Effects of aging and working memory demands on prospective memory

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Abstract

The current study used event-related brain potentials (ERPs) to examine the effects of aging, increasing the working memory demands of the ongoing activity, and a prospective memory load on the neural correlates of prospective remembering and target recognition. The behavioral data revealed that the success of prospective memory was sensitive to working memory load in younger, but not older, adults and that a prospective memory load had a greater effect on the performance of older adults than that of younger adults. The ERP data revealed age-related differences in the neural correlates of the detection of prospective cues, post-retrieval processes that support prospective memory, and target recognition. Our results support the hypothesis that there are age-related differences in the ability to recruit preparatory attentional processes that underlie prospective memory, and demonstrate that younger and older adults may recruit somewhat different neural generators to support prospective memory and working memory.

Descriptors: ERPs, Aging, Prospective memory, Working memory, Partial Least Squares analysis

Over the course of an average day we are frequently required to remember to do things in the future. In some instances, information related to realizing an intention may be actively maintained for several seconds until it is appropriate to perform an action. For example, when placing a call to a restaurant for a reservation it may be necessary to remember the number while locating a phone. This type of memory maintenance is thought to be supported by short-term or working memory (Baddeley, 1986; Cowan, 1995). In other instances, it may be necessary to maintain information related to an intention for a longer period of time while one is engaged in a variety of ongoing activities. For example, one might intend to phone the restaurant for a reservation following the completion of a meeting where it is likely that the ongoing conversation precludes the ability to actively rehearse the intention to place the call. This type of memory maintenance is thought to be supported by prospective memory (Ellis, 1996; Meacham & Leimen, 1975).

In the laboratory, working memory is commonly studied by having individuals actively maintain lists of stimuli (e.g., words) for several seconds while also performing some additional cognitive operations (Baddeley, 1986); in contrast, prospective memory is commonly studied by having individuals perform some reasonably engaging task (e.g., judging the pleasantness of words) while also detecting prospective memory cues (e.g., a specific word or class of words) that are presented over the course

of task performance (McDaniel & Einstein, 2000). The engaging nature of the ongoing activity in a prospective memory task is typically thought to preclude maintenance of the prospective memory cues in working memory (Marsh & Hicks, 1998). Evidence from behavioral studies indicates that the efficiency of both of these forms of memory maintenance tends to decline in later adulthood (Henry, MacLeod, Phillips, & Crawford, 2004; Zacks, Hasher, & Li, 2000) and that age-related differences in prospective memory may interact with the working memory demands imposed by the ongoing component of the task (Kidder, Park, Hertzog, & Morrell, 1997; Logie, Maylor, Della Sala, & Smith, 2004). In light of this evidence, the present study used event-related brain potentials (ERPs) to examine the degree to which the effects of aging on the neural correlates of prospective memory were sensitive to the working memory demands of the ongoing activity.

Preparatory Attention Processes and Memory Processes Theory

The preparatory processes and memory processes theory of prospective memory (Smith, 2003; Smith & Bayen, 2004a) provides a conceptual framework within which to explore the relationship between the effects of aging, the working memory demands of the ongoing activity, and a prospective memory load. In this theory successful prospective memory is thought to be supported by two types of processes. Preparatory attentional processes are thought to facilitate the recognition of prospective cues as stimuli that requires a prospective response and retrospective memory processes are thought to support the retrieval from memory and realization of an intention once a cue is recognized. The engagement of preparatory attentional processes requires the allocation of working memory capacity that results in a reduction in

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capacity that is available for performance of the ongoing activity (Smith, 2003). Evidence for the engagement of preparatory attentional processes is revealed by the prospective interference effect (Marsh, Hicks, Cook, Hansen, & Pollos, 2003; Smith, 2003) that reflects a slowing of response time for ongoing activity trials when a prospective memory component is added to the task.

Based on the preparatory processes and memory processes theory, age-related differences in prospective memory are thought to result from a decline in the efficiency of preparatory attentional processes in later adulthood (Smith & Bayen, 2004b). In support of this idea, failures to detect prospective memory cues are known to contribute to age-related declines in prospective memory (West & Craik, 2001). Some work directly related to possible interactions between the effects of aging and the allocation of working memory capacity in support of prospective memory indicates that age-related differences in prospective memory increase as the working memory or attentional demands of the ongoing activity rise (Kidder et al., 1997; Logie et al., 2004). In contrast, work by Einstein and colleagues demonstrates that the effects of aging and the attentional demands of the ongoing activity on prospective memory can be independent in some contexts (Einstein, McDaniel, Smith, & Shaw, 1998; Einstein, Smith, McDaniel, & Shaw, 1997). The locus of this discrepancy probably lies in the demands of the secondary tasks that were used across studies, as it is known that taxing the central executive of working memory results in a significant reduction in the success of prospective memory, whereas taxing the slave systems of working memory has relatively little effect on the success of prospective memory (Marsh & Hicks, 1998).

ERPs, Prospective Memory, and Aging

The presentation of a prospective memory cue that elicits a prospective response is consistently associated with two modulations of the ERPs (i.e., N300 and prospective positivity; West, Herndon, & Crewdon, 2001). The N300 reflects a phasic negativity over the occipital-parietal region between 300 and 400 ms after the onset of a prospective memory cue. The amplitude of the N300 is greater for prospective cue hits than for prospective cue misses, indicating that it is associated with the detection of prospective cues (West & Ross-Munroe, 2002). Supporting the idea that preparatory attentional processes facilitate the detection of prospective memory cues (Smith, 2003), some data indicate that the amplitude of the N300 is modulated by the working memory demands of the ongoing activity in younger adults (West, Bowry, & Krompinger, in press). The prospective positivity reflects a sustained modulation over the parietal region between 500 ms and 1000 ms to 1200 ms after onset of the prospective cue (West et al., 2001) that is limited to prospective hits (West & Krompinger, 2005). Initial work led to the suggestion that the prospective positivity was associated with the retrieval of an intention from memory (West & Ross-Munroe, 2002). More recent work comparing the ERP correlates of recognition memory and prospective memory are not, however, consistent with this interpretation. For instance, West and Krompinger (2005) demonstrated that the prospective positivity could be distinguished from the parietal old-new effect that is commonly associated with the recognition of an old item within the literature on recognition memory (Mecklinger, 2000; Rugg, 1995).

