Distinct and Shared Cognitive Functions Mediate Event- and Time-based Prospective Memory Impairment in Normal Aging

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Abstract

Prospective memory (PM) is the ability to remember to perform an action at a specific point in the future. Regarded as multidimensional, PM involves several cognitive functions that are known to be impaired in normal aging. In the present study, we set out to investigate the cognitive correlates of PM impairment in normal aging. Manipulating cognitive load, we assessed event- and time-based PM, as well as several cognitive functions, including executive functions, working memory and retrospective episodic memory, in healthy subjects covering the entire adulthood. We found that normal aging was characterized by PM decline in all conditions and that event-based PM was more sensitive to the effects of aging than time-based PM. Whatever the conditions, PM was linked to inhibition and processing speed. However, while event-based PM was mainly mediated by binding and retrospective memory processes, time-based PM was mainly related to inhibition. The only distinction between high- and low-load PM cognitive correlates lays in an additional, but marginal, correlation between updating and the high-load PM condition. The association of distinct cognitive functions, as well as shared mechanisms with event- and time-based PM confirms that each type of PM relies on a different set of processes.

KEYWORDS: binding, episodic memory, executive functions, normal aging, prospective memory.

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Introduction

Prospective memory (PM) refers to the ability to remember to perform an action at a specific point in the future. In contrast with retrospective episodic memory and despite the fact that PM is continuously called upon in everyday life (e.g., remembering to mail a letter as you pass the mailbox, or to attend an appointment at 3 pm), its study has only recently come to the attention of researchers. Consequently, PM is still poorly understood. Moreover, patients consulting for memory problems often complain of PM lapses - a fact which underlines the importance of studying PM, particularly in older people.

According to the nature of the retrieval, a distinction has been made within PM (Einstein & McDaniel, 1996) between event-based PM (EBPM), which is remembering to perform an action when an external cue occurs (e.g., the mailbox), and time-based PM (TBPM), which is remembering to perform an action at a particular time or after a given period of time. Two components have been identified in PM: the “prospective” one (remembering that something has to be done) and the “retrospective” one (remembering what has to be done). Whereas PM tasks administered in early studies were naturalistic and consequently lacked experimental control, several laboratory PM tasks have since been developed, where participants are asked to perform a given action when a particular cue appears or at a given time, while they are busily engaged in an ongoing activity.

Prospective Memory in Normal Aging

A reduction in the efficiency of cognitive resources is assumed to contribute to age-related decline observed in a number of cognitive domains, including memory, particularly its prospective aspect (Henry, MacLeod, Phillips, & Crawford, 2004). In aging, there have been conflicting findings for EBPM tasks, with some studies reporting no age-related deficits (Einstein & McDaniel, 1990; Einstein, McDaniel, Richardson, Guynn, & Cunfer, 1995) and others highlighting significant impairments (Logie, Maylor, Della Sala, & Smith, 2004; Maylor, 1996, 1998; Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997; West & Covell, 2001). By contrast, in the case of TBPM, the findings converge toward a deleterious effect of age (d’Ydewalle, Bouckaert, & Brunfaut, 2001; Einstein et al., 1995; Jäger & Kliegel, 2008). One possible explanation for this more deleterious age effect is that TBPM may involve more self-initiated processes than EBPM (Einstein & McDaniel, 1990; Einstein et al., 1995; Park et al., 1997). This is in line with Craik’s theory (1986) according to which less environmental support would require the use of more effortful self-initiated processes, inducing a decrease of cognitive efficiency in elderly individuals. However, this hypothesis is not supported by D’Ydewalle, Luwel and Brunfaut’s results (1999), as these authors observed greater accuracy in the time-based condition than in the event-based one for older subjects. They attributed this result to the decrease in processing speed in adulthood and suggested that older subjects are quite capable of performing TBPM tasks in a satisfactory manner, if the timing constraints of the task allow them to dedicate sufficient time to time monitoring after processing ongoing items. Moreover, the assumption that TBPM undergoes greater deterioration than EBPM is a fragile one for two reasons. First, it is difficult to make strict comparisons of EBPM and TBPM, as the tasks that are used have different levels of complexity and vary from one study to the next (see Henry et al., 2004, for a review). One way of overcoming this issue would therefore be to assess performance on comparable EBPM and TBPM tasks. Second, it is not obvious that TBPM tasks do indeed involve a greater number of self-initiated processes, as EBPM tasks may actually require the sustained allocation of resources in order to detect PM cues under monitoring conditions (as opposed to spontaneous retrieval, see Einstein, McDaniel, Thomas, Mayfield, Shank, & Morrisette, 2005; McDaniel & Einstein, 2000). According to the Multiprocess Theory of PM (see McDaniel & Einstein, 2000, 2007), EBPM relies on either automatic or controlled processes, depending on the characteristics of the prospective memory task (i.e. target cue distinctiveness, associative strength between the target cue and the intended action, level of emphasis given to the PM task, length of the PM retention interval), the nature and demands of the ongoing task (i.e. focal processing of the target, degree of engagement and demands of the ongoing task), and the characteristics of the individuals. More precisely, non-distinctive target cue, non-focal target cue, weak association between the target cue and the intended action, highly demanding and absorbing ongoing task would necessitate the involvement of strategic monitoring. By contrast, PM would be based on spontaneous retrieval when the task contains the opposite characteristics. Hence, PM performance may differ according to the amount of attentional resources that are required. Okuda, Fujii, Ohtake, Tsukiura, Yamadori, Frith et al. (2007) investigated, in young subjects, TBPM and EBPM in a positron emission tomography study. They found that different subregions of the rostral prefrontal cortex were involved in EBPM and TBPM, and reported additional activation of several frontal, parietal and temporal cortices, as well as the cerebellum in the TBPM task, suggesting the engagement of additional processes in TBPM. The identification of distinct neural substrates for the two tasks supports the idea that different cognitive processes are involved in EBPM and TBPM.

In previous studies, the cognitive load induced throughout the ongoing activity has been manipulated in order to influence the availability of attentional resources in PM. While some studies have reported a deleterious effect of cognitive load on PM performance in young adults (Mäntylä, Del Missier, & Nilsson, 2009; Marsh & Hicks, 1998; Stone, Dismukes, & Remington, 2001; but see also van den Berg, Aarts, Midden, & Verplanken, 2004; West, Bowry, & Krompinger, 2006), the interaction between age and cognitive load is unclear: while Park et al. (1997), for instance, found no interaction between age and load, others did (Einstein, Smith, McDaniel & Shaw, 1997; Kidder, Park, Hertzog, & Morrell, 1997; Logie et al., 2004; Mäntylä, 1994). Furthermore, the interaction between cognitive load and the nature of the PM task remains unclear. While some studies have demonstrated either a beneficial or deleterious effect of cognitive load on EBPM, with no effect on TBPM (d'Ydewalle, Bouckaert, & Brunfaut, 2001; Logie et al., 2004), others have shown a more deleterious effect on TBPM than on EBPM (Khan, Shamra, & Dixit, 2008). These divergent results could be due to the use of different procedures for manipulating load. Whereas some studies manipulated the complexity of the ongoing task (d'Ydewalle et al., 2001; Kidder et al., 1997; Logie et al., 2004; van der Berg et al., 2004), others added a second ongoing task to increase the difficulty (Einstein et al., 1997; Khan et al., 2008; Marsh & Hicks, 1998; Park et al., 1997). While an increase in ongoing complexity elicits the allocation of more attentional resources to the ongoing task, the addition of a supplementary task means that attentional resources have to be divided between three tasks, instead of two. We therefore took the view that an increase in the complexity of the ongoing task would be a purer way of testing the cognitive load effect. Accordingly, we decided to use mental arithmetic as the ongoing activity in both EBPM and TBPM, where load was manipulated by varying the difficulty of the calculations.

