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Does frequency matter? ERP and behavioral correlates of monitoring for rare and frequent prospective memory targets

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ABSTRACT

Behavioral and event-related potential (ERP) correlates of monitoring in an event-based prospective memory (PM) task were compared during blocks with rare versus frequent PM target presentations relative to an ongoing-task only condition. For both rare and frequent PM conditions, behavioral interference costs in terms of longer reaction times (RTs) were observed. Likewise, during both PM blocks a sustained ERP positivity with a frontal focus was identified on ongoing-task trials. While PM target identification and RT interference costs were larger during the PM-frequent relative to the PM-rare condition, the same sustained frontal positivity was observed during both PM blocks. These findings suggest that successful monitoring is associated with the adoption of a more general prospective retrieval mode, irrespective of target frequency. Moreover, preparatory attentional modulations directed at relevant target features played an important role for subsequent PM performance, as evident in larger P2 amplitudes during PM blocks.

1. Introduction

Prospective memory (PM) refers to the delayed realization of intentions, for instance remembering to pass a message to your colleagues the next time you see them. Frequently, such intentions will not be realized during the course of a busy day, sometimes with serious consequences. PM has found increasing interest among memory researchers during the last two decades, both in terms of the cognitive processes involved and its practical implications for everyday functioning (e.g., for maintaining health and independence in old age; see Kliegel, McDaniel, & Einstein, 2008, for an overview). Theorists agree that generally, monitoring processes play an important role in successfully maintaining delayed intentions and in initiating the intended action in the appropriate situation. However, it remains unclear precisely how these monitoring processes support PM performance, and whether resource allocation towards PM monitoring – associated with costs on ongoing activities – is always necessary.

According to the preparatory attentional and memory processes (PAM) theory of PM (e.g., Smith, 2003; Smith & Bayen, 2004, 2005), attentional resources dedicated to monitoring are necessary for successful PM performance regardless of task characteristics. By contrast, the multi-process framework (Einstein & McDaniel, 2005; McDaniel & Einstein, 2000) postulates that delayed intentions can be retrieved spontaneously without active monitoring for PM target occurrence under certain task conditions. This may be the case, for instance, when PM targets are highly associated with the appropriate target action. Both theories concur that monitoring processes are necessary to successfully carry out delayed PM intentions under many task conditions, for instance when several PM targets are used (Einstein & McDaniel, 2005; McDaniel & Einstein, 2000; Smith, Hunt, McVay, & McConnell, 2007). The retrieval mode and target checking theory (Guynn, 2003, 2008) attempts to specify monitoring processes more directly. According to this framework, a sustained prospective retrieval mode enables individuals to treat stimuli as cues for retrieving PM intentions, and hence is necessary for PM. This strategic process is sometimes complemented by periodic item checking for relevant features defining PM targets.

In the laboratory, monitoring processes are usually inferred on the basis of behavioral costs to an ongoing task. This so-called prospective interference effect (Marsh, Hicks, Cook, Hansen, & Pallos, 2003; Smith, 2003) is typically observed in terms of longer ongoing-task reaction times (RTs) in the presence (versus absence) of a PM task. Participants first encode PM target stimuli and a specified response to be initiated whenever a PM target is presented. PM target events are then embedded within the ongoing task. Typically, several target events occur (either recurring or different stimuli) to allow for a more reliable measurement of PM performance. Consistent with PM requirements outside the laboratory, in most behavioral studies PM targets occur rarely (i.e., in 2–10% of all ongoing-task trials). Importantly, the character of the PM task may vary considerably when PM targets occur more often

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(see also Monsell, 2003 for related findings in explicit task-switching paradigms). Graf and Uttl (2001) suggested that so-called "vigilance tasks" and "PM proper tasks" form two ends of a continuum. According to this framework, at one end of this continuum (termed "vigilance"), processing resources are allocated to PM-target monitoring completely, and hence, behavioral costs to ongoing activities may be substantial. On the other side of this continuum (termed "PM proper"), PM intentions stay less active in working memory, as many ongoing trials intervene. Consequently, tasks with frequent and rare target occurrences would differ in the degree of monitoring necessary to support successful PM performance, as intentions are more likely kept active in working memory with frequent compared to rare PM targets. Recent evidence suggests that the amount of attention devoted to the PM task is subject to adjustments based on task experience. That is, behavioral costs are reduced when PM targets are not presented despite PM instructions (Loft, Kearney, & Remington, 2008). Following this logic, even more attentional resources might be invested to monitor for subsequent PM targets when they occur frequently, and hence behavioral costs might increase substantially. Alternatively, it might be less demanding to maintain a PM intention when it must be carried out more often, because successfully detected PM targets may serve as reminders of the PM intention. For instance, passing a message to one colleague may remind you of your intention to pass this message to someone else as well. Following this idea, less PM monitoring would be necessary for successful PM performance if targets occur frequently. So far, the precise nature of PM monitoring processes and their relation to variations in target frequency remains open.

To further characterize the cognitive processes underlying performance in PM tasks, neural activity has been measured along with behavioral performance. To this end, predominantly two methods have been applied in previous studies, namely functional magnetic resonance imaging (fMRI) and event-related potentials (ERPs). A recent fMRI study (Reynolds, West, & Braver, 2009) compared transient and sustained neural activity during a PM task. Transient activity during ongoing trials was taken to reflect periodic item checking (see also Guynn, 2003), but was not observed during ongoing trials. By contrast, sustained activity during ongoing trials was taken to reflect controlled processes associated with strategic monitoring, and was observed in a network of brain areas including the anterior prefrontal cortex (PFC; specifically lateral Brodmann area 10). Notably, this region has been implied previously in so-called *stimulus-independent* cognitive processing directed away from external stimuli and towards internal mental representations (Burgess, Dumontheil, & Gilbert, 2007; Burgess, Gilbert, & Dumontheil, 2007). Moreover, sustained activity in the anterior PFC was correlated with faster RTs for PM targets, thus providing further evidence for a functional role of sustained activity in the anterior PFC for PM performance (Reynolds et al., 2009).

So far, several investigations have used ERPs to assess the neural activity during PM tasks (e.g., West & Bowry, 2005; West & Krompinger, 2005; West, McNerney, & Krauss, 2007; West, McNerney, & Travers, 2007; West, Scolaro, & Bailey, 2011; Zöllig et al., 2007; see also a recent review by West, 2011). For instance, West, Bowry, and Krompinger (2006) first mentioned a sustained positivity at frontal electrodes on ongoing trials in PM-blocks compared to blocks without PM instructions. Consistent with the well-established role of the frontal cortex for executive control functions, all investigations reported ERP modulations at frontal electrodes.[1] Three recent studies focused on the prospective interference effect in particular (i.e., the comparison of ongoing-task trials with and without PM instructions; Chen, Huang, Jackson, & Yang, 2009; Chen, Huang, Yang, Ren, & Yue, 2007; Knight, Ethridge, Marsh, & Clementz, 2010; see also West et al., 2006). Ongoing trials in PM-blocks were associated with larger ERP amplitudes compared to ongoing trials without PM instructions in several short time windows between 200 ms and the end of the recording epoch (400 or 600 ms). Notably, later time windows in which sustained processes related to maintaining a delayed intention over time should be particularly pronounced, were not evaluated in these investigations.