The effects of aging on the N300 and prospective positivity have been examined in two studies. In both of these the amplitude of the N300 was attenuated in older adults relative to younger adults, particularly over the right hemisphere (West &

Covell, 2001; West, Herndon, & Covell, 2003). This finding led to the proposal that age-related differences in prospective memory result from a decline in the functional integrity of a neural system that supports the detection of prospective memory cues (West, 2005). The effect of aging on the prospective positivity has been somewhat mixed in previous studies. West and Covell (2001) observed that the amplitude of the prospective positivity was attenuated in older adults relative to younger adults in a study using perceptually salient prospective memory cues. Data from a more recent study (West et al., 2003), however, demonstrate that the effect of aging on the prospective positivity observed by West and Covell (2001) may have resulted from a confounding of the prospective positivity and the P3 component that is known to be highly sensitive to the aging process (Friedman, Kazmerski, & Fabiani, 1997). West et al. (2003) used prospective cues that were not expected to elicit a strong P3 component and there were no age-related differences in the amplitude of the prospective positivity. Given this finding, it appears that aging may have relatively little effect on the amplitude of the prospective positivity.

The neural basis of the prospective interference effect has been explored in studies using positron emission tomography (Burgess, Quayle, & Frith, 2001) and ERPs (West et al., in press) methodologies. The study using ERPs examined the effect of a prospective memory load on the amplitude of the P3 component elicited by target stimuli in the *N*-back task (West et al., in press). We predicted that the addition of a prospective memory load would lead to a reduction in the amplitude of the target P3 based on the assumption of preparatory attentional processes and memory processes theory that the recruitment of preparatory attentional processes consume working memory capacity (Smith, 2003) and the idea that the amplitude of the P3 component provides an index of the allocation of attentional resources that support target processing (Kok, 1997; Strayer & Kramer, 1990). This prediction was not supported by the data. The addition of a prospective memory load had no discernable effect on the amplitude of the P3 elicited by target stimuli and instead was associated with a sustained modulation over the occipital-parietal and anterior frontal regions that persisted over most of the analyzed epoch.

The Current Study

The current study was designed to examine the effects of aging and the working memory demands of the ongoing activity on the ERP correlates of prospective memory and the effects of aging on the ERP correlates of the prospective interference effect. As a secondary question we also examine the effects of aging on the ERP correlates of target recognition for stimuli held in working memory. In the study, younger and older adults performed a *N*-back working memory task where memory load was one or two items. This task allowed us to vary working memory load while holding other aspects of stimulus processing constant, in contrast to studies where the attentional demands have been modulated by the addition of a secondary task (Einstein et al., 1997; Logie et al., 2004). For half of the blocks individuals performed only the *N*-back task, for the other blocks a prospective component was added to the *N*-back task. If preparatory attentional processes support the detection of prospective cues, we expected the amplitude of the N300 to be modulated by *N*-back load in the younger adults (West et al., in press). Given evidence that aging is associated with a reduction in working memory capacity or attentional resources (Craik & Byrd, 1982), we expected that aging would be associated with a reduced ability

to recruit preparatory attentional processes in order to support the detection of prospective memory cues (Smith & Bayen, 2004b; West & Craik, 2001). Therefore, *N*-back load was expected to have little effect on the amplitude of the N300 in older adults. In contrast to the N300, aging and the working memory demands of the ongoing activity were not expected to influence the amplitude of the prospective positivity (West et al., 2003, in press). If the ERP correlates of the prospective interference effect reflect the allocation of preparatory attentional processes and aging disrupts preparatory attentional processes (Smith & Bayen, 2004b), we expected the amplitude of modulations of the ERPs related to this effect to be attenuated in older adults. Finally, the ERP correlates of *N*-back target recognition were expected to be sensitive to aging, given extensive literature demonstrating age-related declines in working memory (Zacks et al., 2000).

Given the potential for component overlap in the ERP data and the possibility that younger and older adults may recruit different neural generators in order to support task performance, Partial Least Squares analysis (PLS; Wold, 1975) was used to examine the relationship between age, ERP amplitude, and task design. As an example of component overlap, the time course and topography of the N2 elicited by target stimuli held in working memory and the N300 elicited by prospective memory cues may be similar; however, these two components should be differentially sensitive to task conditions associated with working memory and prospective memory (West & Wymbs, 2004). Within the context of aging, evidence from the functional neuroimaging literature indicates that aging is associated with both differences in the magnitude of activation within a given region and differences in the neural structures that are recruited by younger and older adults during task performance (Cabeza, 2002).

PLS analysis is a multivariate data analytic technique that allows one to identify spatiotemporal relationships between neural activity and experimental design (Lobaugh, West, & McIntosh, 2001; McIntosh, Bookstein, Haxby, & Grady, 1996). PLS analysis bears some resemblance to principal components analysis (PCA) in that it uses singular value decomposition (SVD) to identify latent variables that are spatially and temporally confounded in manifest ERP waveforms (Dien & Frishkoff, 2004). The primary difference between PLS analysis and PCA is that PLS analysis uses a constrained covariance matrix that, in the current application, is limited to task-related variance (i.e., differences between task conditions) in the ERP data set. The SVD yields three pieces of information that are used to interpret the relationship between ERP amplitude and task design: singular values, design scores, and electrode saliences. The singular values are similar to Eigenvalues and are used to determine the proportion of the covariance that is attributable to each latent variable. The design scores represent orthogonal contrasts between task conditions and can reflect either main effects or interactions. The design scores provide an assessment of the expression of a given latent variable across the various task conditions or groups. For instance, a main effect of age on a latent variable would reflect differences in the sizes of the design scores between younger and older adults that are similar across task conditions. In contrast, an age by condition interaction would reflect differences in the pattern of design scores between younger and older adults across task conditions. The electrode saliences represent the temporal and spatial expression of the latent variables across the scalp and are similar to component loading in PCA. Because

the covariance matrix for the PLS analysis is limited to task-related variance, the electrode saliences express modulations of ERP components that differ across task conditions or groups. For instance, an enhancement of the P3 component in the 1-back condition relative to the 2-back condition for target stimuli could be expected to reflect a departure of the electrode saliences from zero over the parietal region between 400 and 600 ms after stimulus onset (West et al., in press).