Prospective Memory and Cognitive Functions

Executive resources have to be allocated in order to periodically bring the intended action to mind (McDaniel & Einstein, 2000), and the main executive functions (shifting, inhibition, and updating; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), are known to be sensitive to age effects (Fisk & Sharp, 2004). Despite the strong hypothesis that deficits in these processes mediate PM difficulties in older adults, a few studies attempted to estimate executive functions, attention and working memory in conjunction with PM. These studies showed significant relationships between PM and other cognitive functions, in either young subjects (e.g., Marsh & Hicks, 1998), older but not young subjects (Martin, Kliegel, &

McDaniel, 2003; Park et al., 1997; West & Craik, 2001) or both (Cherry & LeCompte, 1999; Kidder et al., 1997). These correlations concerned working memory (Cherry & LeCompte, 1999; Kidder et al., 1997; Park et al., 1997; West & Craik, 2001), executive functions (Marsh & Hicks, 1998; Martin et al., 2003; West & Craik, 2001), retrospective episodic memory (Cherry & LeCompte, 1999), processing speed (West & Craik, 2001) and metamemory (Kliegel & Jäger, 2006; Mäntylä, 2003; Zeintl, Kliegel, Rast, & Zimprich, 2006). All these studies used EBPM tasks, with the exception of Park et al. (1997) and Martin et al. (2003), who used both EBPM and TBPM tasks. Lastly, Kliegel, Ramuschkat, and Martin (2003) found that EBPM and TBPM relied on different executive processes, with EBPM requiring inhibition and TBPM requiring shifting; these authors also showed that age-related PM performance was related to executive functioning, for EBPM as well as for TBPM. Time monitoring has typically been evaluated within TBPM tasks. Findings have consistently shown a relationship between TBPM performance and time-checking frequency (Einstein et al., 1995; Khan et al., 2008; Mäntylä et al., 2009), and an increase in time monitoring frequency during the period directly preceding the target time has been found to have a beneficial effect (Kvavilashvili & Fisher, 2007). Moreover, some authors have suggested that reduced time-monitoring in older adults could be responsible for TBPM impairment (Einstein et al., 1995; Park et al., 1997).

Other studies have attempted to link PM performance to metamemory, but results are far from clear-cut. While some of them point to a significant relationship between PM and reports of prospective and retrospective memory failures in daily life (Kliegel & Jäger, 2007; Mäntylä, 2003), other reveal no such links (Zeintl et al., 2006). Using the Prospective and Retrospective Memory Questionnaire (PRMQ; Crawford, Smith, Maylor, Della Sala, & Logie, 2003; Smith, Della Sala, Logie, & Maylor, 2000 ; see Method for its description), some studies pointed to a significant relationship between PM and reports of prospective and retrospective memory failures in daily life (Kliegel & Jäger, 2007; Mäntylä, 2003), while others did not reveal such a link (Zeintl et al., 2006). Meeks, Hicks and Marsh (2007) did not find any significant link between PM and the PRMQ, but they showed a significant correlation between PM and task-related prediction and postdiction scores as well as between those task-related metamemory indices and the PRMQ. Thus, both self-knowledge of memory from daily-life and memory task self evaluation are indices of metamemory but may be differentially implicated in PM outcomes. Meeks et al. (2007) suggested that individual memory self efficacy beliefs may modulate the way in which an individual approaches a task and, by extension, the way he or she performs it. In the present study, we chose to use the PRMQ as an index of metamemory.

Finally, some authors have suggested that PM performance depends on the quality of the association between the PM cue and the action that has to be carried out (Cohen, West, & Craik, 2001; Guynn & McDaniel, 2007). According to the theory of reflexive-associative processes (McDaniel & Einstein, 2007; McDaniel, Guynn, Einstein, & Breneiser, 2004), in EBPM tasks, when the cue and the action are strongly associated, seeing the cue will reflexively bring the intended action to awareness. If the association is strong enough, the mere perception of the cue will rapidly and automatically trigger the retrieval of the associated action. Involvement of binding processes in TBPM tasks may be less critical than in EBPM tasks. As evoked earlier, TBPM mostly requires self-initiated processes such as strategic monitoring. However, binding could also contribute to TBPM performance since an association between the target time and the intention exists. Since a binding impairment in aging has already been demonstrated (Mitchell, Johnson, Raye, Mather, & d'Esposito, 2000), especially in episodic memory (Kessels & Hobbel, 2008; Naveh-Benjamin, 2000; Overman & Becker, 2009), it can be hypothesized that age-related difficulties in PM are strongly linked to a binding impairment. However this hypothesis has never yet been tested. To our knowledge, only a very recent study (Wang, Dew, & Giovanello, 2010) have investigated PM and associative memory conjointly, but their study was focused on the latter and designed to evaluate the effect of divided attention (induced by a PM task) on it. They found an age-related impairment both in associative memory and PM and a trend toward a *negative* correlation between PM and associative memory, probably reflecting the use of different individual strategies (e.g. focus on one task to the detriment of the other) rather than a true relationship between these two cognitive functions.

Previous studies have assessed only a limited number of cognitive functions, preventing any firm conclusion on the cognitive bases of PM decline in aging. Furthermore, the cognitive functions involved in PM may vary according to the characteristics of the task and the amount of cognitive resources required by the task. In order to unravel this issue, we assessed EBPM and TBPM, manipulating the cognitive load, in 72 young, middle-aged and older healthy participants. We also assessed a wide range of cognitive functions, including executive functions, processing speed, sustained attention, retrospective episodic memory, metamemory, and binding, in order to find out which processes contribute the most to the deleterious effects of aging on different measures of PM. First of all, in order to determine whether age, the nature of the PM task and the cognitive load of the ongoing task affected PM performance, we performed an analysis of variance. Second, we performed correlations between PM and all the other cognitive scores in order to determine which of them were linked to PM. Then, to find out exactly which cognitive functions predicted PM variability and contributed to PM impairment in aging, we performed stepwise regressions on the different measures of PM. Finally, mediation analyses were performed to identify the existence of variables that could be responsible for the age-related PM decline.

Method

Participants

Twenty-nine young, 20 middle-aged and 23 older subjects were enrolled in this study. All were screened by means of a health questionnaire for any history of neurological or psychiatric conditions, head trauma and alcohol or drug abuse. The adults over 50 years old were screened for cognitive impairment using the Dementia Rating Scale (Mattis, 1976). All the subjects included in the present study had normal performance for their age and education. All subjects had had at least eight years of schooling. The mean number of years of schooling was higher for young than for middle-aged and older groups (*ps* < 0.05), while no difference was found between the middle-aged and older groups ($p = 0.94$) (Table 1). Given the reorganization of the French educational system, the number of school years is not a good index of the education level when considered alone. Thus, the mean number of school years was combined with the vocabulary level, assessed by the Mill Hill test (Deltour, 1993) to obtain a more accurate index (by calculating z-scores and averaging them). While the older group had a vocabulary level higher than the younger one ($p < 0.01$; *ps* non significant for the other comparisons), there was no difference between the three groups for the composite index of the education level.

(Table 1 about here)

Procedure

The experimental protocol featured two sessions, separated by a one-week interval. The protocol included laboratory EBPM and TBPM tasks, a prospective and retrospective everyday memory failures self-report questionnaire allowing us to assess metamemory, and a set of complementary cognitive tasks. The EBPM task took place during the first session and the TBPM task during the second session, in order to avoid any time estimation occurring during the EBPM task (see below).

Prospective memory tasks.

The tasks were inspired by the one devised by D'Ydewalle et al. (2001). The design is illustrated in Figure 1. In both event-based and time-based PM conditions, mental arithmetic constituted the ongoing activity. Two levels of difficulty characterized the cognitive load factor: during the first 12 minutes, the subjects had to add up three 2-digit numbers (high-load condition), and during the following 12 minutes they had to add up two 2-digit numbers (low-load condition). The numbers were displayed one at a time on the computer screen, and when the 'equals' sign appeared, the subjects had to mentally add them up and, if successful, say the result out loud. After the presentation of the *equal* sign, which duration varied from one to the next, an answer appeared on the screen for a duration of five seconds and the subject had to say whether or not it was the correct one. Half the answers proposed by the computer were correct and half were incorrect. Calculation times had previously been determined on the basis of a pilot study with a different group of young and older subjects: we selected calculations for which there was no age-related difference in resolution time, and the presentation time for each of these calculations corresponded to the subjects' mean resolution time in the pilot study.