ERP modulations with latencies around 200 ms at frontal electrodes have been reported previously in the context of other experimental manipulations. For instance, larger P2 amplitudes have been reported for trials in which deviant item features are task relevant (e.g., Luck & Hillyard, 1994; Potts, 2004; Ruz & Nobre, 2008) or under conditions of increased arousal (e.g., following caffeine intake; Ruijter, Lorist, Snel, & De Ruiter, 2000). However, these modulations were restricted to the P2 time range, and were not sustained over several hundred milliseconds. Given this transient time course, it seems unlikely that they reflect a sustained retrieval mode and/or continuous preparatory attentional processes. As the P2 modulations described above occur particularly under conditions of interference from competing stimuli or task demands, they have been taken as evidence for a focus towards specific relevant item features as a result of top-down control of attention (see also Luck, Woodman, & Vogel, 2000). In a recent PM study, Knight et al. (2010) examined ongoing trials with and without a PM intention. In this investigation, PM targets were defined by the conjunction of two features (words printed in red) embedded in a lexical decision task. Modulations of ERP components around 200 ms post-stimulus onset were taken as evidence for preparatory attention aimed at identifying relevant stimulus features defining PM targets (see also Guynn, 2003, 2008). The specific timing and location of these effects may have been affected by this particular choice of relevant features and by their conjunction. Notably, the ERP epochs only spanned 600 ms, consistent with previous ERP studies (Chen et al., 2007, 2009). Hence, ERP analyses between ongoing-task trials with and without PM intentions have been restricted to stimulus evaluation during early time windows; sustained ERP differences more likely associated with maintaining a controlled retrieval mode across trials have not been evaluated so far. It thus remains unclear how these early ERP modulations relate to the *sustained* fMRI activity in anterior PFC reported by Reynolds et al. (2009), which has been directly associated with actual PM performance.

One central aspect that may influence how participants monitor for PM targets and that differs between the studies described so far is the frequency of PM target events. In investigations examining the neural correlates of controlled processes during PM tasks, typically relatively frequent PM targets have been used. For instance, in two ERP studies examining correlates of prospective monitoring (Chen et al., 2007, 2009), PM targets occurred in 20% of all trials, and in the fMRI study detailed above (Reynolds et al., 2009) PM targets occurred in 11% of all trials. By contrast, behavioral studies typically rely on fewer target events (Einstein & McDaniel, 2005). For instance, two recent behavioral studies demonstrate that PM interference effects are smaller when a particularly large number of intervening ongoing trials is presented between PM targets (fixed number of 89 versus 32 between each PM target presentation,

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[1] Note that some ERP investigations reported a sustained frontal positivity, coupled with an additional occipital-parietal slow-wave negativity (see West et al., 2006, and West, McNerney, & Travers, 2007, for details on more posterior ERP correlates of monitoring). Posterior activity has been predominantly observed with an average reference. By contrast, a mastoid reference was used in the present analysis, as well as in the investigations by Chen et al. (2007, 2009). With a mastoid reference, the frontal positivity was not associated with a negative deflection at opposite sites of the scalp (see Luck, 2005).

corresponding to 3 versus 1% PM target frequency; Loft & Yeo, 2007, Experiment 3), or when no PM targets are presented following PM instructions (Loft et al., 2008). If PM target frequency influences the degree or the type of monitoring processes recruited to support PM performance, the neural correlates of PM monitoring recently proposed might be characteristic for conditions with frequent PM targets only. This would have important implications, because the conclusions drawn from neuro-scientific approaches to PM may strongly differ from behavioral paradigms (or everyday situations) with typically fewer target events. Given the potential impact of PM target frequency on the nature of monitoring, it is surprising that so far monitoring for frequent versus rare PM target occurrences has not been directly compared. We addressed this open question by explicitly examining whether ERP and behavioral correlates of PM monitoring are affected by frequent versus rare PM target occurrences. PM target stimuli were selected according to two criteria. First, they were not particularly salient. Second, attending to the feature that identified stimuli as PM targets was not critical for ongoing-task performance (i.e., non-focal PM target stimuli). Under these conditions, both the multi-process framework and PAM theory concur that monitoring processes are necessary for successful PM performance (McDaniel & Einstein, 2000; Smith et al., 2007). Hence, we expected behavioral costs in the ongoing task for both PM conditions relative to the control condition without PM instructions. As each successfully identified PM target could serve as a reminder of the PM task, we expected better PM performance for the frequent compared to rare PM condition.

ERPs were employed to further characterize monitoring processes. To allow the examination of slow-wave brain activity, the present ERP epochs spanned 1000 milliseconds following stimulus presentation. We expected neural correlates of PM monitoring to be evident for both frequent and rare PM conditions relative to the control condition. In line with the proposed role of the frontal cortex for maintaining and carrying out delayed intentions, we expected sustained ERP modulations predominantly over frontal electrode sites (see also footnote 1). Based on the recent fMRI findings described above and the assumption of a functional relationship between monitoring and successful PM performance, we expected an association between PM performance and the ERP correlates of monitoring. If adopting a prospective retrieval mode is a prerequisite for identifying PM targets (as suggested by Guynn, 2003, 2008), the ERP correlate for PM monitoring should be observable whenever participants successfully identify PM targets, *irrespective* of PM target frequency. By contrast, differences in the ERP correlates of PM monitoring for frequent and rare PM conditions would suggest differences in the degree of monitoring processes supporting PM performance, as suggested by Graf and Uttl (2001). Consistent with the process of target checking (Guynn, 2008) and recent ERP findings (e.g., Knight et al., 2010), we expected a P2 modulation reflecting selective attention to relevant features defining PM targets.

2. Methods

2.1. Participants

Nineteen students completed the experiment. We had to exclude three participants from the analyses. Of these, two never pressed the PM key in one or both of the PM blocks, and one misunderstood the PM instructions and responded to a different stimulus. The final sample thus consisted of 16 participants (3 males; mean age 23.4 years, range 19–29 years). All participants were native speakers of German, right-handed and reported to have normal or corrected-to-normal vision. Participants reported themselves to be in good physical and mental health. All participants gave informed consent and received course credit or a monetary incentive for participation.

2.2. Materials

The stimuli were strings of 8–12 letters, which were either German words or pronounceable non-words. The words were low-frequency German words from the CELEX database (Baayen, Piepenbrock, & Gulikers, 1995), occurring either 4–5 or 0–1 times per million. We created the non-words by randomly replacing all vowels/umlauts in the words with randomly chosen different vowels/umlauts.

For the experimental blocks, we created two target sets and two filler sets that were matched for word frequency and string length, respectively. Each target set contained a total of 116 target strings (starting with the letters *G*, *H*, or *M*) and each filler set contained 1384 non-target strings (strings with all remaining starting letters). During the experiment, the program randomly chose one filler set and one target set, and the stimuli were randomly drawn from these sets without replacement. The four possible target-list × filler-list combinations were counterbalanced across participants. To avoid repetition priming, a given stimulus never occurred both as a word and as the corresponding non-word within a single session. For the practice phase, we chose 24 words and created 24 corresponding non-words in a similar way.