One advantage of the current implementation of PLS analysis is the combination of latent variable analysis with permutation tests and bootstrap resampling techniques that provide an integrated omnibus test of the significance of each latent variable (using a permutation test) and a local assessment of the expression of each latent variable over the full spatial and temporal distribution of the ERP data set (using bootstrap resampling). As a general comparison to ANOVA, the permutation test results are conceptually similar to the *F* ratio that provides an omnibus test of differences between conditions reflecting main effects and interactions. Because not all time points will contribute equally to significant latent variables, bootstrap resampling serves to identify time points that reliably contribute to a given latent variable. The results of the bootstrap analysis are conceptually similar to performing *t* tests at individual points across time and space.

Method

Participants

Forty individuals participated in the study. Eighteen younger adults (range 18–21 years) and 18 older adults (range 66–93 years) provided complete data for the study. Data for 2 individuals in each age group were lost due to excessive ocular and movement artifacts in the EEG. There were 15 right-handed individuals in each group. The younger adult group included 11 women and the older adult group included 7 women. The groups did not differ on a self-reported index of satisfaction with their health status, the Geriatric Depression Scale, or the information subtest of the WAIS (Table 1). The older adults had completed more years of formal education than the younger adults and the younger adults completed more items on the digit symbol substitution test than the older adults.

Table 1. Demographic Data for Younger and Older Adults with *t* Test for Group Differences

	Younger	Older	<i>t</i> (34)
Age			
<i>M</i>	19.78	76.00	
<i>SD</i>	0.81	5.80	
Health			
<i>M</i>	1.28	1.44	– 0.92
<i>SD</i>	0.57	0.51	
Geriatric Depression Scale			
<i>M</i>	1.22	1.61	– 0.68
<i>SD</i>	1.80	1.65	
Information			
<i>M</i>	23.83	25.39	– 1.25
<i>SD</i>	3.90	3.57	
Education			
<i>M</i>	14.17	16.61	– 3.00
<i>SD</i>	1.15	3.26	
Digit symbol			
<i>M</i>	76.06	46.50	9.34
<i>SD</i>	10.11	8.83	

Materials and Procedure

The stimuli were 21 consonants from the English alphabet presented in the colors red, blue, green, or yellow. The stimuli were displayed in uppercase letters, measured 15 mm × 10 mm, and occupied 1.70° × 1.15° of visual angle when viewed from 50 cm. Each stimulus was displayed for 500 ms followed by a blank screen for 1500 ms and then the letter for the next trial was presented.

The task design was a 2 (prospective load: no prospective memory, prospective memory) × 2 (*N*-back: 1-back, 2-back) factorial with five blocks of trials for each condition (one practice block of 20 trials and four test blocks of 100 trials each). The prospective load and no prospective load conditions were counterbalanced across participants. All individuals performed the 1-back blocks followed by the 2-back blocks within the prospective load conditions. This procedure was adopted because in pilot work we discovered that some older adults experienced significant difficulty when starting the task in the prospective load 2-back condition and that this difficulty was reduced when the 1-back blocks were completed first. Each block included three types of trials (i.e., targets 30%, nontargets 60%, and prospective cues 10%). In the no prospective memory condition individuals made *N*-back judgments for the letters and were told that letter color was irrelevant; in the prospective memory condition individuals made *N*-back judgments for most letters and prospective responses for letters that were presented in a color specified at the beginning of each block. Each color was used as a prospective memory cue once in the 1-back condition and once in the 2-back condition. For the no prospective memory condition individuals were instructed to press the Y key with the right index finger if the current letter matched the *N*-back letter and the N key with the right middle finger if the current letter was not a *N*-back match. The Y and N keys were relocated on the keyboard so that they were beside one another. For the prospective memory condition individuals were instructed to make *N*-back judgments for all letters other than those presented in the prospective color. Individuals were also instructed that when a letter was presented in the prospective color they should respond by pressing the V key with the left index finger. A display indicating the prospective color for a given block was presented for 2 s at the beginning of each block (e.g., prospective memory color = RED) followed by a blank screen for 2 s and then the first letter. For the 1-back condition, target trials represented the second letter of a repetition in the series of letters (e.g., S P P); for the 2-back condition, target trials represented the second letter of a repetition following one intervening letter (e.g., L Q L). For the 1-back and 2-back conditions nontarget trials were those trials that did not represent 1-back or 2-back repetitions or prospective cues.

Electrophysiological Recording and Analysis

The EEG (bandpass 0.01–100 Hz, 34 dB/Oct, digitized at 256 Hz, gain 2500, 12 bit A/D conversion) was recorded from an array of 45 tin electrodes sewn into an Electro-cap or affixed to the skin with an adhesive patch (Fpz, Fz, Pz, Oz, Iz, Fp1, Fp2, Af3, Af4, F3, F4, F7, F8, F9, F10, Fc1, Fc2, Fc5, Fc6, Ft9, Ft10, C3, C4, T7, T8, Cp1, Cp2, Cp5, Cp6, P3, P4, P7, P8, Po3, Po4, O1, O2, Po9, Po10, left mastoid M1, right mastoid M2, left lateral ocular Lo1, right lateral ocular Lo2, left inferior ocular Io1, right inferior ocular Io2). Vertical and horizontal eye movements were recorded from electrodes placed below and beside the eyes. During recording all electrodes were referenced to electrode Cz; for data analysis, they were re-referenced to an average reference, electrode Cz was reinstated, and a 20-Hz lowpass filter was applied.

ERP analysis epochs were extracted off-line and included –200 ms of prestimulus activity and 1200 ms of poststimulus activity. ERPs were averaged for correct trials for 1-back target (young $M = 58.00$, $SD = 11.60$; old $M = 54.78$, $SD = 14.53$) and nontarget trials (young $M = 177.33$, $SD = 39.45$; old $M = 177.83$, $SD = 30.82$) and 2-back target (young $M = 50.28$, $SD = 9.05$; old $M = 46.33$, $SD = 14.13$) and nontarget trials (young $M = 167.94$, $SD = 30.78$; old $M = 176.72$, $SD = 45.33$) in the no prospective condition and for 1-back target (young $M = 57.94$, $SD = 9.97$; old $M = 47.17$, $SD = 12.12$), nontarget (young $M = 178.17$, $SD = 27.60$; old $M = 161.72$, $SD = 31.87$), and prospective cue (young $M = 23.67$, $SD = 6.34$; old $M = 22.06$, $SD = 7.74$) trials and 2-back target (young $M = 41.33$, $SD = 16.58$; old $M = 38.17$, $SD = 13.18$), nontarget (young $M = 161.22$, $SD = 47.39$; old $M = 173.50$, $SD = 38.83$), and prospective cue (young $M = 18.44$, $SD = 7.28$; old $M = 23.61$, $SD = 8.08$) trials in the prospective memory condition. Ocular artifacts associated with blinks were corrected using a covariance technique that simultaneously modeled artifact and artifact-free EEG (SourceSignal Imaging, San Diego, <http://www.sourcesignal.com>). Trials contaminated by other artifacts (peak-to-peak deflections over 100 μ V) were rejected before averaging.