In the EBPM task, subjects had to press the D key when the answer displayed on the screen was over 100 and the L key when the number was made up of two identical digits (e.g., 77). In the high-load condition, four prospective cues appeared in the same order every three minutes (the subjects were not informed about the three-minute interval): D, L, D, L. The low-load condition was similarly constructed.

In the TBPM task, instructions were to "press alternatively the D and L buttons every three minutes, regardless of what was happening on the screen, starting with D at the third minute"; the experimenter also stressed not to respond before the target number of minutes. A full point was provided if the subjects answered within 5 seconds following the targeted minute, and half a point, if the answer was comprised between 6 and 10 seconds after the targeted minute. In order to check the time, a clock displaying minutes and seconds was positioned to the right of the subject, at an angle of 90° relative to his or her gaze toward the screen. Consequently, the subject had to turn his or her head round to check the time. Frequency of time monitoring was recorded by the experimenter, constituting an additional and specific measure of TBPM processing.

(Figure 1 about here)

Altogether, there were 16 PM trials, 8 for the EBPM task (four in each load condition), and 8 for the TBPM task (again, four in each load condition). The dependent variable was the number of correct answers given during the PM trials.

At the end of each PM task, participants were asked to recall the instructions (what they had to do under which conditions). No subject failed to remember any component of the PM tasks.

Complementary cognitive tasks.

In the light of the literature and in order to test our hypotheses, we measured several cognitive functions thought to play a role in PM. On the basis of Miyake et al.’s findings (2000), we assessed the following three executive functions: shifting, inhibition, and updating. We also measured binding, which refers to the mechanism supported by the episodic buffer component of working memory and defined as the system allowing for the integration and maintenance of different items of information in an episodic representation (Baddeley, 2000), sustained attention, processing speed, retrospective episodic memory and metamemory.

Metamemory.

To evaluate memory self-efficacy beliefs, subjects were asked to complete the Prospective and Retrospective Memory Questionnaire (PRMQ; Crawford, Smith, Maylor, Della Sala, & Logie, 2003; Smith, Della Sala, Logie, & Maylor, 2000). The PMRQ is composed of 16 questions about retrospective and prospective memory failures in everyday life. Subjects had to rate the frequency of occurrence of their memory failures on a five-point Likert scale (from 1 = never, to 5 = very often). This questionnaire was administered prior to the other cognitive tasks.

Shifting.

Task-set switching, was used to test the ability to shift between two different task sets (for full description, see Mayr & Kliegl, 2000). This task consisted in an alternate-runs paradigm. Within each block, participants had to perform alternating four-trial runs of two tasks (aaaabbbb, etc.), so that a shift occurred every four trials. Sixteen words were used, repeated eighteen times. Each item was accompanied by a sign that changed every four trials: when the item was accompanied by a heart, subjects had to make a living/non-living judgment on each word; when the item was accompanied by a cross, subjects had to decide whether it represented something larger or smaller than a soccer ball. To answer “living” or “larger” subjects had to press the D key, while answer “non-living” or “smaller” required the subjects to press the L key. The dependent variable for this task was the switch cost, that is, the difference in response times between the situation where there was a shift and the situation where there was none.

Inhibition.

Inhibition was assessed using the random letter generation task (Baddeley, 1966). Participants were asked to say consonants out loud in a random sequence, attempting to produce a set of 50 letters at the rate of one letter per second. They were told to avoid repeating the same letter sequence and avoid producing alphabetical sequences (forward and backward), acronyms and parts of words. The score was the number of letters produced minus errors (vowels and prohibited sequences).

Updating.

The running span task (Quinette, Guillery, Desgranges, de la Sayette, Viader, & Eustache, 2003) was used to assess updating. Sixteen strings of consonants of variable length (4, 6, 8 or 10 letters) were provided orally, with no prior information about the length of the consonant string, and subjects were required to recall the four most recent items in the right order.

Binding in working memory.

The binding task measured the ability to associate verbal and spatial features in working memory (Quinette, Guillery-Girard, Noël, de la Sayette, Viader, Desgranges et al., 2006). Four colored uppercase letters were displayed in the center of a 5 x 4 grid, accompanied by four colored crosses displayed randomly in the other squares of the grid. Subjects had to mentally associate each of the four colored letters with the location of the cross of the same color. After a five-second presentation phase, a black fixation cross appeared at the center of the blank screen. The grid then appeared again, but this time with only one black lowercase letter in one of the squares. Subjects had to decide if the letter was in the correct square in relation to the letter-location match they had performed mentally. A total of 20 trials were administered.

Attention and processing speed.

The BAMS-T (Lahy, 1978) was used to obtain two scores, one for sustained attention, the other for processing speed. The BAMS-T is a crossing-out task, which involves a single page filled with rows of eight different symbols. Subjects were instructed to cross out every instance of the three target symbols, which are indicated at the top of the page, within the space of five minutes. Two scores are calculated: the speed and the accuracy of the perceptual processing. The speed score was calculated as follows: (total number of crossings-out)/(time in seconds). The accuracy score was calculated as follows: (number of correct crossings-out/number of omissions)/(number of correct crossings-out/number of errors).

Retrospective episodic memory.

Lastly, we tested retrospective episodic memory using the Encoding, Storage, Retrieval task (ESR), described elsewhere (Kalpouzos, Chételat, Landeau, Clochon, Viader, Eustache et al., 2009; see also Eustache, Desgranges, & Lalevée, 1998), where the subjects had to memorize two lists of 16 words and immediately recall them. For the first list, subjects were asked to say, for each word, if the first and last letters were in alphabetic order, which constituted shallow incidental encoding. The encoding of the second list took the form of deep intentional encoding: subjects were asked to memorize the list and generate a sentence containing each word. The score retained for analysis corresponded to the sum of words correctly recalled in both lists.

Statistical Analyses

First of all, in order to determine whether age, the nature of the PM task, and the cognitive load of the ongoing task affected PM performance, we performed a Group (young vs. middle-aged vs. older) x Nature of PM (event-based vs. time-based) x Cognitive load (high vs. low) repeated-measures ANOVA. Regarding TBPM, we also analyzed time monitoring, using a Group (young vs. middle-aged vs. older) x Cognitive load (high vs. low) x Period (first minute vs. second minute vs. third minute) ANOVA. Second, one-way ANOVAs were performed on the complementary cognitive tasks to explore their sensitivity to age (young vs. middle-aged vs. older). Third, Pearson correlations between PM measures and the scores obtained on the complementary cognitive tasks were assessed for the whole sample in order to search for links between PM and cognitive functions. The same correlations were then assessed again, controlling for age (partial correlations), in order to find out whether they were mainly due to age or not. For both series of correlations, the Benjamini and Hochberg procedure was used to control the false discovery rate. This method consists in correcting the *p*-values according to the total number of tests performed (here correlations) and the *p*-value ranks (see Benjamini & Hochberg, 1995). Fourth, forward stepwise regression analyses were performed on PM measures, including all complementary cognitive tasks and age as regressors. These analyses allowed us to identify those factors which might account for inter-individual variability in PM performance. Where relevant, a second model was assessed, forcing age into the model in order to determine whether this inclusion would change the role of the other variables in PM variability. Finally, mediation analyses were performed to go further stepwise regressions, testing the possible mediating influence of cognitive functions on the relationship between aging and PM. For all these analyses, results were considered to be significant at a threshold of $p < 0.05$.

