecchierini, 2002). This may be the case because we investigated normal levels of sleepiness in a sample of young adults, as compared to a sleep-deprivation manipulation (Grundgeiger et al., 2014) and a sample of older adults (Ohayon & Vecchierini, 2002). Our findings regarding the prospective component also stand in contrast to several studies that indicated a detrimental effect of sleepiness on attention (Byun et al., 2017; Henelius et al., 2014; Kraemer et al., 2000; Lowe et al., 2017; Maire et al., 2014; Shattuck & Matsangas, 2015), which underlies the prospective component of PM (e.g., Burgess et al., 2001). As indicated by the PVT in Experiment 2, sleepiness did not affect attention, and, presumably, in turn the prospective component was spared.

Sleep quality also had no effect on the prospective component of PM in upright posture. This is in line with studies on sleep quality and PM (Fabbri et al., 2015; Rendell et al., 2007, 2009). As the prospective component in nonfocal PM tasks is based on attentional processes, our findings support evidence against an effect of sleep quality on attention (Benitez & Gunstad, 2012; Popp et al., 2015).

The moderating effect of body posture on the relationship between sleep quality and the prospective component concurs with findings from both PM research (Fabbri et al., 2014, 2015) and working-memory research (Muehlhan et al., 2014), which is plausible given the presumed relationship between working memory and the prospective component of PM (Arnold et al., 2015). The moderation implies that the impact of sleep quality on the prospective component of PM depends on whether the task condition promotes sleepiness such as supine posture. Possibly, participants can compensate for poor sleep quality or for strong sleepiness, but not for both at the same time. From our finding, we can derive new research questions regarding PM in patients with sleep disorders who often suffer from impairments in more than one sleep-related variable. In such patients, PM may be impaired strongly and more permanently, which may be even enhanced by reclined or supine working postures.

Compensation may explain why there were no main effects of sleepiness and sleep quality on the prospective component. Drummond, Gillin, and Brown (2001) suggested that brain regions related to attention are activated more strongly after sleep deprivation and thereby reduce detrimental effects of sleep deprivation on attention-switching tasks. The same may hold for PM tasks under sleepiness, leading to a preserved prospective component. We propose that the prospective component is impaired after participants suffered from poor sleep quality only when they encounter conditions that promote sleepiness, because they fail to compensate in such situations. Future studies should be conducted to investigate the recruitment of brain regions for PM tasks under sleepiness-inducing conditions to establish possible mechanisms of compensation.

Regarding the retrospective-memory component of PM, both experiments yielded convincing evidence for the null hypothesis. That is, neither did sleepiness or sleep quality affect the retrospective component, nor did body posture moderate the effect of sleep quality on the retrospective component. As the retrospective component of our PM task entailed recognition memory, these findings add to the literature that speaks against an effect of sleepiness and sleep quality on recognition (Drummond et al., 2000; Gobin et al., 2015; Lo et al., 2016; Stenuit & Kerkhofs, 2008; Swann et al., 2006). The retrospective recognition component may be spared by sleepiness and sleep quality because it largely relies on automatic familiarity processes (Mandler, 1980). In fact, Swann et al. showed that participants rely more heavily on automatic processes after sleep restriction as compared to unimpaired sleep, thus preserving recognition memory.

Although our results show convincingly that sleepiness did not affect the prospective nor retrospective component of PM, this does not mean that sleep-related variables do not have an impact on PM at all. Our results show that moderate levels of sleepiness, as commonly found in everyday life, did not impair PM. In general, it is reassuring to know that moderate levels of sleepiness or poor sleep quality by themselves do not compromise PM in the workplace, as short sleep and poor sleep quality have become more prevalent in modern society (e.g., Kronholm et al., 2008). However, it appears that extreme levels of sleepiness, such as after total sleep deprivation or partial sleep restriction, impair PM (Grundgeiger et al., 2014; Lowe et al., 2017). Sleep deprivation led to high KSS ratings (mean of 7.89 in Grundgeiger et al., 2014), whereas supine posture in the current study resulted in moderate KSS ratings (mean = 4.62). Thus, in the present experiments, PM may have been spared because sleepiness was only at moderate level. These comparably low levels of sleepiness may also explain why attentional processes and, as a result, the prospective component of PM were spared. Also, we only examined sleep-related variables in healthy young students.

Individuals with sleep disorders affecting sleep quality (e.g., sleep apnea, Fornas et al., 1995) or office workers whose sleep quality is compromised by low back pain (e.g., Murase et al., 2015), may show impairment in PM. This calls for further investigation.