2.3. Procedure

The three conditions of the experiment were presented in blocks of 500 trials each and were separated by a pause of 3 min in which participants filled out a questionnaire. Each block was further divided into four equal parts of 125 trials separated by short breaks of 1 min to avoid fatigue.

Prior to the actual experiment, 48 ongoing lexical-decision-task trials were included as practice. During practice, a visual feedback "too slow" was given if participants did not respond within 1500 ms, and the feedback "wrong" whenever an error occurred in the lexical decision task. Feedback was given during practice to ensure that participants performed as fast and as accurately as possible. At the end of practice, participants received feedback regarding the proportion of correct responses and their average RT in the entire practice block.

Frequency of PM target occurrence was manipulated within participants. All participants first completed a control block of ongoing-task trials alone, then two blocks with the embedded PM task. The concern was to avoid carry-over effects from the PM conditions to the control condition (i.e., continued monitoring for PM targets). After completion of the control block, participants received one PM block with rare target occurrence, and one PM block with frequent target occurrence. The order of these two blocks was counterbalanced across participants. During the ongoing lexical-decision task, in each trial, a fixation cross appeared with a mean onset latency of 1250 ms, randomly jittered between 1150 and 1350 ms, to prevent anticipatory responding. Each item was presented at the center of a white screen in black upper case letters (font size 24). Participants were asked to categorize each item as a word or a non-word, with equal emphasis on speed and accuracy. Participants gave their response with the left or right index finger via button press on a response box. The assignment of response keys (left versus right) to the *word* and *non-word* response options was counterbalanced across participants. Each item was displayed until the participant gave a response. Following the response, a blank screen was presented for 500 ms. Participants received no performance feedback during the actual experiment.

After completion of the ongoing-task control block, participants received instructions for the first PM block. One half of the participants were asked to press the far right key, the other half to press the far left key on the response box whenever a letter string started with the letters *G*, *H*, or *M*. The target letters were presented before each PM block, one at a time for 5 s each. To ensure that all participants had encoded the three letters, they were asked to count backwards from 100 in steps of 3s for 30 s, and to then reproduce the target letters. If participants were not successful, the presentation of the target letters was repeated.

During the PM blocks, PM targets were embedded into the ongoing task. The exact distance between two targets was randomized within a certain trial-range to discourage a strategy of counting trials, particularly for the frequent PM target condition. In the rare-target condition, PM targets appeared on 3% of the trials. There were thus 16 targets, 4 in each block of 125 trials, with 22 to 27 ongoing trials between any two PM targets. In the frequent-target condition, targets appeared on 20% of the trials, with a minimum of two and a maximum of six ongoing trials between any two PM target trials. In this condition, there were thus 100 targets, 25 in each block of 125 trials. The total experiment lasted about 90 min. Participants were debriefed after completion.

2.4. EEG recording and ERP data preprocessing

EEG activity was recorded from 40 scalp sites placed according to the extended 10–20 system with sintered Ag/AgCl electrodes using a ground on the right forehead. Vertical and horizontal electrooculogram (EOG) was recorded from electrodes placed above and below the left eye and at the outer canthus of each eye. Electrode impedance was kept below 5000 Ω. The activity of all scalp electrodes was initially referenced to the right mastoid and re-referenced offline to averaged mastoids. EEG and EOG were recorded continuously with a NyAmp Express amplifier (DC; 100 Hz high-frequency cutoff; 1000 Hz digitization rate). EEG data were further analyzed using Vision Analyzer 2 software (Brain Products, Gilching, Germany). The continuous EEG was downsampled to 500 Hz and a .1–30 Hz band-pass filter was applied offline. If single channels showed artifacts, a spherical spline algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989) was used for interpolation, with a maximum of two channels interpolated for a given participant. Trials containing voltage steps > 100 μV (e.g., muscular activity) were removed prior to the removal of eye movements. Eye movements were corrected via independent component analysis (Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997), using the ocular correction ICA tool in Vision Analyzer 2, based on an artifact-free segment with a length of 180 s. Finally, trials with remaining artifacts (i.e., voltage steps > 50 μV, voltage differences of >100 μV within a 200 ms time window) were removed.

EEG epochs extended from 200 ms prior to stimulus onset until 1000 ms, for a total duration of 1200 ms. Averages were constructed for each participant for a total of five conditions[2] (mean trial numbers and range are given in parentheses): ongoing trials in the control block (ongoing only: 415.13, 240–488), ongoing trials during the PM-rare block (PM-rare: 336.13, 187–452), ongoing trials during the PM-frequent block (PM-frequent 199.75, 118–271). Ongoing-task trials occurring within 30 s before a PM-rare target hit (before hit: 64.53, 22–108) and before a PM-rare target miss (before miss: 69.93, 25–107) were analyzed in 15 participants who contributed a minimum of 20 artifact-free trials for these analyses. Due to PM target frequency, this analysis was not feasible for the frequent PM condition.

We chose an α-level of .05 for all analyses. Greenhouse-Geisser corrections for the violation of sphericity were used if necessary and are reflected in the p-values along with the respective epsilon values (ε) and uncorrected degrees of freedom. Partial eta squared (η_p^2) is reported as an estimate of effect size for main and interaction effects. Following the statistical analyses, a lowpass filter of 15 Hz was applied to the EEG waveforms and is reflected only in the figures.

3. Results

3.1. Behavioral performance

Behavioral analyses focused on two aspects. First, we compared hit rates and RTs on PM targets between the PM-rare and PM-frequent conditions. Second, we assessed ongoing-task RTs and accuracy (i.e., the proportion of correct lexical decisions) in separate repeated-measures ANOVAs including the factor Condition (ongoing only, PM-rare, PM-frequent). The two trials following a PM target were excluded from analyses of ongoing-task performance to avoid inclusion of residual response processes prompted by PM targets. Consistent with the cutoff criteria used for ERP analyses, outliers (RTs faster than 200 ms or slower than 3000 ms) were removed prior to statistical analyses. Moreover, error trials were discarded for the RT analyses (see also Marsh et al., 2003).

3.1.1. PM performance

Consistent with expectations, participants were very accurate in detecting PM targets in the frequent-PM condition (PM target hit rate: $M = 89.3\%$, SD = 9.4; range 69–100 out of 100 PM targets). In the PM-rare condition, PM target hit rate was considerably lower ($M = 55.5\%$; SD = 18.9; range 5–15 out of 16 PM targets), $F(1,15) = 52.17$, $p < .001$, $\eta_p^2 = .78$. RTs on PM target hits were faster during the PM-frequent ($M = 822$ ms, SD = 121 ms) compared to the PM-rare condition ($M = 1027$ ms, SD = 313 ms), $F(1,15) = 9.78$, $p < .01$, $\eta_p^2 = .40$.

3.1.2. Interference costs on ongoing-task performance

Accuracy in the ongoing lexical decision task was consistently high across the three conditions (ongoing-only condition: $M = 95\%$, SD = 3.8%; PM-rare condition: $M = 96\%$, SD = 2.6%; PM-frequent condition: $M = 95\%$, SD = 2.4%), $F(2,30) = 1.18$, $p = .32$, $\eta_p^2 = .07$). Consistent with prior investigations (e.g., Marsh et al., 2003), no interference was evident in terms of reduced accuracy in the ongoing task.