Results

PM Performance

The ANOVA revealed a main effect of Group, $F(2, 69) = 23.82$; $MSE = 1.48$; $p < 0.001$, where performance decreased with age, a main effect of Nature of PM, $F(1, 69) = 8.27$; $MSE = 1.42$; $p < 0.01$, where EBPM scores were lower than TBPM ones, and a main effect of Cognitive load, $F(1, 69) = 16.91$; $MSE = 0.60$; $p < 0.001$, where PM scores were higher in the low-load than in the high-load condition. The ANOVA also showed a significant interaction effect between the Group and Nature of PM factors, $F(2, 69) = 3.64$; $MSE = 1.42$; $p < 0.05$. Further post hoc tests (Tukey's HSD) demonstrated that the age-related decline in EBPM was "gradual", as impairment started in middle age (young vs. middle-aged $p = 0.005$ and young vs. older $p < 0.001$) and continued (as a trend, middle-aged vs. older $p = 0.07$) into old age (see Fig. 2). TBPM performance gradually decreased with age, but the difference between the young and oldest subjects was the only one that reached significance (young vs. older p = 0.04; young vs. middle-aged p = 0.13; middle-aged vs. older p = 0.99). In addition results showed that older subjects performed better on TBPM than on EBPM (p = 0.006; p = 0.99 for young subjects and p = 0.89 for middle-aged ones). Although there was no significant interaction effect between the Group and Cognitive load factors, $F(2, 69) = 1.47$; $MSE = 0.60$; $p = 0.24$, in order to test our hypothesis regarding a Cognitive load effect in aging, post hoc tests (Tukey's HSD) were performed to pinpoint specific effects. The results are shown in Figure 2. PM performance in the high-load condition decreased significantly between young adulthood and middle age (p = 0.001), and this decline continued between middle age and old age, though without reaching significance (p = 0.30). In the low-load condition, we found the same pattern of significance (young vs. middle-aged p = 0.04; middle-aged vs. older p = 0.67; young vs. older $p < 0.001$). While we observed a significant difference between the high cognitive load condition and the low one for the older group (p = 0.02), this difference was significant neither for the young nor for the middle-aged groups (p = 0.81 and p = 0.18). Neither the Nature x Cognitive load nor the Nature x Cognitive load x Group interactions were significant, $F(1, 69) = 2.93$; $MSE = 0.52$; $p = 0.09$ and $F(2, 69) = 0.21$; $MSE = 0.52$; $p = 0.81$. Nevertheless, when Tukey's HSD post hoc tests were performed in order to test our hypothesis of a differential effect of Cognitive load on EBPM and TBPM, we found that EBPM performance in the high-load condition was significantly lower than the scores in the other three conditions ($p < 0.001$ for all comparisons). In other words, EBPM performance was sensitive to cognitive load, whereas TBPM performance was not.

(Figure 2 about here)

Concerning time monitoring, a Group (young vs. middle-aged vs. older) x TBPM Cognitive load (high vs. low) x Period (first minute vs. second minute vs. third minute)

ANOVA was performed. As subjects were supposed to press a key every third minute, an increase in time monitoring was expected in the run-up to every third minute. None of the effects involving the Group factor was significant. However, the main effects of Cognitive load, $F(1, 69) = 11.46$; $MSE = 3.94$; $p < 0.01$, Period, $F(2, 138) = 190.15$; $MSE = 5.70$; $p < 0.001$, and their interaction, $F(2, 138) = 6.20$; $MSE = 1.44$; $p < 0.01$, were significant. As illustrated in Figure 3, the number of times the subjects checked the clock significantly increased between the first and third minutes. There was a greater increase in frequency in the low-load condition than in the high-load one. Tukey's HSD revealed that the difference between the high-load and low-load conditions for the first minute was the only one that did not reach significance ($p = 0.97$; $p < 0.001$ for other comparisons).

(Figure 3 about here)

Age Effects on the Complementary Cognitive Tasks

Results on the complementary cognitive tasks are shown in Table 2. One-way ANOVAs demonstrated an age group effect on inhibition and updating, $F(2, 69) = 9.23$; $MSE = 29.13$; $p < 0.001$ and $F(2, 69) = 6.26$; $MSE = 10.91$; $p < 0.01$, but not on shifting, $F(2, 69) = 1.53$; $MSE = 106559$; $p = 0.22$. Processing speed, $F(2, 69) = 8.42$; $MSE = 270.85$; $p < 0.01$, binding, $F(2, 69) = 24.14$; $MSE = 0.02$; $p < 0.001$, and retrospective episodic memory, $F(2, 49) = 15.99$; $MSE = 9.29$; $p < 0.001$, were significantly impaired by aging, whereas sustained attention was not, $F(2, 69) = 1.25$; $MSE = 0.02$; $p = 0.29$.

(Table 2 about here)

For the PRMQ, a Group (young vs. middle-aged vs. older) x Nature of memory failures (prospective vs. retrospective) ANOVA failed to reveal an effect of Group on memory self-efficacy beliefs, $F(2, 69) = 0.84$; $MSE = 26.04$; $p = 0.44$, but did reveal an effect of Nature of memory failures, $F(1, 69) = 6.33$; $MSE = 11.61$; $p < 0.05$, which interacted with age group, $F(2, 69) = 3.47$; $MSE = 11.61$; $p < 0.05$. An analysis of the interaction using

Tukey's HSD demonstrated that the Nature of memory failures effect was due solely to the subjects in the young group, who reported more prospective than retrospective memory failures (p = 0.004; p = 0.98 and p = 1 for the middle-aged and older groups).

Cognitive Correlates of PM

Since no significant interaction was found between Nature of PM and Cognitive load, correlations between the cognitive scores on the complementary tasks and the PM scores were performed separately, according to the nature of PM and according to the cognitive load. This also allowed us to retain a higher variability in PM measures (on 8 points). The scores in the high- and low-load conditions were added up for EBPM and for TBPM, while the EBPM and TBPM scores were added up for the high-load and the low-load conditions. It should be noted that in order to obtain a single measure reflecting the increase in time monitoring revealed by the ANOVA (see above), we subtracted the averaged number of fixations on the clock during the first and the second minutes from the averaged number of fixations during the third minute for each subject.

Pearson correlations between PM performance and the other cognitive functions for the whole sample are reported in Table 3. All measures of PM were linked to inhibition, processing speed, and, except for TBPM, binding and retrospective episodic memory. Additionally, shifting correlated marginally with EBPM, and updating was marginally linked to high-load condition performance. No significant correlation was found between TBPM and time monitoring. Finally, none of the measures of PM significantly correlated either with sustained attention or with PRMQ indices of prospective and retrospective memory failures. In sum, all measures of PM were linked to inhibition and processing speed, but we also found specific patterns of correlations according to the nature of PM. EBPM was additionally linked to binding, retrospective episodic memory and, marginally to shifting.

(Table 3 about here)

When we controlled for age, none of the above-mentioned correlations remained significant, except the relationship between EBPM and binding which became marginal after correction for multiple tests with the Benjamini and Hochberg procedure (r = 0.36; *p* = 0.08), suggesting that the links between PM and the other cognitive functions were due to age variability.

Stepwise Regressions

Twenty subjects were excluded from the stepwise regressions because of missing data for the retrospective episodic memory measure. As a result, 21 subjects between 18 and 39 years, 12 subjects between 40 and 59 years and 19 subjects between 60 and 80 years were included in these analyses. To ensure that the exclusions did not affect our previous results and to be consistent across all the results, we performed ANOVAs on PM performance and complementary cognitive tasks without these 20 subjects. The analyses globally yielded the same pattern of results (see note below Tables 2, 3 and Fig. 2 for further detail).

(Table 4 about here)

Forward stepwise regression analyses were performed for EBPM and TBPM, as well as for the high-load and low-load conditions (see Table 4). Variance in EBPM was mainly accounted for by binding and retrospective episodic memory. When age was forced into the model, we found that age explained a significant proportion of variance. Binding was included in the second step and retrospective episodic memory in the third. Both accounted for a significant proportion of PM variance and their inclusion in the model reduced age to a nonsignificant role. The only regressor included in the model for TBPM was inhibition. As with EBPM, when age was forced into the model, we found that it made a significant contribution to PM variability. No other factor explained a significant proportion of variance.