Our findings have implications for the use of dynamic workstations. Such devices may be used for supine working posture without impairing PM as an important work-related memory function. However, sleep quality must be considered. If a worker’s sleep quality is poor, working in supine posture should be avoided as it impairs PM. The possibility to lie down at work and thereby reducing back pain temporarily (Waddell, 1992) and preventing back problems over the long haul may reduce absenteeism, associated economic cost, and mental-health problems related to back pain (e.g., Hagen et al., 2006).

To our knowledge, this is the first study to investigate possible effects of dynamic workstations on PM, and it may thus motivate a myriad of follow-up studies. For instance, future studies should investigate whether the present results generalize from PM to other cognitive functions and from supine posture to reclined posture, which may elicit weaker effects. Future studies should include middle-aged participants for reasons of external validity: Complaints about low back pain are more common in middle-aged adults than in young adults (e.g., Eriksen, Svendsrød, Ursin, & Ursin, 1998). Also, the present study needs to be replicated with actual dynamic workstations as well as with real-life PM tasks that occur during an office workday. To conclude, much more research is needed to evaluate effects of dynamic workstations on work performance; the present study is a first step toward this goal.

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Footnotes

[1] Caffeine consumption, morningness-eveningness, and variables derived from the sleep diary were not related to PM and are not reported in this paper.

[2] The *BF* for the regression weights were computed from analyses including only one predictor at a time.

[3] Two participants had to be excluded from this analysis due to missing data.

[4] For Bayesian repeated-measures ANOVAs, the BF_{10} and BF_{01} indicate the likelihood of the whole model, not that of the main effects and interactions separately. The $BF_{\text{Inclusion}}$ reported here represents the Bayes Factor for the main effects and the interactions separately.

[5] The pattern of results is the same for non-logarithmized reaction times.

Table 1

Group Parameter Estimates for the MPT Model and 95% Bayesian Credibility Intervals for Experiments 1 and 2.

Parameter	Experiment 1	Experiment 2	
		Upright	Supine
Prospective component *P*	.83 [.78, .89]	.81 [.73, .88]	.84 [.77, .91]
Retrospective component *M*	.94 [.92, .96]	.93 [.89, .96]	.87 [.82, .92]
Color match detection C_1	.70 [.66, .73]	.58 [.47, .68]	.51 [.40, .63]
Color non-match detection C_2	.87 [.85, .88]	.90 [.86, .92]	.87 [.83, .90]

Note. $\hat{R}$ < 1.05 for all parameters. MPT = multinomial processing tree.

Table 2

Unstandardized Regression Weights, 95% Bayesian Credibility Intervals, and Bayes Factors for All Predictors in Experiment 1.

PM Component	Predictor	Regression Weight	BF_{01}
Prospective Component *P*	KSS_{before}	.13 [−.03, .30]	3.51
	KSS_{after}	−.02 [−.14, .11]	10.75
	PSQI	−.01 [−.09, .07]	12.78
Retrospective Component *M*	KSS_{before}	.06 [−.08, .19]	14.94
	KSS_{after}	−.08 [−.18, .01]	4.15
	PSQI	−.01 [−.08, .05]	12.16

Note. KSS = Karolinska Sleepiness Scale. PSQI = Pittsburgh Sleep Quality Index. BF_{01} = Bayes Factor indicating evidence for the null hypothesis.

Table 3

Means and 95% Confidence Intervals (in Brackets) of Measures Obtained With the Epworth Sleepiness Scale, the Psychomotor Vigilance Task, and the Karolinska Sleepiness Scale for the Two Posture Groups in Experiment 2.

Measure		Upright	Supine
ESS		5.50 [4.86, 6.14]	6.00 [5.30, 6.70]
PSQI		4.15 [3.57, 4.73]	4.83 [4.29, 5.37]
PVT	False Alarms	3.35 [1.58, 5.11]	2.64 [1.18, 4.10]
	Lapses	0	0.04 [-.02, .09]
	Logarithmized Reaction Times	5.79 [5.74, 5.83]	5.82 [5.79, 5.81]
KSS	Time 1	3.32 [2.97, 3.67]	3.25 [2.92, 3.57]
	Time 2	4.00 [3.52, 4.48]	4.62 [4.18, 5.07]

Note. ESS = Epworth Sleepiness Scale. PSQI = Pittsburgh Sleep Quality Index. PVT = Psychomotor Vigilance Task. KSS = Karolinska Sleepiness Scale.