By contrast, costs were observed in terms of longer RTs, as suggested by a main effect of Condition, $F(2, 30) = 49.39$, $p < .0001$, $\eta_p^2 = .77$. Paired contrasts indicated that RTs were longer for trials in the PM-rare condition ($M = 795$ ms, SD = 129 ms) relative to the ongoing-only condition ($M = 665$ ms, SD = 93 ms), $p < .01$, as well as for the PM-frequent condition ($M = 847$ ms, SD = 130 ms) relative to the PM-rare condition ($p < .01$). An interaction of behavioral RT costs and the order in which participants completed the PM rare and frequent conditions was observed, $F(1,14) = 6.62$, $p < .05$, $\eta_p^2 = .32$, indicating that responses during the PM-rare block were slightly slower for participants who completed the PM-frequent block first. Importantly, reliable RT interference costs in the same direction (i.e., larger for the PM-frequent condition) and of similar effect sizes were still observed in both counterbalanced conditions, $\eta_p^2 = .79$ (PM rare first) and .85 (PM frequent first), $Fs(2,14) > 25.63$, $ps < .0001$.

3.2. ERP results

3.2.1. ERP correlates of prospective monitoring

As illustrated in Fig. 1, both PM conditions were associated with very similar waveforms, namely a sustained positivity relative to trials in the control block. To compare ERP correlates of prospective monitoring for the PM-rare and PM-frequent condition, mean amplitudes between 600 and 900 ms following stimulus cue onset were evaluated in a mixed-model ANOVA with the factors Condition (ongoing-only, PM-rare, PM-frequent) × Anterior-Posterior Electrode site (AP) × Left-Central-Right Electrode site (LCR). For this analysis, we selected 9 electrode sites covering lateral and midline parts of the scalp (F7, Fz, F8, T7, Cz, T8, P7, Pz, P8). To further characterize the topographical distribution of ERP effects across these electrode sites, reliable interactions with the factor Condition were followed up with subsidiary ANOVAs where appropriate. Following our central hypothesis, two planned contrasts were specified for the factor Condition, namely PM-rare versus ongoing-only, and PM-frequent versus ongoing-only.

The overall ANOVA with the factors Condition × AP × LCR revealed a main effect of condition, $F(2,30) = 5.25$, $p < .05$, $\eta_p^2 = .26$, which was modulated by two-way interactions with the factors AP and LCR and a three-way interaction (see Table 1). Subsidiary ANOVAs indicated reliable main effects of condition at frontal and central electrode sites, and interactions of Condition × LCR at frontal, central and parietal electrode sites (all $ps < .05$). Planned contrasts for each electrode revealed reliable ERP differences relative to ongoing-task only at F7, Fz, T7, Cz and Pz for the PM-rare condition, and at F7, Fz, T7 and Cz for the PM-frequent condition (all $ps < .05$). Consistent with the proposed functional relevance for PM monitoring, for both contrasts, effect sizes were largest at frontal electrodes F7 and Fz (see Table 1), as also evident in Fig. 2. The order in which participants completed the PM rare and frequent conditions did not influence the magnitude of the ERP correlate for PM monitoring [interaction with block order: $F(2,28) < 1$, $p = .49$].

We then examined a potential relationship between these proposed neural correlates of PM monitoring and PM target performance measures. Assuming that larger ERP amplitude differences should be associated with larger performance benefits, we correlated the magnitude of the ERP differences between PM and control conditions (i.e., the mean of the five electrodes with reliable effects) with mean RTs of PM target hits (Reynolds et al., 2009). Indeed, larger ERP correlates of PM monitoring were associated with faster responses to PM targets for the PM-frequent ($r = -.53$) and for the PM-rare condition ($r = -.44$), $ps < .05$.[3] By contrast, larger

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[2] In the present investigation, PM targets could be both words and non-words, hence the classification as a word or non-word was irrelevant for the PM task. Importantly, no reliable main effects or interactions with Stimulus Type (word versus non-word) were found in the time windows of the present analyses: all $Fs < 2.46$, all $ps > .14$ (for 600–900 ms), all $Fs < 1.49$, all $ps > .21$ (for the P2 analysis, 160–210 ms). Therefore, word and non-word stimuli were collapsed for all subsequent analyses.

[3] Controlling for individual differences in general processing speed by considering baseline RT in the ongoing task as a covariate did not change this pattern of results (partial $rs = -.43$ and $-.53$, for the PM-rare and PM-frequent conditions, respectively; all $ps < .05$).