Finally, forward stepwise regressions for the high- and low-load conditions demonstrated that the only variable that could significantly account for performance was age.

Mediation analyses

Stepwise regressions underlie variables that could be predictive of PM performance. To go beyond the above results, mediation analyses were performed on the 52 subjects to evaluate the possibility that different cognitive functions mediate the effect of age on PM. Mediation effects were tested following the procedure proposed by Baron and Kenny (1986; see also Frazier, Tix & Barron, 2004). To conclude that a specific function mediates relation between age and PM there must be {a} a significant relation between age and PM, {b} a significant relation between age and the mediator, {c} a significant relation between the mediator and PM when controlling for age, and finally {d} the strength of the relationship between age and PM must be reduced when the mediator is added to the model. When the relationship between the predictor (e.g. age) and the dependant variable (e.g. PM) becomes non significant, the mediation is complete; when the relationship between the predictor and the dependant variable decreases but remains significant, the mediation is partial (Brauer, 2000; Frazier et al., 2004). Results are presented in Figure 4.

(Figure 4 about here)

Regressions were assessed on the 52 subjects to test criteria {a}, {b} and {c} as described above. Binding and retrospective memory influences on age-EBPM relationship ($\beta = -0.65$; $p < 0.001$) were the only ones responding to criteria {a}, {b} and {c}. Multiple regressions performed to test condition {d} showed that binding and retrospective memory partially mediated the effect of age on EBPM ($\beta = -0.31$; $p < 0.05$ and, $\beta = -0.45$; $p < 0.005$, respectively) when they were tested independently. However, when binding and retrospective memory were included in the same regression, they fully mediated the effect of age on EBPM, resulting in a non significant age-EBPM relationship (β = -0.14; p = 0.37; see Fig. 4).

A mediation of the age-TBPM relationship by binding processes could be expected from stepwise regression results. All the criteria were not entirely fulfilled to conclude to a mediation. In fact, despite a significant link between age and TBPM (β = -0.39; $p < 0.005$) and between age and inhibition (β = -0.53; $p < 0.001$), the relationship between inhibition and TBPM controlling for age (criterion {c}) was only marginal (β = -0.27; p = 0.08). Nevertheless, the multiple regression revealed that the age-TBPM link, controlling for inhibition, became not significant (β = -0.25; p = 0.10).

Discussion

The present study sought to assess the impact of aging and its cognitive correlates on PM, investigating the entire adulthood. Our results showed that PM decline started in middle age and, in contrast to the literature, EBPM was more affected by age than TBPM. Cognitive load also affected PM, but only in the older group and in the EBPM condition. We also identified distinct cognitive correlates of PM, according to the condition. While inhibition and processing speed were common to all PM conditions, their implication in each of the PM conditions differs and additional cognitive functions were specifically related to EBPM in particular.

Prospective Memory in Aging

Using EBPM and TBPM tasks that were designed to be as comparable as possible, we found that age had a more deleterious effect on EBPM than on TBPM. One important feature of the present study is that we investigated PM across the whole adult lifespan, from 18 to 84 years. While a decrease in PM from 40-50 years onwards had already been demonstrated

(Mäntylä & Nilsson, 1997), very few studies had investigated performance in middle age. Interestingly, EBPM was not only the condition that was the most impaired with aging, but was also the one that was impaired the earliest. This result contradicts previous studies that assumed that EBPM is less sensitive to the effects of aging than TBPM because the former requires fewer self-initiated processes, which are known to be impaired in aging (Craik, 1986). However, and as predicted by the Multiprocess Theory (McDaniel & Einstein, 2000, 2007), EBPM does not rely solely on successful automatic detection of PM cues, as it may also require controlled processes. In the present experiment, it can be assumed that EBPM did indeed require controlled processes, as i) the subjects were not informed of the frequency of appearance of the prospective cues (they were only told that they were few and far between), and ii) these cues were not as distinctive as they have been in previous studies (Park et al., 1997; Vogel, Dekker, Brouwer, & de Jong, 2002). Thus, the EBPM task we used must have required controlled processes in order to continuously monitor the items displayed on the screen and detect the cues. Although the same time intervals were used in both the EBPM and TBPM tasks, the fact that subjects knew when a response had to be provided in the TBPM may have resulted in more efficient resource-sharing in the multitasking. As a result, the older subjects may have performed better on the TBPM task because they were able to organize their time. This hypothesis has been put forward in naturalistic studies where older individuals outperform their younger counterparts, probably because they organize their daily lives more efficiently (Rendell & Thomson, 1999).

As indicated in the methodological section, TBPM was always performed after EBPM, after a one-week interval. As a result, we cannot rule out the hypothesis that subjects' better performance on TBPM in comparison to EBPM could be linked to a training effect on the ongoing task, making the TBPM task easier to achieve, due to lower attentional demands allocated to the ongoing task. Indeed, analyses on the ongoing task revealed that performance was higher in the TBPM condition than in the EBPM condition, but the lack of significant interaction between Nature of PM (EBPM versus TBPM) and Group on the ongoing task indicates that the effect of practice on this task was the same for all subjects (results not shown). Moreover, we assume that the training effect between the two sessions would be limited thanks to the one-week interval.

PM performance in high-load and low-load conditions displayed the same pattern of an age-related decrease in middle age that continued at the same pace into old age. However, the cognitive load of the ongoing task only had a deleterious effect in the EBPM task and for the older group. The increase in task complexity forced subjects to engage more controlled processes in order to perform the ongoing activity, thus reducing the amount of available resources for the PM task. This result goes against the findings of Khan et al. (2008), who observed the opposite pattern, that is, a greater effect of cognitive load on TBPM than on EBPM. One explanation for this is that Khan et al. manipulated cognitive load in a different way, introducing a second ongoing task to increase load.

There was thus a differential effect of age on PM according to the condition. The correlation analyses showed that age-related PM decline stemmed from various cognitive impairments, and specified which of these were either systematically or specifically involved in this decline.

Systematic Cognitive Correlates of Age-related PM Decline

Inhibition and processing speed correlated with PM in all conditions, that is, EBPM, TBPM, and the low and high cognitive load conditions. As these cognitive functions are impaired in older people, their involvement may have mediated the age-related PM impairment. Successful multitasking relies on the ability to inhibit one task in order to perform another task. Our results consistently suggested that the older subjects had difficulty inhibiting the processing of the ongoing activity in order to perform the PM task (Kliegel et al., 2003; West & Craik, 2001). In line with the hypothesis of a general slowdown with age, contributing to a decline in accuracy in many different cognitive functions (Salthouse, 1996), processing speed also seems to mediate age-related PM decline (Salthouse, Berish, & Siedlecki, 2004). Our findings are consistent with previous results highlighting the implication of inhibitory and processing speed deficits in PM decline with aging (Kliegel & Jäger, 2006).

While the mechanisms of inhibition and processing speed subserved PM decline in aging in all conditions, their respective contributions differed for each of them, and other cognitive functions were found to be specific to each condition.

Specific Cognitive Correlates of Age-related EBPM and TBPM Impairment

Taking into account all the analyses, it seems that our EBPM task required several controlled processes, in opposition to the TBPM one that involved a reduced range of cognitive functions. While, additionally to inhibition and processing speed, EBPM was linked to binding, retrospective memory and marginally to shifting, no supplementary correlation was found between TBPM and the other cognitive functions.