Partial Least Squares analysis. The basic ERP data matrix for the PLS analyses contained subjects and conditions in the rows and ERP amplitudes for all time points and channels, except for the four ocular electrodes, in the columns (0–1200 ms, at each electrode). The input data matrix for the analyses was obtained by mean-centering the columns of the ERP data matrix with respect to the grand mean. The averages within task were thus expressed as deviations around zero. SVD was then performed on these matrices to identify the structure of the latent variables. Three outputs were derived from the SVD that were used to interpret the relationships between ERP amplitude and task design. The first was a vector of singular values, which represents the unweighted magnitude of each latent variable and can be used to calculate the proportion of the cross-block covariance matrix (i.e., the percentage of task-related variance) attributable to each latent variable. The second and third outputs contain the structure of the latent variables and are orthogonal pairs of vectors (salience). One vector defines the design saliences or design scores representing contrasts between task conditions across the latent variables. The other vector represents the electrode saliences that characterize the temporal and spatial expression of the latent variable across the scalp. The significance of the latent variables singular values was determined using a permutation test (500 replications) that provides an exact probability of observing the singular value by chance (e.g., $p = .001$). The stability of the ERP saliences at each time point and location in space was established through bootstrap resampling (200 replications) that provides a standard error. The ratio of the salience to its bootstrapped standard error is approximately equal to a z score; therefore, bootstrap ratios greater than 2.5 can be taken to indicate stable saliences or points that differ from zero. Matlab code to perform the PLS analyses can be obtained at (<http://www.rotman-baycrest.on.ca:8080>).

Results

Behavioral Data

For all analyses the alpha level was set at $p < .05$. Data for target and nontarget trials were included in a set of 2 (group: young,

Table 2. Proportion Correct as a Function of Age, Prospective Memory Load, N-Back Load, and Trial

	Target	Nontarget	Prospective memory cue
Younger adults			
No prospective memory			
1-back			
<i>M</i>	0.78	0.91	—
<i>SD</i>	0.10	0.11	—
2-back			
<i>M</i>	0.69	0.87	—
<i>SD</i>	0.07	0.20	—
Prospective memory			
1-back			
<i>M</i>	0.76	0.91	0.69
<i>SD</i>	0.10	0.08	0.18
2-back			
<i>M</i>	0.60	0.89	0.59
<i>SD</i>	0.16	0.06	0.22
Older adults			
No prospective memory			
1-back			
<i>M</i>	0.72	0.89	—
<i>SD</i>	0.11	0.06	—
2-back			
<i>M</i>	0.58	0.84	—
<i>SD</i>	0.14	0.14	—
Prospective memory			
1-back			
<i>M</i>	0.62	0.81	0.66
<i>SD</i>	0.12	0.09	0.18
2-back			
<i>M</i>	0.46	0.80	0.65
<i>SD</i>	0.16	0.17	0.21

Table 3. Mean Response Time as a Function of Age, Prospective Memory Load, N-Back Load, and Trial

	Target	Nontarget	Prospective memory cue
Younger adults			
No prospective memory			
1-back			
<i>M</i>	572.78	546	—
<i>SD</i>	84	89	—
2-back			
<i>M</i>	643	623	—
<i>SD</i>	144	149	—
Prospective memory			
1-back			
<i>M</i>	683	673	726
<i>SD</i>	118	132	115
2-back			
<i>M</i>	736	738	770
<i>SD</i>	160	198	141
Older adults			
No prospective memory			
1-back			
<i>M</i>	695	658	—
<i>SD</i>	123	98	—
2-back			
<i>M</i>	847	786	—
<i>SD</i>	178	137	—
Prospective memory			
1-back			
<i>M</i>	902	838	863
<i>SD</i>	147	145	139
2-back			
<i>M</i>	953	892	900
<i>SD</i>	187	148	189

old) $\times$ 2 (prospective load: no prospective memory, prospective memory) $\times$ 2 (*N*-back load: 1-back, 2-back) $\times$ 2 (trial: target, nontarget) ANOVAs to examine the effects of aging, prospective memory load, and working memory load on performance of the *N*-back component of the task. The analysis of the accuracy data revealed that each of the main effects was significant (Table 2); older adults were less accurate than younger adults, $F(1,34) = 12.48$, $MSE = 0.042$, $\eta^2 = .27$, accuracy was higher in the no prospective memory condition than the prospective condition, $F(1,34) = 15.93$, $MSE = 0.013$, $\eta^2 = .32$, in the 1-back condition than in the 2-back condition, $F(1,34) = 29.37$, $MSE = 0.017$, $\eta^2 = .46$, and for nontarget trials than for target trials, $M = 0.65$, $F(1,34) = 281.63$, $MSE = 0.012$, $\eta^2 = .89$. Four of the two-way interactions were significant. The effect of prospective memory load was greater for older adults, $M = .09$, than for younger adults, $M = .02$, $F(1,34) = 4.88$, $MSE = 0.034$, $\eta^2 = .13$, and the effect of trial was greater for older adults than for younger adults, $F(1,34) = 4.48$, $MSE = 0.012$, $\eta^2 = .12$. Also the effect of prospective memory load was greater for target trials than for nontarget trials, $F(1,34) = 10.35$, $MSE = 0.006$, $\eta^2 = .23$; the effect of *N*-back load was greater for target than nontarget trials, $F(1,34) = 23.26$, $MSE = 0.01$, $\eta^2 = .41$.

