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Beyond prospective memory retrieval: encoding and remembering of intentions across the lifespan

HERING, Alexandra, *et al.*

Abstract

Combining behavioral and electrophysiological measures, we investigated the role of memory processes for prospective memory development in three different age groups over the lifespan. We focused on age differences during intention encoding, retention and retrieval in order to assess if potential age-associated performance differences in adolescence and older age can be explained by associated neurophysiological differences. Our research aim was to understand the impact of memory-related factors such as intention load and encoding time on prospective remembering, focusing especially on encoding and retention, which are two so far scarcely investigated phases. Adolescents, younger and older adults worked on a semantic judgment task with an embedded prospective memory task. Participants had to encode either one or two intentions; the encoding time was either four or eight seconds long. Younger and older adults outperformed adolescents behaviorally. Furthermore, performance was better for remembering one intention compared to remembering two intentions. On the neural level, we found age-specific modulations for the [...]

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**Beyond Prospective Memory Retrieval: Encoding and Remembering of Intentions
across the Lifespan**

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Abstract

Combining behavioral and electrophysiological measures, we investigated the role of memory processes for prospective memory development in three different age groups over the lifespan. We focused on age differences during intention encoding, retention and retrieval in order to assess if potential age-associated performance differences in adolescence and older age can be explained by associated neurophysiological differences. Our research aim was to understand the impact of memory-related factors such as intention load and encoding time on prospective remembering, focusing especially on encoding and retention, which are two so far scarcely investigated phases. Adolescents, younger and older adults worked on a semantic judgment task with an embedded prospective memory task. Participants had to encode either one or two intentions; the encoding time was either four or eight seconds long. Younger and older adults outperformed adolescents behaviorally. Furthermore, performance was better for remembering one intention compared to remembering two intentions. On the neural level, we found age-specific modulations for the fronto-polar slow wave (FPSW) and the temporal-parietal slow wave (TPSW) that were sensitive to the number of intentions. Adolescents showed differences between encoding one or two intentions in the FPSW, while older adults showed these differences for the TPSW. Maintaining an intention increased fronto-central sustained activity compared to no intention. Furthermore, the activity during intention maintenance was sensitive to the number of intentions. Prospective positivity amplitudes during retrieval were smallest in adolescents and largest in older adults, but were not influenced by the memory manipulations. Parietal slow wave activity increased with increasing number of intentions, reflecting post-retrieval coordination between the ongoing and prospective memory task. In sum, only activity of the FPSW and the TPSW showed that age-related differences were influenced by memory-related factors during encoding, whereas these interactions were not observed for retention or retrieval. Our findings suggest that

intention encoding and its efficiency play an important role in explaining age differences in prospective memory.

Key words: prospective memory, lifespan, encoding, maintenance, retrieval, event-related potentials, development

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Beyond Prospective Memory Retrieval: Encoding and Retention of Intended Actions across the Lifespan

1.1. Introduction

Remembering delayed intentions, referred to as prospective memory, is a crucial ability for everyday life (Brandimonte et al., 1996; Kliegel et al., 2008b). Taking medication, paying bills or calling your mother for her birthday are real life examples that indicate the importance of successful prospective remembering for the development and maintenance of autonomy and independence (cf. Crovitz and Daniel, 1984; Hering et al., 2018b; Kliegel and Martin, 2003). Development of prospective memory performance follows an inverted U-shaped function across the lifespan; there is a steady increase from childhood to adulthood and a pronounced decline in older adulthood (e.g., Kretschmer-Trendowicz and Altgassen, 2016; Kvavilashvili et al., 2008; Mattli et al., 2014).

From a conceptual perspective, prospective remembering consists of multiple sub-phases that each may relate to age differences in the overall outcome in a prospective memory task (Ellis and Kvavilashvili, 2000; Kliegel et al., 2011). The first phase requires encoding of the intention, in that the intention is formed or planned for its execution at a later point in the future. Secondly, the intention is stored in memory during the intention retention phase, until the appropriate moment occurs in the future. This phase usually co-occurs with an ongoing task, another cognitive activity distracting the individual from continuous rehearsal of the delayed intention. Thirdly, at the appropriate moment—which can either be triggered by an event (event-based task) or at a specific time or after a period of time (time-based task; Einstein and McDaniel, 1990)—the intention is retrieved from memory and, fourthly, executed according to the initial plan.

Previous research has mainly focused on the retrieval and execution phases and shown that they rely on executive functions and working memory (e.g., Bisiacchi et al., 2009; Rose et al., 2010; Schnitzspahn et al., 2013; Zuber et al., 2016). Specifically, after cue detection,

one has to inhibit working on the ongoing task and switch to the prospective memory task; furthermore, the ongoing task and the prospective memory task have to be maintained and simultaneously managed in working memory. However, the focus on the retrieval stage of prospective memory has led to a neglect of the role of memory-related aspects that are relevant in the phases preceding retrieval and execution, namely intention encoding and intention retention. These memory-related aspects mainly refer to the content of the intention and the knowledge when the intention has to be executed. The aim of the present study was to examine underlying neurophysiological correlates that may explain differences in prospective memory performance across the lifespan, particularly focusing on the intention encoding- as well as intention retention-related processes.

1.2. Intention encoding

There exist only a few studies that examine the impact of the encoding phase on (age-related) prospective memory performance (e.g., Altgassen et al., 2015; Hering et al., 2014a; Zöllig et al., 2010). In episodic memory, encoding and retrieval are thought to recruit similar processes that are reflected by neuronal activation in the same brain regions (Craig and Rose, 2012; Nyberg et al., 2000). The functional link between encoding and retrieval is also apparent in prospective memory. Behaviorally, it has been shown that children's prospective memory performance benefits from planning skills that are indicative for better encoding (Mackinlay et al., 2009; Martin and Kliegel, 2003). Older adults seem to encode their intentions less efficiently than younger adults, which in turn is predictive of their weaker prospective memory performance (Kliegel et al., 2007; Kliegel et al., 2000).