A novel contribution of the present study is that PM impairment, more specifically EBPM one, may also be due to a deficit in binding. That is, PM impairment could result from a deficit in associating the action to be performed with the PM cue. Binding processing is mainly subserved by the frontal cortex (Mitchell et al., 2000; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000; Sperling, 2007), and the dysfunction of this brain area in aging (Kalpouzos, Chételat, Baron, Landeau, Mevel, Godeau et al., 2009) may contribute to an age-related binding deficit (Mitchell et al., 2000; Sperling, 2007). This is in line with the reflexive-associative theory of PM (Guynn & McDaniel., 2007; McDaniel & Einstein, 2007; McDaniel et al., 2004). McDaniel et al. (2004) found that intention retrieval is mediated by a reflexive-associative process when the target cue and the action are closely associated. However, when they are not, retrieval of intentions seems to be more consistent with a discrepancy-plus-search model. As older subjects have greater difficulty binding several elements together in memory, they cannot fall back on a reflexive-associative process and are forced to allocate more resources to the task. As shown by the regression analyses, binding accounted for the greatest proportion of variance in EBPM performance, whereas it was not predictive of TBPM performance. Here, the greater difficulty displayed by the older subjects in EBPM can be explained by the weak association between the target cue and the action to be performed.

As suggested above, more controlled processes may have been required in the EBPM task than in the TBPM task. The fact that additional cognitive functions were found to be related to EBPM scores reinforces this idea. After binding, retrospective episodic memory was the second factor that accounted for EBPM variability. Thus, besides the deleterious effect of age on both aspects of memory (prospective memory and retrospective episodic memory; shown through the analyses of variance), our results support the hypothesis of a deleterious effect of retrospective episodic memory decline on EBPM. Several studies have failed to find a significant relationship between PM and retrospective episodic memory (see, for example, Einstein & McDaniel, 1990; Kidder et al., 1997). Nevertheless, as PM contains a retrospective component (the intention content, i.e., what the subject has to do once a cue is detected), searching for such link is not counterintuitive. In these studies, the retrospective component of PM was limited to a simple action, whereas in the present one, subjects had to remember two prospective actions and their associated targets. Although shifting also correlated with EBPM, it did so to a lesser degree than binding and retrospective episodic memory, as it did not account for a significant proportion of EBPM variance.

The major implication of binding and retrospective memory in age-related PM performance has been confirmed by the mediation analyses which showed that, beyond being predictive of EBPM performance, binding and retrospective memory age-related decline were responsible for age-related EBPM impairment. It is likely that the more the task involves binding and retrospective memory (e.g. task with low link between prospective memory cue and intention, and with several information to memorize), the more it will be sensitive to the age effects. We can hypothesize that the controlled processes, likely responsible for the greater impairment of EBPM than of TBPM in aging, correspond to these two age-related impaired cognitive functions.

In contrast with EBPM, which had specific correlations with supplementary cognitive functions, TBPM had not. Nevertheless, inhibition was the only process to account for a significant proportion of variance in TBPM performance, while it was not predictive of EBPM performance. Inhibition processes therefore seem to play a particular role in TBPM. The fact that TBPM variability could be explained either by inhibition or by age, depending on the model, suggests that these two factors shared a common variance and were jointly responsible for TBPM difficulties. However, the mediation role of inhibition on TBPM age-related decline has to be confirmed.

Regarding time monitoring, we found a classic J-shaped distribution in all groups (i.e., more frequent time checking as targeted minutes approached) which was greater in the low-load condition. This is consistent with Occhionero, Esposito, Cicogna, and Nigro’s suggestion (2010) that time monitoring is an index of resource allocation in TBPM tasks, insofar as a time-monitoring decrease can be observed when more attentional resources have to be allocated to the ongoing activity. Moreover, when the ongoing task is sufficiently low-demanding to enable subjects to allocate resources to time monitoring, older subjects can compensate for their TBPM impairment by increasing their time-monitoring frequency

(Mäntylä et al., 2009; see also d'Ydewalle et al., 2001). In our study, the older subjects did not show any increase in comparison with the young subjects, resulting in reduced TBPM capabilities. However, and in contrast to previous studies, we failed to find a significant link between TBPM scores and time monitoring, which may be due to a lack of statistical power in our correlation analyses.

In sum, the present study clearly demonstrated that different cognitive processes are involved in PM, depending on the nature of the task, EBPM involving a larger range of cognitive functions than TBPM.

Specific Cognitive Correlates of Age-related PM Impairment for High and Low Cognitive Loads

The distinction between the cognitive correlates of low-load and high-load conditions in PM was not as demonstrative as it was for EBPM and TBPM. Indeed, the only distinction between these two conditions concerned updating, which has been shown to decline during aging and tended to correlate with the high load condition. As a result, the greater deficit in the high-load condition compared with the low-load one, for the older subjects, may have been linked to the implication of updating in the former. The absence of distinct cognitive correlates, with the exception of the updating factor, could be due to the fact that the cognitive correlates of EBPM and TBPM were shared in both conditions, thus preventing the emergence of specific correlates for the high- and low-load conditions. In future studies, the number of cues will have to be increased, in reasonable ratio, in order to assess the cognitive correlates of PM in the high-load and low-load conditions separately for EBPM and for TBPM. Moreover, it would be interesting to test whether PM performance is subserved by shared or distinct cognitive correlates when cognitive load is manipulated either via an increase in the complexity of the ongoing task itself or via the addition of a second ongoing task.

Prospective Memory and Metamemory in Aging

Reports of prospective and retrospective memory failures in daily life, assessed via the PRMQ (Smith et al., 2000), proved not to be sensitive to the effects of aging. However, further analyses demonstrated that younger subjects reported more prospective memory failures than retrospective memory failures, whereas middle-aged and older subjects reported prospective and retrospective memory failures to be equally frequent. More importantly, these reports were not linked to PM performance. This has previously been demonstrated by several authors (Hertzog & Hultsch, 2000) who concluded that reports of difficulty in everyday remembering tasks were not predictive of their objective difficulties in laboratory tasks, notably for PM (Zeintl et al., 2006; but see also Kliegel & Jäger, 2006; Mäntylä, 2003). The absence of a correlation between PRMQ and PM performance could be explained by a lack of correspondence between the experimental task and the context of the prospective and retrospective memory failures. The fact that the young group was the only one to report prospective rather than retrospective memory failures is in line with findings of naturalistic studies, which have observed better PM performance for older subjects than for younger ones (Rendell & Thomson, 1999; see Henry et al., 2004, for a review). More specifically, we can assume that PM performance in the laboratory is most closely linked to PM metamemory when the assessment refers to the experimental task itself (Meeks et al., 2007).

Conclusion

By assessing different PM conditions and several cognitive functions in healthy individuals covering the entire adult lifespan, we were able to gain an integrative view of PM impairment in normal aging, specifying its cognitive correlates. This study showed that, with advancing age, PM decline is linked to the impairment of several cognitive functions, notably inhibition and processing speed, which are particularly vulnerable to the effects of age. Concerning the nature of the PM task, we found that EBPM was more affected than TBPM. This finding goes against several previous studies, which have suggested a more deleterious effect of age in TBPM tasks. Consistent with the Multiprocess Theory of PM, our findings support the hypothesis that EBPM relies on controlled processes, as well as automatic ones, resulting in the greater sensitivity of EBPM to the effects of aging. While inhibition and processing speed correlate with all PM measures, their respective contributions differed according to the conditions, and other cognitive functions were found to be specific to one particular condition. EBPM appears to be strongly dependent upon binding and retrospective episodic memory and, to a lesser extent, upon shifting, whereas TBPM relies mainly on inhibition. Further research is needed to clarify whether cognitive load influences the relations between distinct cognitive functions and age-related PM impairment or whether load influences the strength between those cognitive functions and PM decline.

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Figures Captions

Figure 1. Design of the event-based (a) and time-based (b) prospective memory (PM) tasks (see Method).

Figure 2. Interaction effects between age (young, middle-aged and older groups) and nature of PM (event-based and time-based conditions) and between age and cognitive load (high and low load conditions). The Y-axis displays the mean scores obtained by each group in the EBPM and TBPM conditions (on the left) and in the low and the high load PM conditions (on the right). t: trend; *p<.05; **p<.01.