The analysis of mean response time also revealed that each of the main effects was significant (Table 3). Older adults were slower than younger adults, $F(1,34) = 18.13$, $MSE = 114379.66$, $\eta^2 = .35$, response time was slower in the prospective memory condition than the no prospective memory condition, $F(1,34) = 88.83$, $MSE = 13863.95$, $\eta^2 = .72$, response time was slower in the 2-back condition than the 1-back condition, $F(1,34) = 30.12$, $MSE = 15803.15$, $\eta^2 = .47$, and for nontarget

trials than for target trials $F(1,34) = 11.93$, $MSE = 7225.54$, $\eta^2 = .26$. The prospective memory load by *N*-back load interaction was significant, $F(1,34) = 9.79$, $MSE = 4856.20$, $\eta^2 = .22$, and was qualified by a significant Age $\times$ Prospective Memory Load $\times$ *N*-Back Load interaction, $F(1,34) = 4.86$, $MSE = 4856.20$, $\eta^2 = .13$, that remained marginally significant when the data were log transformed to adjust for the effect of age-related slowing, $F(1,34) = 3.94$, $p = .055$, $MSE = 0.009$, $\eta^2 = .10$. This interaction reflected the tendency for the prospective interference effect to be greater for older adults, $M = 194$ ms, than for younger adults, $M = 119$ ms, in the 1-back condition and to be similar for older adults, $M = 105$ ms, and younger adults, $M = 104$ ms, in the 2-back condition.

Data for prospective cue trials were included in a set of 2 (age: young, older) $\times$ 2 (*N*-back load: 1-back, 2-back) ANOVAs to examine the effect of aging and *N*-back load on prospective memory (Table 2). An analysis of prospective cue hits failed to reveal any significant effects (age $F < 1$, *N*-back load, $F[1,34] = 2.80$, $MSE = 0.017$, $\eta^2 = .08$). These findings were surprising based on evidence indicating that *N*-back load can modulate the efficiency of prospective memory (West et al., in press). Given this, separate *t* tests were performed for younger and older adults comparing accuracy for prospective cue trials in the 1-back and 2-back conditions. For younger adults the effect of *N*-back load was significant, $t(17) = 3.24$, with accuracy being lower for 2-back prospective cue trials than for 1-back prospective cue trials; for older adults the effect of *N*-back load was not significant, $t(17) = 0.08$, and there was little difference in accuracy for 1-back and 2-back prospective cue trials.

In an effort to gain a clearer understanding of the reasons for the failure to find age-related difference in the accuracy of prospective memory, we examined false alarm rates for prospective responses in younger and older adults. Prospective false alarms were slightly more frequent in older adults, $M = 0.028$, than in younger adults, $M = 0.007$, $F(1,34) = 6.64$, $MSE = 0.001$, $\eta^2 = .16$, revealing a small age-related difference in the likelihood of identifying target and nontarget stimuli as prospective cues. Given the age-related difference in prospective cue false alarms, measures of discrimination (d') and bias (c) were calculated for the prospective memory data. The effect of age was not significant for either of these measures, $F < 1$, indicating that levels of discrimination (younger = 1.88, older = 1.90) and bias (younger = -0.07 , older = 0.00) were similar in the younger and older adults. These data indicate that the frequency of prospective responses was similar in younger and older adults and that older adults were no more biased than younger adults to accept targets and nontargets as prospective cues. Analysis of the mean response time data revealed that prospective responses were slower for older adults than for younger adults (Table 3),

$F(1,34) = 9.56$, $MSE = 3390.26$, $\eta^2 = .22$, and that this effect did not interact with N -back load, $F < 1$.

Electrophysiological Data

Two sets of PLS analyses were performed on the ERP data. One analysis examined the effects of working memory load and one analysis examined the effects of prospective memory load. For these analyses the data for younger and older adults were first analyzed separately, followed by a combined analysis including the data for both groups. This approach allowed us to examine the structure of the ERPs in each group and then to consider similarities in and differences between the groups.

Working Memory Demands

Figures 1 and 2 portray the grand averaged ERPs for younger and older adults in the 1-back and 2-back conditions at select electrodes.

Younger adults. The analysis of the younger adults' data revealed three significant latent variables ($p = .000$, $p = .006$, $p = .032$) that accounted for 55.43%, 21.47%, and 15.16% of

Figure 1. Grand average ERPs at electrodes Fz, C3, Pz, and Po10 for younger and older adults and nontarget, target, and prospective cue trials. The modulation of the N2 and N300 by targets and prospective cues are marked by the (a) and (b), respectively; the modulation of the P3 and prospective positivity are marked by the (c) and (d), respectively. The tall bar represents stimulus onset and the short bars represent 400-ms increments.

Figure 2. Grand average ERPs at electrodes Po9 and Po10 for younger and older adults demonstrating the effect of *N*-back load on the N2 and N300 for target and prospective memory cue trials, respectively. The tall bar represents stimulus onset and the short bars represent 400-ms increments.

the crossblock covariance. The first latent variable captured the neural correlates of prospective memory. The design scores were negative for prospective cue trials and positive for nontarget trials and 2-back target trials (Figure 3A). The electrode saliences revealed sustained modulations over the occipital-parietal region (Po10) and parietal and central regions (Cp5 and Pz) that reflect the expression of the N300 and prospective positivity, respectively. The second latent variable captured the effect of *N*-back load on the neural correlates of target recognition. The design scores were negative for nontarget and prospective cue trials and positive for target trials, being larger for 1-back targets than for 2-back targets (Figure 3B). The electrode saliences revealed modulations of the N2 (Po10, Fz) and P3 (Pz). The third latent variable revealed a neural correlate of preparatory attention, capturing the effect of *N*-back load on the neural correlates of prospective memory. The design scores were positive for 1-back prospective cue trials and negative for 2-back prospective cues trials (Figure 3C). The electrode saliences expressed the N300 over the occipital-parietal region (Po10) and more sustained modulations over the frontal regions (Fz, F9). The findings related to the first and third latent variables are

consistent with predictions derived from the preparatory processes and memory processes theory of prospective memory, indicating that working memory load should influence the detection of prospective cues reflected in the amplitude of the N300 and have relatively little effect on post-retrieval processes that underlie prospective memory reflected in the amplitude of the prospective positivity.

Older adults. The analysis of the older adults' data revealed two significant latent variables ($p = .000$, $p = .004$) that accounted for 54.09% and 24.17% of the crossblock covariance. The first latent variable captured the neural correlates of prospective memory. The design scores were negative for prospective cue trials and positive for nontarget and target trials (Figure 3D). The electrode saliences reflected sustained modulations over the occipital-parietal (Po10) and frontal-central (Fz, Cp5) regions. The second latent variable captured the effect of *N*-back load on the neural correlates of target recognition. The design scores were positive for target trials, being greater for 1-back targets than 2-back targets and negative for nontarget trials (Figure 3E). The electrode saliences revealed an enhancement of the N2 over the occipital-parietal region (Po10) and a modulation of the P3 over the anterior frontal region (Af3). The third latent variable in this analysis was not significant ($p = .52$). This finding is consistent with the prediction that aging is associated with a decline in the ability to recruit preparatory attention in order to support prospective memory.