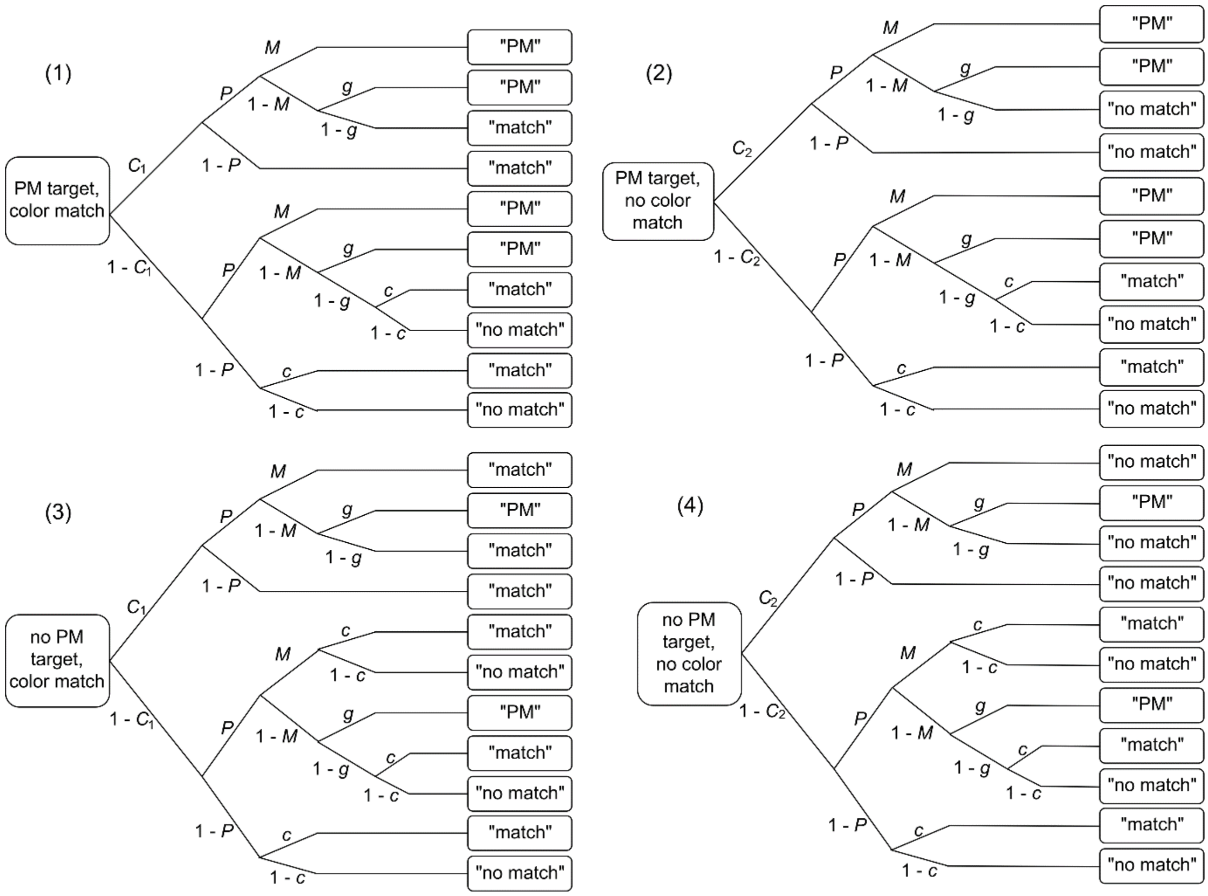

Figure 1. The multinomial processing tree model of event-based prospective memory by Smith and Bayen (2004). C_1 = probability to detect that the colors match; C_2 = probability to detect that the colors do not match; *P* = prospective component; *M* = retrospective component; *c* = probability to guess that the colors match; *g* = probability to guess that the word is a prospective-memory target. Adapted from “A multinomial model of event-based prospective memory” by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, p. 758. Copyright 2004 by the American Psychological Association.

Appendix A

Response frequencies aggregated over participants in Experiments 1 and 2

		Experiment 1	Experiment 2	
Item type	Response		Upright	Supine
Target, color match	"match"	453	196	199
	"no match"	79	45	73
	"PM"	1,238	539	523
Target, no color match	"match"	56	29	24
	"no match"	504	237	253
	"PM"	1,210	514	518
No target, color match	"match"	14,695	6,072	5,950
	"no match"	2,860	1,670	1,887
	"PM"	145	58	113
No target, no color match	"match"	1357	488	605
	"no match"	16,204	7,240	7,232
	"PM"	139	72	113

Note. "PM" = Prospective-memory response.