Note: ANOVA on 52 subjects demonstrated the same pattern of results except that the main effect of Nature of PM became marginal, $F(1, 49) = 3.83$; $p < 0.06$. Post hoc tests revealed that, in EBPM, older group had weaker performance than younger and middle-aged groups ($p < 0.001$ and $p < 0.05$). There was no age effect on TBPM. The effect of nature was only significant for the older group ($p < 0.01$).

Figure 3. Interaction effect for time monitoring between Load condition (high vs. low load) and period (first minute vs., second minute vs. third/critical minute). The Y-axis displays the time-checking frequency (number of times the subjects checked the clock, averaged over the three groups).

Figure 4. Mediation analyses on the relationships between age and event-based prospective memory (a; b; c) and between age and time-based prospective memory (d). Numbers refer to betas of the regressions and numbers in italic in parentheses represent the betas of the regressions controlling for the mediator. t: trend; *p<.05; **p<.01; ***p<.001.

Figure 1.

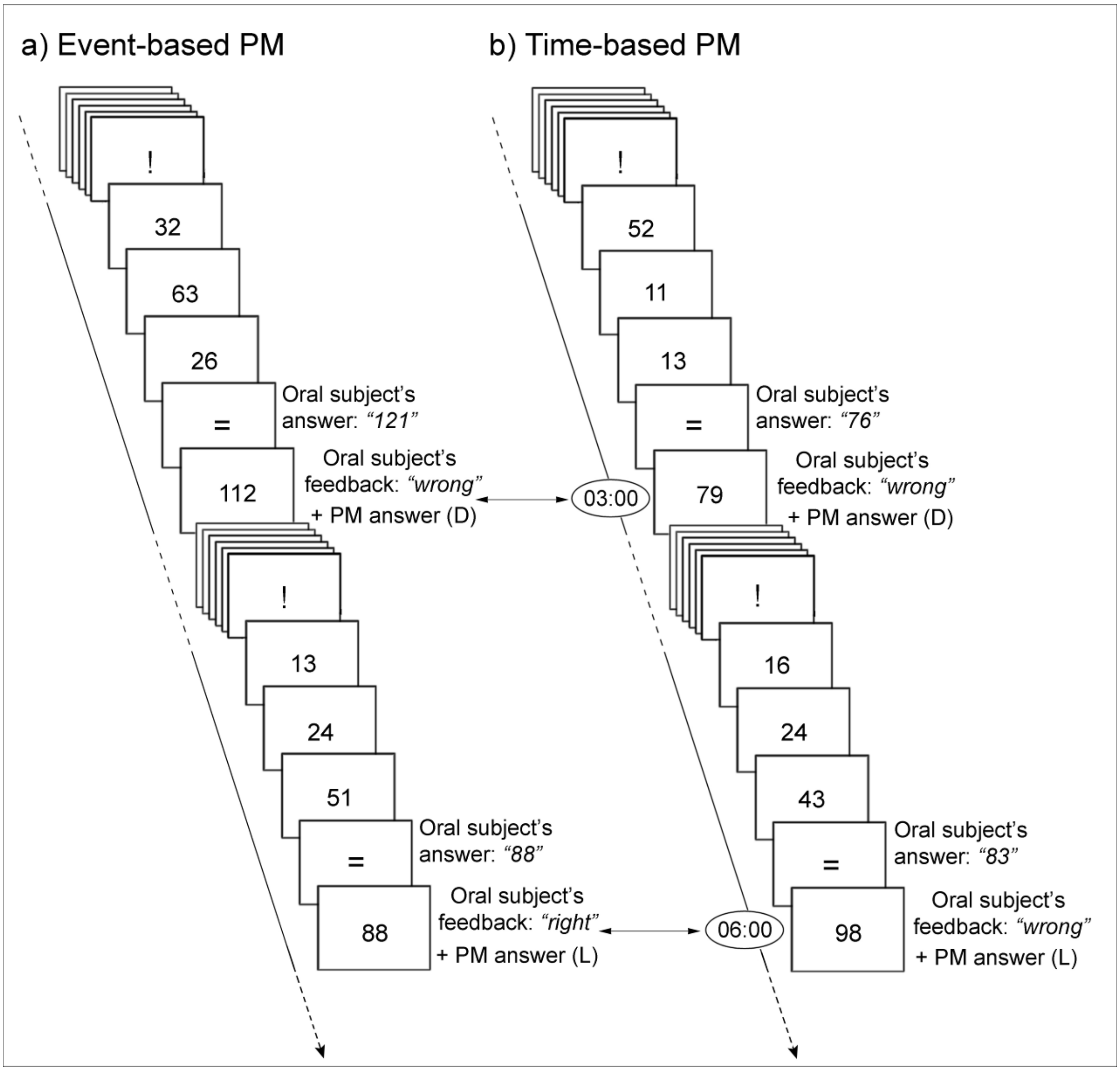
a) Event-based PM
!
32
63
26
=
Oral subject's answer: "121"
112
Oral subject's feedback: "wrong" + PM answer (D)
!
13
24
51
=
Oral subject's answer: "88"
88
Oral subject's feedback: "right" + PM answer (L)
b) Time-based PM
!
52
11
13
=
Oral subject's answer: "76"
03:00
79
Oral subject's feedback: "wrong" + PM answer (D)
!
16
24
43
=
Oral subject's answer: "83"
06:00
98
Oral subject's feedback: "wrong" + PM answer (L)

Figure 2

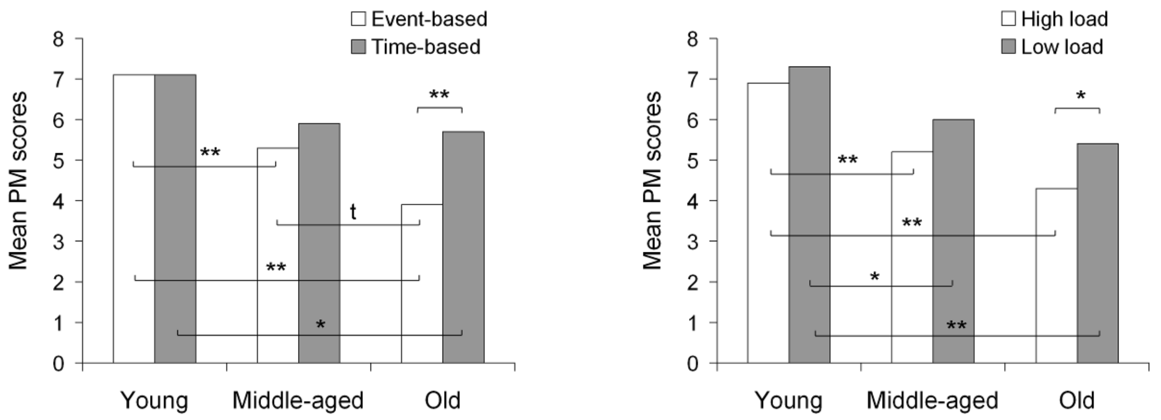
Event-based
Time-based
Mean PM scores
8
7
6
5
4
3
2
1
0
**
t
**
*
**
Young
Middle-aged
Old
High load
Low load
Mean PM scores
8
7
6
5
4
3
2
1
0
**
**
*
**
*
Young
Middle-aged
Old

Figure 3

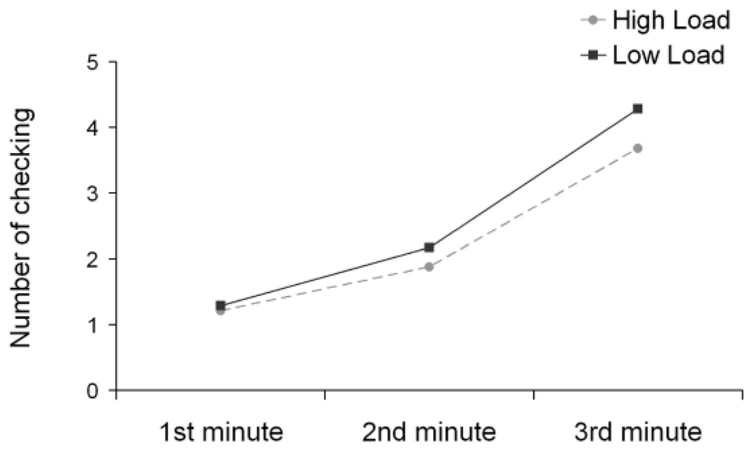
High Load
Low Load
Number of checking
0
1
2
3
4
5
1st minute
2nd minute
3rd minute