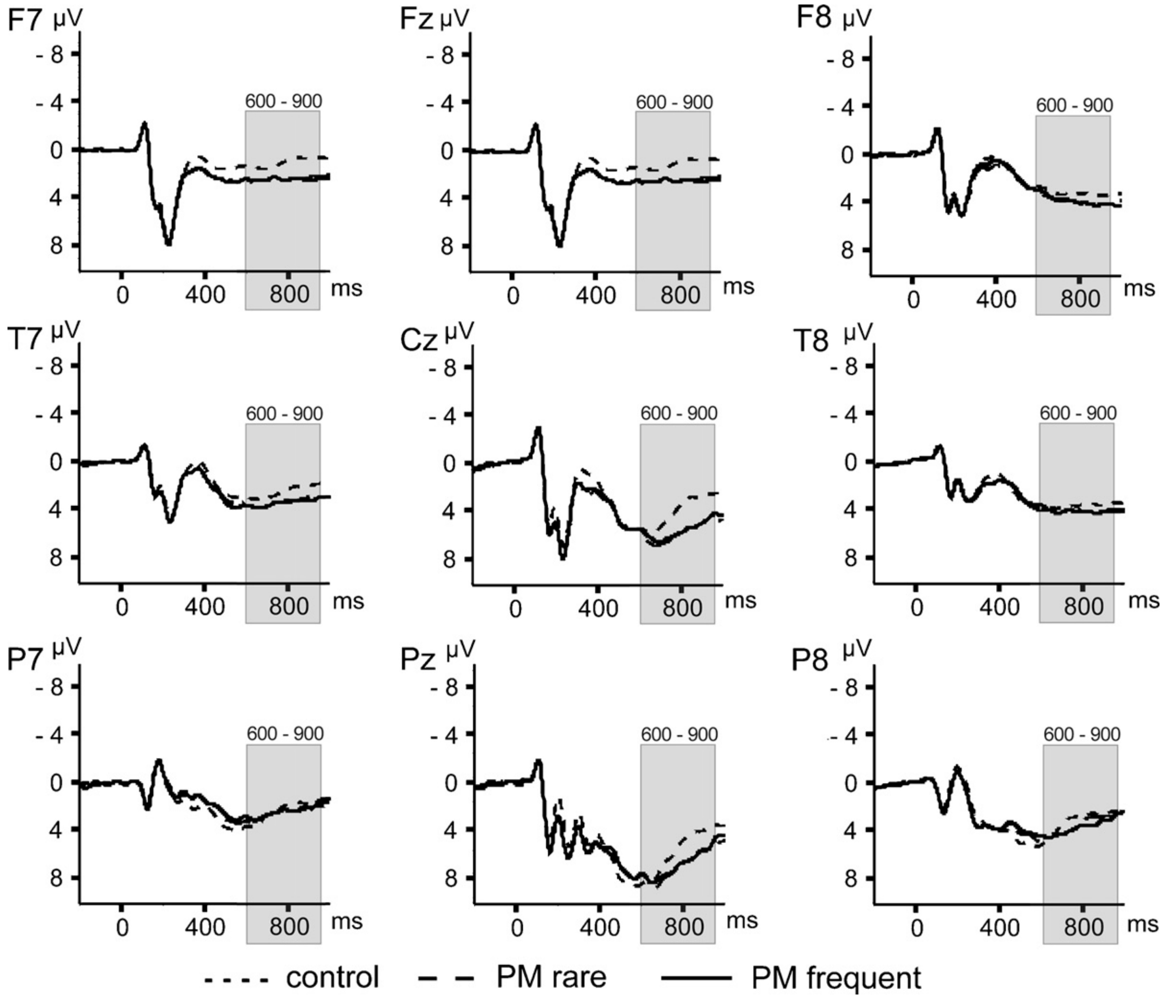

Fig. 1. ERP waveforms for ongoing-only/control (dotted line), PM-rare (dashed line) and PM-frequent conditions (solid line) at nine electrode sites used for the analyses of the correlate for PM monitoring ($n = 16$ participants). Reliable PM monitoring effects were found at electrodes F7, Fz, T7 and Cz for both PM conditions and at Pz for the PM-rare condition.

Table 1
ANOVA results for mean ERP amplitudes between 600 and 900 ms for ongoing-task trials in the control block, in the PM-frequent and in the PM-rare conditions.

Time window/Specific electrode site	Factor or contrast	*F*	df1, df2	*p*	ε	η_p^2
600–900 ms	Condition	5.25	2, 30	<.05		.26
	Condition × AP	4.83	4, 60	<.05	.57	.24
	Condition × LCR	6.65	4, 60	<.0001		.31
	Condition × LCR × AP	3.09	8, 120	<.05	.58	.17
Frontal (F7, FZ, F8)	Condition	11.01	2, 30	<.0001		.42
	Condition × LCR	7.87	4, 60	<.0001		.34
Central (T7, CZ, T8)	Condition	4.65	2, 30	<.05		.24
	Condition × LCR	5.12	4, 60	<.01	.66	.25
Parietal (P7, PZ, P8)	Condition	1.58	2, 30	.22		.10
	Condition × LCR	4.60	4, 60	<.01		.24
F7	PM rare versus CON	16.73	1, 15	<.01		.53
	PM frequent versus CON	20.55	1, 15	<.0001		.58
FZ	PM rare versus CON	22.63	1, 15	<.01		.60
	PM frequent versus CON	15.70	1, 15	<.01		.51
T7	PM rare versus CON	5.98	1, 15	<.05		.29
	PM frequent versus CON	7.16	1, 15	<.05		.32
CZ	PM rare versus CON	13.94	1, 15	<.01		.48
	PM frequent versus CON	5.41	1, 15	<.05		.27
PZ	PM rare versus CON	6.61	1, 15	<.05		.31
	PM frequent versus CON	3.69	1, 15	.07		.20

Note. CON – control block, AP – anterior-posterior electrode sites, LCR – left, central or right electrode sites. Contrast for single electrodes are reported for those electrodes with reliable main effects of condition. $N = 16$ participants.

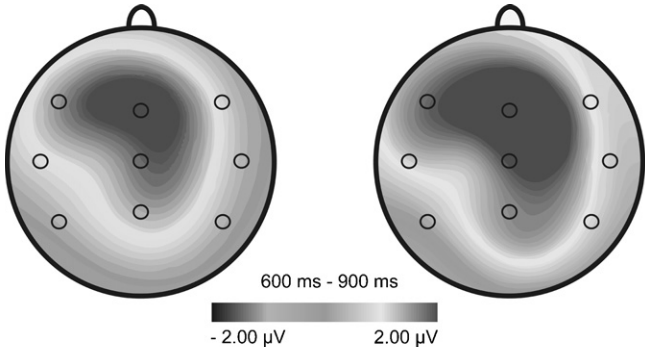

Fig. 2. Topographical map of the ERP correlate for prospective monitoring, for PM-rare (left) and PM-frequent condition (right) relative to ongoing-task trials in the control block between 600 and 900 ms. Note the extremely similar topography of both effects.

ERP amplitudes were not associated with higher PM target hit rate ($ps > .14$).

3.2.2. *ERP correlates of early attentional aspects of stimulus evaluation*

To determine whether PM monitoring also affected early attentional aspects of stimulus evaluation, we evaluated the activity during the P2 time window in a corresponding ANOVA. As illustrated in Fig. 3, two positive peaks emerged in the ERP waveforms around 200 ms following stimulus onset. By contrast, only one peak at 185 ms was evident in the difference waveforms (i.e. rare and frequent PM targets minus ongoing trials only, respectively), suggesting both peaks in the ERP waveforms originated in a common positivity superimposed on a smaller negative peak. Hence, the time window for the evaluation of the P2 effect was centered around the peak of the difference wave, and spanned 160–210 ms. To account for the mid-central topography of the P2, analyses focused on the following electrode sites: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4.

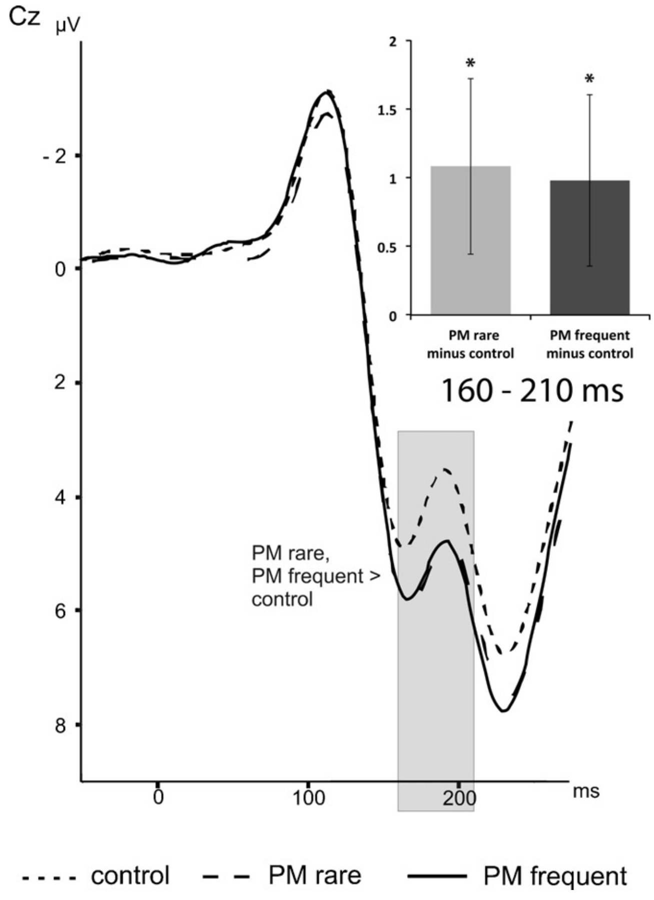

Fig. 3. Detailed view on the early part of the waveforms depicted in Fig. 1 at electrode site Cz. The P2 effect was evaluated at nine selected electrode sites between 160 and 210 ms, and reflected larger amplitudes during PM blocks relative to the control condition. The bar graphs (top right) illustrate reliable ERP amplitude differences across these nine electrode sites for both PM blocks relative to the control condition between 160 and 210 ms (error bars reflect 95% confidence intervals).