Combined analysis. The combined analysis revealed four significant latent variables ($p = .000$, $p = .000$, $p = .000$, $p = .004$) that accounted for 45.00%, 15.92%, 11.61%, and 10.88% of the crossblock covariance. The first latent variable captured the neural correlates of prospective memory and was more strongly expressed in younger adults than in older adults (Figure 4A). The design scores were negative for prospective cue trials and positive for target trials and were attenuated in the older adults. The electrode saliences reflected a sustained modulation over the occipital-parietal region (Po10) and a later modulation over the left central-parietal region (Cp5 and Pz), reflecting the prospective positivity. The second latent variable captured the effect of *N*-back load on the N2 and P3 elicited by target stimuli and was again more strongly expressed in younger adults than in older adults. The design scores were positive for target trials and negative for nontarget and prospective cue trials and were attenuated in older adults (Figure 4B). In the younger adults the design score was larger for 1-back targets than for 2-back targets. The electrode saliences expressed modulations of the N2 (Po10) and P3 (Pz) components and a central-parietal slow wave (Pz). The third latent variable captured the neural correlates of prospective remembering in the older adults (Figure 4C). In older adults the design scores were positive for prospective cue trials and negative for target trials; in contrast, in younger adults the design scores failed to reveal any systematic pattern of differences. The electrode saliences revealed a sustained modulation over the left frontal region (F3) and a modulation over the occipital region (Oz) between 500 and 800 ms. Together the pattern of design scores and electrode saliences revealed by the first and third latent variables lead to the suggestion that younger and older adults may recruit somewhat different neural generators to support prospective memory. The fourth latent variable revealed the neural correlates of preparatory attention in the younger adults (Figure 4D). In the younger adults the design scores were positive

Figure 3. Results of the group PLS analyses contrasting target, nontarget, and prospective cue trials in younger adults (left panel) and older adults (right panel). A: The first latent variable reflecting the neural correlates of prospective memory in the younger adults. B: The second latent variable reflecting the neural correlates of target recognition in the younger adults. C: The third latent variable reflecting neural correlates of preparatory attention in the younger adults. D: The first latent variable reflecting the neural correlates of prospective memory in the older adults. E: The second latent variable reflecting neural correlates of target recognition in older adults.

for 1-back prospective cue trials and negative for 2-back prospective cue trials; in contrast, for the older adults the design scores were near zero across all task conditions. This finding converges with the results of the group analyses in indicating that older adults may not be able to recruit preparatory attention to support prospective memory. The fourth latent variable represented an enhancement of the N300 over the right occipital-parietal (Po10) and frontal (Fz) regions and a more sustained left hemisphere modulation (Cp5).

Prospective Memory Demands

The grand averaged ERP data related to the prospective interference effect for younger and older adults are presented in Figure 5.

Younger adults. The analysis of the younger adults' data revealed three significant latent variables ($p = .000$, $p = .000$, $p = .016$) that accounted for 49.48%, 26.78%, and 10.68% of the crossblock covariance. The first latent variable appeared to capture the neural correlates of 1-back target recognition. The design scores were negative for target trials, being greater for 1-back than 2-back trials, and were positive for nontarget trials (Figure 6A). There was little effect of prospective memory load on the design scores for this latent variable. The electrode saliences for the first latent variable represented an enhancement of the N2 component over the occipital-parietal (Po10) and frontal (Fz) regions, an enhancement of the P3 over the parietal region (Pz), and a later slow wave over the parietal region (Pz). The second latent variable expressed a clear effect of

Figure 4. Results of the combined PLS analysis contrasting the ERPs elicited by target, nontarget, and prospective cue trials. A: The first latent variable reflecting the neural correlates of prospective memory that are more strongly expressed in the younger adults than in the older adults. B: The second latent variable reflecting the neural correlates of target recognition that was also more strongly expressed in the younger adults than in the older adults. C: The third latent variable reflecting the neural correlates of prospective memory in the older adults. D: The fourth latent variable reflecting the neural correlates of preparatory attention in the younger adults.

Figure 5. The grand average ERPs at electrodes Af3, Pz, Po9, and Po10 in younger and older adults for target and nontarget trials in the prospective load and no prospective load conditions. The modulation of the P3 by prospective memory load is marked by the (a) and the occipital-parietal sustained effect is marked by the (b). The tall bar represents stimulus onset and the short bars represent 400-ms increments.

prospective memory load. The design scores were negative for no prospective memory trials and positive for prospective memory trials (Figure 6B). The electrode saliences for this latent variable represented a modulation of the P3 over the parietal region (Pz) and a sustained modulation over the occipital-parietal (Iz) and frontal-polar (Fpz) regions. The expression of the P3 in the electrode saliences for the second latent variable supports the hypothesis that the addition of a prospective memory load consumes working memory capacity. The third latent variable captured the neural correlates of 2-back target recognition. The design scores were positive for 1-back trials and negative for 2-back trials, being greater for targets than for nontargets (Figure 6C). The electrode saliences for this latent variable reflected a modulation over the frontal region at around 200–500 ms (F3) and over the parietal and occipital regions (Po3) slightly later.