Figure 4

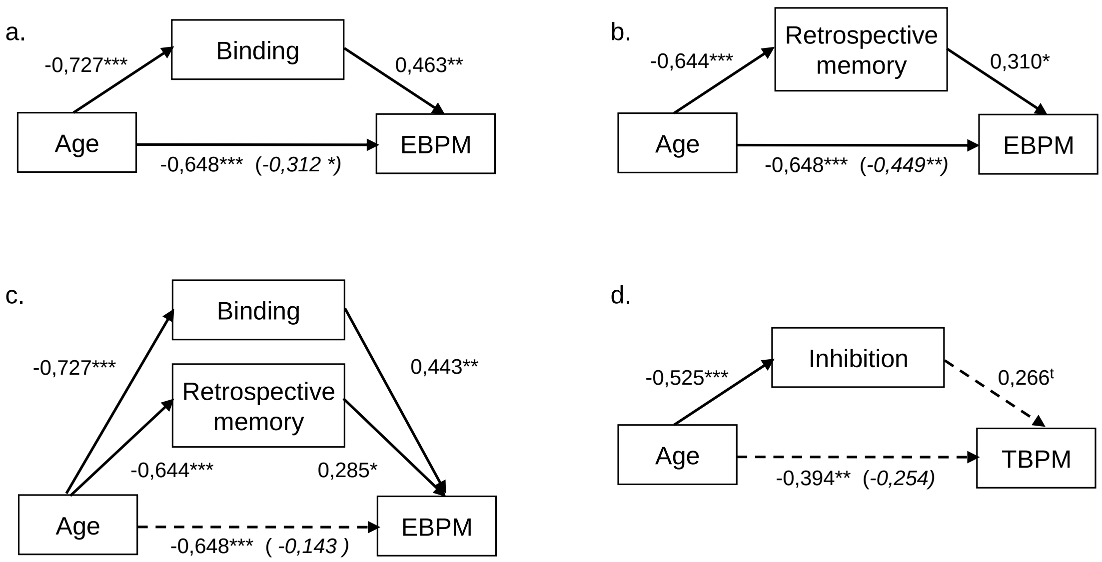
a.
Binding
-0,727***
0,463**
Age
EBPM
-0,648*** (-0,312 *)
b.
Retrospective memory
-0,644***
0,310*
Age
EBPM
-0,648*** (-0,449**)
c.
Binding
-0,727***
0,443**
Retrospective memory
-0,644***
0,285*
Age
EBPM
-0,648*** (-0,143)
d.
Inhibition
-0,525***
0,266t
Age
TBPM
-0,394** (-0,254)

Table 1. Population

	Young group	Middle-aged group	Older group
Number	29	20	23
Women/men	14/15	13/7	13/10
Age: mean ± SD	24.3 ± 4.5	51 ± 7	68.2 ± 6.7
(age range)	(18 - 35)	(40 - 59)	(60 - 84)
Educational background: mean ± SD	13.8 ± 1.8	11.5 ± 3.8	11.7 ± 2.7
(educational range)	(12 - 20)	(8 - 20)	(8 - 17)
Vocabulary score (Mill Hill/44)	32.3 ± 4.1	33.5 ± 5.5	36.4 ± 4.8

SD: standard deviation

Table 2. Complementary cognitive tasks scores for young, middle-aged and older groups.

	Young group	Middle-aged group	Older group
Executive Functions			
Shifting (in ms)	383 ± 241	489 ± 411	537 ± 337
Inhibition (/50)	26.69 ± 5.56 [a]	24.00 ± 5.38 [a’]	20.22 ± 5.20 [b’c]
Updating (/16)	10.10 ± 3.69 [a]	8.25 ± 3.14	6.87 ± 2.90 [c]
Processing Speed	63.71 ± 18.44 [a]	74.06 ± 13.60	63.71 ± 18.44 [c]
Sustained Attention	0.81 ± 0.14	0.86 ± 0.11	0.81 ± 0.14
Binding in Working Memory	0.92 ± 0.08 [ab]	0.82 ± 0.13 [ac]	0.67 ± 0.17 [bc]
Retrospective Episodic Memory (/32)	19.43 ± 2.06 [ab]	16.25 ± 2.70 [c]	14.00 ± 4.01 [c]
PRMQ			
Prospective failures (/40)	19.62 ± 4.39	17.10 ± 4.08	17.13 ± 4.50
Retrospective failures (/40)	16.24 ± 3.33	16.10 ± 4.63	17.17 ± 5.12

Note: [a] differed significantly from older group; [b] differed significantly from middle-aged group; [c] differed significantly from younger group; [a’] [b’] and [c’] express a trend for the same contrasts ($p < 0.07$). ANOVAs on 52 subjects showed the same pattern of results, except that effect of age on updating was marginal, $F(1, 49) = 2.85$; $MSE = 11.45$; $p < 0.07$.

Table 3. Correlations between complementary cognitive tasks and PM for the whole sample.

	EBPM	TBPM	High Load	Low Load
Executive Functions				
Shifting	-0.32 t	0.12	-0.20	-0.06
Inhibition	0.45**	0.36*	0.49**	0.44**
Updating	0.26	0.15	0.32t	0.14
Processing Speed	0.43**	0.35*	0.48**	0.42**
Sustained Attention	0.26	0.06	0.17	0.23
Binding in Working Memory	0.65**	0.30	0.56**	0.57**
Retrospective Episodic Memory	0.60**	0.11	0.49**	0.41*
Time Monitoring		0.29		
PRMQ				
Prospective failures	0.22	-0.11	0.12	0.04
Retrospective failures	-0.10	-0.20	-0.12	-0.21

Note: t: trend; * $p<0.05$; ** $p<0.01$. When correlations were assessed on 52 subjects, correlations of processing speed became no significant with TBPM and low load condition ($r = 0.24$, ns; and $r = 0.35$, ns; respectively) and marginal with EBPM ($r = 0.41$; $p < 0.10$). Moreover, correlation between TBPM and inhibition became marginal ($r = 0.40$; $p < 0.10$) as well as the low load condition and retrospective memory one ($r = 0.41$; $p < 0.10$). We assumed that these weaker effects were due to the reduced number of subjects, resulting in less statistical power.

Table 4. Forward stepwise regression on PM scores with complementary cognitive tasks and age for the whole sample.

	R^2	Beta	F	*p*
EBPM				
Model 1				
Step 1				
Binding	0.48	0.69	45.27	< *0.001*
Step 2				
Binding	0.56	0.52	22.62	< *0.001*
Retrospective episodic memory		0.34	9.57	*0.003*
Model 2				
Step 1				
Age	0.42	-0.67	56.31	< *0.001*
Step 2				
Age	0.52	-0.31	4.70	*0.035*
Binding		0.46	10.34	*0.002*
Step 3				
Age	0.57	-0.14	0.84	*0.370*
Binding		0.44	10.26	*0.002*
Retrospective episodic memory		0.29	5.26	*0.03*
TBPM				
Model 1				
Inhibition	0.16	0.40	9.50	*0.003*
Model 2				
Age	0.16	-0.39	9.18	*0.004*

High Load Condition				
Age	0.43	-0.65	37.30	< *0.001*
Low Load Condition				
Age	0.33	-0.58	24.92	< *0.001*

Note: Model 1 refers to simple forward stepwise regression and Model 2 represents forward stepwise regressions where age is forced in the model.