Consistent with the mid-central topography of the P2, a main effect of condition without interactions by electrode sites was observed, $F(2,30) = 9.68$, $p < .01$, $\eta_p^2 = .39$. As illustrated in more detail at electrode Cz in Fig. 3, planned contrasts revealed larger amplitudes for PM-rare relative to the control condition, 4.5 versus 3.4 µV, $F(1,15) = 13.03$, $p < .01$, $\eta_p^2 = .47$, and PM-frequent compared to the control condition, 4.4 versus 3.4 µV, $F(1,15) = 11.11$, $p < .01$, $\eta_p^2 = .43$. The order in which participants completed the PM rare and frequent conditions did not influence the magnitude of the P2 modulation [interaction with block order: $F(2,28) = 1.12$, $p = .34$].

3.2.3. *ERP correlates preceding prospective hits and misses*

To compare ERP correlates of PM monitoring preceding a PM target hit or miss, mean amplitudes between 160–210 ms and 600–900 ms for trials occurring within 30 s before a PM-rare target hit or miss were compared to ongoing trials in the control condition. As illustrated in Fig. 4 and detailed in Table 2, both before PM target hits and misses, a sustained positivity relative to the control condition was observed between 600 and 900 ms, consistent with the general pattern described above for all ongoing trials. As illustrated in Fig. 5, the P2 effect was reduced in magnitude to a trend, $F(2,26) = 3.01$, $p = .087$, $\eta_p^2 = .19$. Planned contrasts revealed a reliable P2 effect for trials preceding PM target hits, $F(1,14) = 14.36$, $p < .01$, $\eta_p^2 = .53$, 4.6 versus 3.3 µV, but not for trials preceding PM target misses (4.2 versus 3.3 µV, $p = .23$). To assess whether the P2 effect was completely absent or rather delayed in latency for trials preceding PM target misses, the following time window between 210 and 260 ms was also evaluated for this condition. This post-hoc analysis revealed a reliable P2 effect in this later time window, $F(1,14) = 30.11$, $p < .0001$, $\eta_p^2 = .68$, 7.0 versus 5.5 µV for trials preceding PM target misses versus ongoing-task only, indicating a delayed P2 effect for trials preceding PM target misses.

4. Discussion

Behavioral and ERP correlates of PM monitoring during blocks with rare and frequent PM target presentations were directly compared to an ongoing-task only condition in the same participants. For both rare and frequent PM conditions, we found behavioral interference costs in terms of longer RTs. A sustained positivity with frontal focus was identified on ongoing-task trials during both PM blocks. While PM target identification and RT costs were higher during the frequent relative to the rare PM target condition, the same sustained frontal positivity was observed during both PM blocks. Three open questions will be discussed in the upcoming sections: in Section 4.1 we will assess evidence for a functional association of the observed sustained frontal ERP effect with PM performance. In Section 4.2, the functional relevance of the observed P2 modulation for PM monitoring will be discussed. In Section 4.3, we will turn to the main question whether PM performance for rare versus frequent targets is supported by distinct monitoring processes.

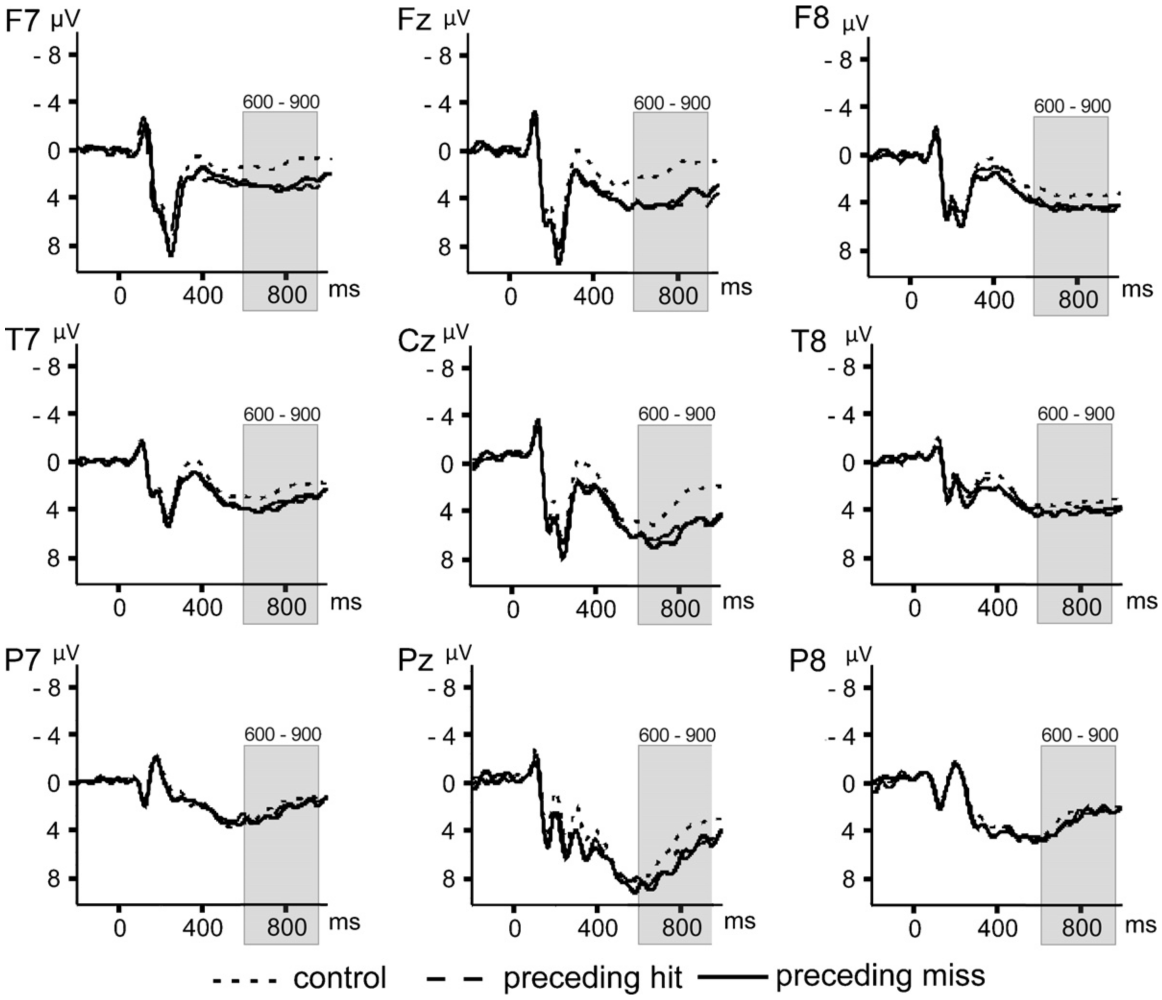

Fig. 4. ERP waveforms for trials preceding PM-rare target hits (dashed line) and misses (solid line) relative to ongoing trials in the control block (dotted line) at nine electrode sites used for the analyses of the correlate for PM monitoring preceding rare PM target hits and misses. Data are shown for 15 participants with sufficient artifact-free trials. Between 600 and 900 ms, we found reliable PM monitoring effects for trials preceding both PM hits and misses at F7, Fz, F8, T7, Cz, and Pz.