Older adults. The analysis of the older adults' data revealed two significant latent variables ($p = .000$, $p = .000$) and a third

that was marginally significant ($p = .07$) that accounted for 48.48%, 22.20%, and 11.91% of the crossblock covariance. The first latent variable captured the neural correlates of 1-back target recognition. The design scores were negative for 1-back target trials and positive for nontarget trials (Figure 6D). The design score for 1-back targets in the no prospective memory condition was also greater than that for 1-back targets in the prospective memory condition. This finding is consistent with the response accuracy data revealing an effect of prospective memory load on stimulus processing in the older adults. The electrode saliences revealed delayed and prolonged enhancements of the N2 (Po10) and P3 (Pz) over the occipital-parietal and parietal regions, respectively. The second latent variable expressed an effect of prospective memory load. The design scores were negative for the no prospective memory condition and positive for the prospective memory condition (Figure 6E). The electrode saliences for this latent variable represented a modulation over the central-parietal region (Cp1) between 400 and 800 ms that may reflect a delayed

Figure 6. Results of the group PLS analyses contrasting the ERPs elicited by target and nontarget trials in the prospective memory and no prospective memory conditions in younger (left panel) and older (right panel) adults. A: The first latent variable reflecting the neural correlates of 1-back target recognition in the younger adults. B: The second latent variable reflecting the neural correlates of the prospective interference effect in the younger adults. C: The third latent variable reflecting the neural correlates of 2-back target recognition in the younger adults. D: The first latent variable reflecting the neural correlates of 1-back target recognition in the older adults. E: The second latent variable reflecting the neural correlates of the prospective interference effect in the older adults. F: The third latent variable reflecting the neural correlates of 2-back target recognition in the older adults.

modulation of the P3 component in the older adults and a sustained modulation that was distributed over the left occipital-parietal (P7) and right frontal-central (Fc6) regions. The third latent variable captured the neural correlates of 2-back target recognition. The design scores were positive for 1-back trials and negative for 2-back target trials (Figure 6F). The electrode saliences for the third latent variable reflected a modulation over the central-parietal region (Cp1) at around 500 ms and sustained modulations over the left frontal and right frontal-temporal regions (F3 and T7).

Combined analysis. The combined analysis revealed five significant latent variables ($p = .000$, $p = .000$, $p = .000$, $p = .000$, $p = .04$) that accounted for 37.86%, 22.61%, 10.16%, 7.65%, and 5.19% of the crossblock covariance. The first latent variable reflected the neural correlates of 1-back target recognition and was more strongly expressed in the younger adults. The design scores were negative for target trials, being larger for 1-back trials than 2-back trials and positive for nontarget trials (Figure 7A). The electrode saliences represented an enhancement of the N2 over the occipital-parietal (Po10) and frontal (Fz) regions and a

Figure 7. Design scores and electrode saliences for the combined PLS analysis comparing the ERPs elicited in the no prospective memory and prospective memory conditions. A: The first latent variable reflecting the neural correlates of 1-back target recognition that are more strongly expressed in the younger adults. B: The second latent variable reflecting the neural correlates of the prospective interference effect in the younger adults. C: The third latent variable reflecting the neural correlates of 1-back target recognition in the older adults. D: The fourth latent variable reflecting the neural correlates of 2-back target recognition in the younger adults. E: The fifth latent variable that may reflect the neural correlates of the prospective interference effect in the older adults.

modulation of the P3 and slow wave over the parietal region (Pz). The second latent captured the effect of prospective memory load in the younger adults and did not reveal systematic differences in the design scores for older adults (Figure 7B). The design scores were negative for trials in the no prospective memory condition and positive for trials in the prospective memory condition in the younger adults. The electrode saliences represented an enhancement of the P3 over the parietal region (Pz) and a sustained modulation over the occipital-parietal (Iz) and frontal-polar (Fpz) regions. The third latent variable appeared to reflect the neural correlates of 1-back target recognition in the older adults (Figure 7C). In the older adults the design scores were negative for target trials, being greater in the 1-back condition than the 2-back condition, and were positive for nontarget trials; in the younger adults the design scores for this latent variable did not reveal any systematic differences. The electrode saliences revealed modulations of the N2 (Po10) and P3 (Cz and Pz), and a later sustained modulation over the parietal region (Pz). The findings related to the first and third latent variables are consistent with evidence indicating that the N2 and P3 are altered by aging (Friedman et al., 1997). The fourth latent variable captured the ERP correlates of 2-back target recognition in the younger adults (Figure 7D). In the younger adults the design scores were positive for 2-back trials and negative for 1-back trials; in the older adults the design scores did not reveal any systematic differences. The electrode saliences for the fourth latent variable reflected modulations over the left frontal (Af3) and parietal (Po3) regions and the right hemisphere extending from the lateral frontal region (F8). The fifth latent variable appeared to capture the ERP correlates of the prospective interference effect in the older adults (Figure 7E). For older adults the design scores were positive for the no prospective memory condition and negative for the prospective memory condition; in contrast, the pattern of design scores in the younger adults was not easily interpretable. The electrode saliences represented a modulation over the right frontal region (Af4), an enhancement of the P3 over the central region (Cz), and a sustained modulation over the right central region (C4). The pattern of design scores revealed in the second and fifth latent variables lead to the suggestion that younger and older adults may have recruited somewhat different neural generators in response to the increased processing demands associated with the addition of a prospective memory load to the task.

Discussion

The current study was designed to examine the effects of aging on the neural correlates of prospective memory within the context of the preparatory processes and memory processes theory of prospective memory. Based on this theory we predicted that aging would be associated with a decline in the ability to recruit preparatory attentional processes that facilitate the processing of prospective cues (Smith & Bayen, 2004b). The behavioral data were partially consistent with predictions derived from the preparatory processes and memory processes theory. The response accuracy data revealed an effect of *N*-back load on the frequency of prospective hits in younger adults, but not in older adults, and an effect of prospective memory load on the probability of a correct response for *N*-back trials that was greater for older adults than for younger adults. Together these findings may indicate that younger and older adults adopted somewhat different attentional allocation policies when faced with the concurrent

task demands of realizing delayed intentions and performing a demanding working memory task (Kliegel, Phillips, & Fischer, 2004). The slowing of response time from the no prospective memory condition to the prospective memory condition was greater for older adults than for younger adults in the 1-back condition and similar for younger adults and older adults in the 2-back condition. The reason for this difference is not readily apparent. It may arise from differences in the allocation of attentional resources by younger and older adults across the two conditions or differences in the processes that are recruited to support prospective memory as the working memory demands of the ongoing activity increase (McDaniel, Guynn, Einstein, & Breneiser, 2004). Further research seems warranted to investigate the factors contributing to age-related differences in the prospective interference effect.

The effects of increasing the working memory demands of the ongoing activity on the ERP correlates of prospective memory in younger adults were similar to those observed in previous research (West et al., in press). There was one latent variable that distinguished prospective cue trials from nontarget trials that was relatively insensitive to *N*-back load (Figure 3A) and one latent variable that distinguished prospective memory cue trials in the 1-back and 2-back conditions (Figure 3C). The first latent variable reflected a sustained modulation over the occipital-parietal region and the prospective positivity, whereas the third latent variable reflected a modulation of the N300. These findings are consistent with the idea that preparatory attentional processes facilitate the processing of prospective cues (Smith, 2003) and are complimented by the behavioral data revealing an effect of *N*-back load on the frequency of prospective cue hits in the younger adults.