Table 2
ANOVA results for mean ERP amplitudes between 600 and 900 ms for ongoing-task trials in the control block, and ongoing-task trials preceding PM-frequent target hits and misses.

Time window/Specific electrode site	Factor or contrast	*F*	df1, df2	*p*	ε	$\eta_p^2 =$
600–900 ms	Condition	12.40	2, 28	<.0001		.47
	Condition × LCR	6.55	4, 56	<.01		.32
Left (F7, T7, P7)	Condition	7.35	2, 28	<.01		.34
	Condition × AP	5.61	4, 56	<.01	.62	.29
Midline (FZ, CZ, PZ)	Condition	13.54	2, 28	<.0001		.49
Right (F8, T8, P8)	Condition	6.07	2, 28	<.01		30
F7	Before hit versus CON	21.83	1, 14	<.0001		.61
	Before miss versus CON	19.43	1, 14	<.01		.58
FZ	Before hit versus CON	23.65	1, 14	<.0001		.63
	Before miss versus CON	23.57	1, 14	<.0001		.67
F8	Before hit versus CON	11.91	1, 14	<.01		.46
	Before miss versus CON	9.71	1, 14	<.01		.41
T7	Before hit versus CON	5.56	1, 14	<.05		.27
	Before miss versus CON	15.95	1, 14	<.01		.53
CZ	Before hit versus CON	13.60	1, 14	<.01		.49
	Before miss versus CON	15.84	1, 14	< .01		.53
PZ	Before hit versus CON	6.62	1, 14	<.05		.32
	Before miss versus CON	4.97	1, 14	<.05		.26

Note. *N* = 15 participants with sufficient artifact-free trials.

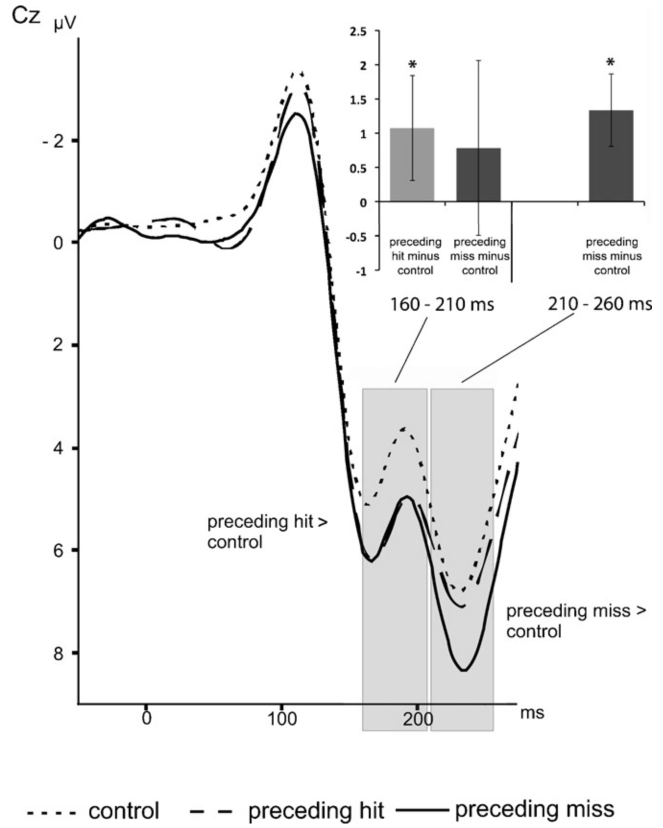

Fig. 5. Detailed view on the early part of the waveforms depicted in Fig. 4 at electrode site Cz. The P2 effect was evaluated at nine selected electrode sites between 160 and 210 ms, and larger amplitudes were observed during trials preceding PM target hits relative to the control condition. By contrast, for trials preceding PM target misses reliable P2 effects were evident between 210 and 260 ms compared to the control block. The bar graphs (top right) illustrate reliable ERP amplitude differences for trials preceding PM target hits relative to the control condition between 160 and 210 ms, and for trials preceding PM target misses between 210 and 260 ms (error bars reflect 95% confidence intervals).

4.1. Is the sustained frontal ERP effect functionally related to PM performance?

As predicted, a sustained positive ERP modulation was observed, with largest effects over fronto-central and left frontal electrode sites. Consistent with the notion that adopting a prospective retrieval mode is a prerequisite for successful PM performance (Guynn, 2003, 2008), the same ERP correlate was observed *irrespective* of PM target frequency. Although no firm conclusions regarding the underlying neural generators can be drawn based on the topography on the scalp, its frontal topography is in line with a growing number of neuroimaging studies employing fMRI (e.g., Burgess, Dumontheil, et al., 2007; Reynolds et al., 2009) and Positron Emission Topography (e.g., Burgess, Scott, & Frith, 2003) reporting PM-related activity in the anterior PFC. The anterior PFC is a region that has been implicated in various higher-order cognitive functions, for instance monitoring for contextual details during memory retrieval (e.g., Ranganath, Johnson, & D'Esposito, 2000) and the maintenance of an (episodic) retrieval mode (e.g., Duzel et al., 1999; see also Guynn, 2003). In general, and beyond specific task requirements, the anterior PFC has been associated with the coordination of several related cognitive operations in the service of a common behavioral goal (see Ramnani & Owen, 2004, for a review). Recent evidence also suggests a functional specificity within the anterior PFC: Whereas the medial part of the anterior PFC has been associated with stimulus-oriented processing (for a review, see Burgess, Dumontheil, et al., 2007; Burgess, Gilbert, et al., 2007), the lateral rostral part of the PFC in particular has been linked to stimulus-independent processing, in which the focus of attention is directed away from stimulus features and towards mental representations (Burgess, Gilbert, et al., 2007). Likewise, in order to successfully identify PM targets, an internal representation of a delayed intention needs to be maintained over time, consistent with the observed activity in anterior PFC during PM tasks (e.g., Burgess, Dumontheil, et al., 2007; Reynolds et al., 2009).

Consistent with the results by Reynolds et al. (2009), in the present investigation, a larger sustained frontal effect was associated with *faster* PM target detection. Although fMRI and ERPs are based on two very different types of physiological data, both measures were associated with the same behavioral index for PM performance. This converging evidence emphasizes the important function of sustained frontal neural activity for PM monitoring, in particular for maintaining delayed intentions.

4.2. Are P2 modulations during PM blocks also functionally related to PM monitoring?

Consistent with prior ERP studies (Chen et al., 2007, 2009; Knight et al., 2010), a P2 modulation was identified that distinguished the two PM blocks from the control condition. During both PM blocks, larger P2 amplitudes were observed between 160 and 210 ms. Consistent with the idea that these ERP effects reflect increased attention to specific stimulus aspects that are relevant for PM target identification, the present results and those obtained in previous ERP studies differ in the precise topography and timing of the observed P2 modulations. For instance, in the study by Knight et al. (2010), PM targets were defined as words appearing in a particular color (red), and corresponding ERP modulations of mean P2 amplitudes were most prominent over occipital regions, thought to be relevant for color discrimination. In our study, in which color was not a relevant feature for target identification, the P2 modulation had a central topography. Notably, the P2 modulation in the present study also did not differ between the two PM blocks, in which the same target features (initial letters) were relevant. By contrast, the observed P2 modulation was delayed for trials preceding rare PM target misses. This unexpected ERP finding may be related to less focused attention preceding PM target misses. It is conceivable that attention might be captured by stimulus features that are not necessarily relevant for PM target identification initially, and is re-directed at task-relevant features later on. However, this ERP pattern needs to be replicated in future studies before a conclusive interpretation can be drawn.

4.3. Evidence for distinct monitoring as a function of PM target frequency?

In this first investigation explicitly comparing monitoring for frequent and rare PM targets, behavioral data indicate performance differences between the PM blocks: we observed longer RTs and improved PM target identification for the frequent PM condition. These findings are consistent with behavioral data reported by Brandimonte, Ferrante, Feresin, and Delbello (2001) who manipulated the instructions and the training phase for a PM task. In a standard PM condition, the ongoing task was explained first, followed by PM task instructions. In a so-called vigilance condition, PM instructions emphasized the dual-task nature of the PM paradigm and participants were additionally reminded of the PM task during a training phase whenever they missed a relatively frequent PM target (which occurred in 17% of the training trials). Participants in the vigilance condition missed fewer PM targets and had slower RTs compared to those in the standard PM condition. These combined instruction- and training-manipulations likely influenced participants' perception of the relative importance of the PM task. Thus, participants who had reasons to believe that the PM task was very important for overall performance showed better PM performance and slower RTs in the ongoing task, consistent with increased effort devoted to the PM task (cf. Smith & Bayen, 2004). Similarly, in the present experiment, both higher PM target identification and longer RTs were observed for the frequent-PM condition. Hence, participants may have achieved higher PM target identification rates at the expense of ongoing-task performance. Increased RT costs for frequent compared to rare PM targets suggest that more attentional resources were devoted to monitoring for PM targets when frequently reminded of PM target occurrence. By contrast, ERPs provide no indication for distinct monitoring processes for frequent versus rare PM target events. How can this apparent discrepancy be explained?

While behavioral measures capture the result of a decision process, ERPs provide the opportunity to examine the cognitive processes leading up to this decision. From a participant's perspective, PM target frequency likely influenced further aspects of how to approach the given task set. Despite equivalent instructions, a task set with more frequently occurring PM targets may be perceived differently, leading to different strategies or allocation policies (Marsh et al., 2005). Recent evidence suggests that participants modify their initial attention allocation away from the PM task if PM targets are no longer presented, or fail to be presented when they are expected following PM instructions (Loft et al., 2008). Notably, participants whose RT cost increased for the PM-frequent relative to the PM-rare conditions showed a concomitant increase in ongoing-task accuracy ($r = .48$, $p < .05$). This pattern of performance suggests that participants emphasized ongoing-task speed in the PM-rare condition and ongoing-task accuracy in the PM-frequent condition, possibly reflecting different criteria how to perform the ongoing task (i.e., a speed-accuracy tradeoff; cf. Horn, Bayen, & Smith, 2011). Recent fMRI studies suggest that the striatum and the basal ganglia are important for such speed-accuracy tradeoff settings (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Forstmann et al., 2010). Both structures are located relatively deep within the brain. Hence, neural activity originating from these structures would not be easily detectable on the surface of the skull using ERPs, possibly accounting for similar monitoring effects across the two PM conditions. This differential criterion setting might also account for the fact that behavioral PM interference costs were larger for those participants who completed the PM-frequent condition before the PM rare condition. Importantly, for both counterbalancing conditions PM interference costs were reliable and effect sizes were similar.

Finally, when comparing PM-rare and PM-frequent conditions, further task characteristics are likely to vary inherently along with PM target frequency. Most notably, each correctly identified frequent PM target presumably serves as an additional reminder for the PM task (see also Loft et al., 2008, for a related argumentation). In the present investigation, this factor also affected RT-variability, which is thought to reflect fluctuations in the efficiency of PM monitoring (West, Krompinger, & Bowry, 2005). That is, responses to the three ongoing trials preceding PM target hits in the PM-rare condition were about 100 ms slower than those preceding target misses (Scullin, McDaniel, & Einstein, 2010; West et al., 2005). Notably, no corresponding RT differences were observed during the frequent-PM condition, suggesting that more constant PM monitoring might take place during the PM-frequent compared to the PM-rare condition. Thus, the mean prospective interference effect across trials might reflect a combination of the amount of monitoring plus further factors, such as criterion setting and response selection, and may not be a unique indicator of monitoring (see also Scullin et al., 2010, for a related argument; West et al., 2005).

Irrespective of target frequency, the same sustained ERP modulation was observed during PM blocks, in line with the idea of a general prospective retrieval mode (Guynn, 2003, 2008). By contrast, periodic target checking may or may not complement prospective retrieval mode for successful PM performance. Moreover, like criterion setting and response selection, target checking would not necessarily be consistently time-locked to stimulus presentation, and hence not be readily observable in ERPs or fMRI (cf. Reynolds et al., 2009, who also did not find evidence for transient activity during ongoing-task trials). Thus, it is conceivable that the perceived importance of the PM task mediated the frequency or intensity of target checking, and as a result may have influenced RTs, but not ERPs. Future studies need to address how target checking and differential criterion setting may be affected by higher perceived task importance.

5. Conclusion

The present data add to extant evidence that PM monitoring is functionally related to PM performance. A sustained frontal ERP effect appears to be a correlate of PM monitoring, and more specifically, maintaining an internal representation of the delayed intention until it is re-activated upon cue presentation. Identical ERP correlates of monitoring for frequent compared to rare PM targets support the notion that successful PM monitoring is associated with the adoption of a prospective retrieval mode irrespective of PM target frequency. Moreover, these results suggest that brain responses associated with PM monitoring in previous neuro-scientific research generalize to paradigms using considerably fewer targets. Due to an increase of perceived importance of the PM-frequent condition, participants may be more inclined to monitor for frequent versus rare PM targets at the expense of slower RTs in the ongoing task. While such task priorities can be expected to heavily influence RTs, they would not necessarily be detectable in ERPs. A second process, the modulation of attention directed at relevant target features, plays an important role for detecting PM targets. Our electrophysiological data suggest distinct roles of this P2 modulation and the sustained frontal effects for a more specific attentional focus on relevant prospective target features and prospective monitoring, respectively.

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