The group analysis of the older adults' data revealed two interesting findings. The pattern of design scores for the first latent variable was quite similar to that observed in the analysis for the younger adults (Figure 3D); in contrast, the analysis for the older adults did not reveal a stable latent variable that reflected an effect of *N*-back load on the ERP correlates of prospective memory. The interaction between aging and *N*-back load on the ERP correlates of prospective memory can also be seen in the fourth latent variable from the combined analysis, where there was a clear effect of *N*-back load for the younger adults and no systematic effects in the older adults (Figure 4D). These findings support the prediction that aging is associated with a decline in the ability to recruit preparatory attentional processes that facilitate the processing of prospective memory cues (Smith & Bayen, 2004b) and is consistent with behavioral data demonstrating that failures of cue detection can contribute to age-related differences in prospective memory (West & Craik, 2001).

The combined analysis also revealed both similarities in and differences between younger and older adults for more sustained modulations of the ERPs associated with prospective remembering. The first latent variable revealed a similar pattern of design scores in younger and older adults that reflected a sustained occipital-parietal modulation and the prospective positivity, with the magnitude of the design scores being attenuated in the older adults (Figure 4A). This finding seems inconsistent with previous research demonstrating that the amplitude of the prospective positivity is similar in younger and older adults (West et al., 2003). The pattern of design scores revealed in the third latent variable from the combined analysis provides insight into this discrepancy. The third latent variable distinguished prospective

cue hits from *N*-back target hits and was more strongly expressed in the older adults than in the younger adults (Figure 4C). The distribution of the electrode saliences for the first and third latent variables over the parietal region was quite similar, but differed over the frontal region. This finding indicates that there may be only partial overlap in the neural generators that younger and older adults recruit in order to support the realization of delayed intentions in this task. Such an outcome would have been obscured in previous research, where the data analytic method used did not permit separation of distinct components that have partially overlapping topographies (West & Covell, 2001; West et al., 2003). The design scores associated with prospective cue trials for the third latent variable from the combined analysis appeared to be insensitive to *N*-back load. This finding parallels the failure to observe an effect of *N*-back load on the frequency of prospective hits in the older adults, and may indicate that the neural system recruited by older adults to support prospective memory is less sensitive to the effects of the working memory demands of the ongoing activity than that recruited by younger adults.

The group and combined analyses of the prospective interference effect revealed two distinct patterns of design scores. One that reflected a general effect of the presence or absence of a prospective memory load (Figures 6B,E; 7A,D) and one that reflected the effect of *N*-back load on the ERPs elicited by target and nontarget trials. The influence of aging on these patterns of neural activity is considered in turn. The second latent variable in the group analyses that reflected the effect of the prospective memory load revealed negative design scores for the no prospective memory condition and positive design scores for the prospective memory condition. This latent variable reflected a modulation of the P3 component over the parietal region and more sustained modulations over the occipital-parietal and frontal regions. The expression of the P3 in the latent variables revealing the prospective load effect supports the idea that the recruitment of preparatory attentional processes draws attentional resources away from stimulus processing in the ongoing activity (Smith, 2003; Smith & Bayen, 2004a), but is inconsistent with our previous research revealing little effect of prospective memory load on the amplitude of the P3 (West et al., in press). Variation in the effect of prospective memory load on the P3 between studies may reflect subtle differences in the attentional allocation policy that was adopted by individuals across the experiments or differences in working memory capacity between individuals in the two samples. Further research examining the influence of attentional allocation policy or individual differences in working memory capacity could resolve this ambiguity (Smith, 2003; Smith & Bayen, 2004a).

The magnitudes of the design scores for the latent variables expressing the effect of prospective memory load were similar for younger and older adults in the group analyses, although the distribution of the electrode saliences differed between the two groups. This difference is clearly portrayed in the combined analysis where the effect of prospective memory load was more

strongly expressed in the second latent variable for younger adults (Figure 7B) and in the fifth latent variable for older adults (Figure 7E). Together these findings may indicate that younger and older adults recruit somewhat different neural generators to meet the increased attentional demands posed by the addition of a prospective memory load to the ongoing activity.

The second pattern to emerge from the analysis of the prospective memory load effect reflected differences in the neural correlates of target recognition in the 1-back and 2-back conditions. In the group analyses the first latent variable was associated with 1-back target recognition (Figure 6A,D) and reflected modulations of the N2 and P3 components, whereas the third latent variable was associated with 2-back target recognition (Figure 6C,F). These differences between the ERPs elicited for 1-back and 2-back targets replicate other data from our laboratory (West et al., in press) that have been interpreted as being consistent with the idea that stimuli represented in working memory are in one of two states of activation (i.e., those that occupy the focus of attention [1-back targets] and those that are activated above baseline but are outside the focus of attention [2-back targets]; Cowan, 1995; McElree, 2001).

In the group analyses the patterns of design scores for the latent variables reflecting *N*-back target recognition were similar for younger and older adults (Figure 6A,C,D,F), although there were differences in the distribution of the electrode saliences between the two groups. In the combined analysis, 1-back target recognition in the younger adults was reflected by the first latent variable (Figure 7A) and 2-back target recognition was reflected by the fourth latent variable (Figure 7D). The expression of both of these patterns was attenuated in the older adults. In contrast, in older adults' 1-back target recognition was expressed in the third latent variable from the combined analysis (Figure 7C). Together these data reveal two effects of aging on the neural generators supporting target recognition: Older adults recruited the same neural generators less extensively than younger adults in some instances, and younger and older adults recruited somewhat different neural generators in other instances. This pattern is consistent with what is often observed in studies using functional neuroimaging methods to examine the effects of aging on working memory (Cabeza, 2002; Rypma & D'Esposito, 2001).

In summary, the results of this study are partially consistent with predictions derived from the preparatory processes and memory processes theory of prospective memory revealing age-related differences in the effect of increasing the working memory demands of the ongoing activity on the amplitude of the N300. These data also demonstrate that younger and older adults may recruit somewhat different neural generators in response to the addition of a prospective memory load to the ongoing activity and to support postdetection processes associated with the realization of delayed intentions. Future research could focus on identifying the task conditions that lead younger and older adults to adopt difference attentional allocation policies in order to support prospective memory.

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