Research on the neural correlates of this prospective memory phase is still in its infancy, and there are only a few published studies on intention encoding so far (Cona et al., 2015a; Hering et al., 2018a; West et al., 2003a; West and Ross-Munroe, 2002; Zöllig et al., 2010). Two negative event-related potentials (ERPs) have been identified to be sensitive for the encoding of intentions: the fronto-polar slow wave (FPSW), occurring between 500 ms

and 1000 ms as increased negativity, and the temporal-parietal slow wave (TPSW), occurring between 800 ms and 1200 ms as increased positivity for realized compared to unrealized intentions (West et al., 2003a; Zöllig et al., 2010). More precisely, they seem to reflect elaborative encoding that benefits later prospective memory retrieval (West et al., 2003a; West and Ross-Munroe, 2002).

From a developmental perspective, there is an interesting diverging pattern for the two components and their implication for different age groups. Whereas the FPSW was observed in adolescents and younger adults, the TPSW was only found in adolescents and older adults (West et al., 2003a; Zöllig et al., 2010). This might reflect different age-specific encoding strategies that influence prospective memory performance, which may represent one important factor in the puzzle of underlying mechanisms for prospective memory development.

Surprisingly, no available EEG study on prospective memory so far has manipulated intention encoding experimentally, which would give conceptually important insights into the impact of intention formation and its neural correlates on prospective memory performance in general and on its development in particular. Thus, the present study set out to extend the literature in this area by systematically varying intention encoding related factors and to examine the neural correlates of those manipulations across the lifespan. This approach will not only be informative for the encoding phase but may also advance our understanding of the so far mostly neglected retention interval.

1.3. Intention retention

The retention phase of prospective memory has rarely been assessed in behavioral experiments given that there is no overt response. Studies using plan retention—as a proxy for the maintenance of intentions during the delay—did not find any age differences across the lifespan (Kliegel et al., 2008a). An alternative to directly assessing retention is to manipulate the demands of storage. Augmenting the intention load by increasing the number of

prospective cues results in performance decrements in older adults (Einstein et al., 1992; Kidder et al., 1997).

By using an electrophysiological approach, more subtle differences between different age groups may be detected in the intention retention phase. Studies on the influence of having an additional prospective memory task present or not while working on an ongoing task suggest the occurrence of frontal, posterior and parietal slow waves between 400 and 900 ms (e.g., Cona et al., 2012b; Cona et al., 2013; Czernochowski et al., 2012). For example, Czernochowski and colleagues compared sustained activity over frontal and posterior regions during the ongoing task in blocks when participants had to maintain an intention (i.e., prospective memory cue) versus in blocks when no intention was present. The sustained activity at fronto-central sites indicates monitoring behavior to detect the prospective memory cue (e.g., Czernochowski et al., 2012; Hering et al., 2018a) and has been conceptually associated with a retrieval mode (West et al., 2011), that represents a persisting state of awareness for the prospective memory cue to appear (Guynn, 2003). Consistently, Czernochowski et al. (2012) found that greater sustained activity was related to faster cue detection indicating that the retrieval mode supports successful prospective remembering. The present study investigated if and how this intention retention-related fronto-central sustained activity might differ between age groups across the lifespan. So far, sustained activity associated with strategic monitoring for the prospective cue during maintenance was mainly investigated in younger adults (Cona et al., 2012b; Cona et al., 2013; Cona et al., 2015a; Czernochowski et al., 2012; Scolaro et al., 2014; West, 2007), with only few studies looking into age differences (Cona et al., 2012a; Hering et al., 2018a; Mattli et al., 2011; West and Bowry, 2005). For instance, Mattli et al. (2011) did not find age differences in slow wave activity related to monitoring in a lifespan sample including children, younger and older adults. Slow wave activity was robustly expressed at frontal and posterior sides independent of age. Studies comparing only younger and older adults found different topographies for

slow wave activity indicating that different neural generators contribute to monitoring in these groups (Cona et al., 2012a; Hering et al., 2018a; West and Bowry, 2005). For example, Cona et al. (2012a) found that slow wave activity was mainly expressed at posterior sites in older adults, whereas in younger adults it was mainly expressed at anterior sites such as the prefrontal cortex. Strategic monitoring and intention maintenance have mainly been studied by comparing ongoing task only activity with activity for the ongoing task while simultaneously maintaining an intention. In the present study, we aim to investigate the maintenance phase by experimentally manipulating the intention load (i.e., one versus two intentions). Extending this line of research to a full lifespan approach is of conceptual importance, given that also behavioral studies have repeatedly shown that monitoring contributes to age differences in prospective memory (Kliegel et al., 2008c).

1.4. Intention retrieval and execution

Even though the focus of the present study was on the encoding and retention phase, in the following section, we briefly review the literature on the retrieval and execution phase. We will also explore selected components of the neural correlates related to intention retrieval across the lifespan given that lifespan ERP studies on prospective memory are generally rare. The retrieval phase requires both detecting the prospective cue and retrieving the intention content. Thereby, the detection of the prospective cue operates similarly to an external prompt for cued recall of episodic memory (Cohen et al., 2001; Einstein et al., 1992). Cue detection seems to be more involved in age-related differences during childhood, adolescence and older adulthood (e.g., Hering et al., 2016; Mattli et al., 2014). Yet, successfully retrieving the intention from memory is a key step in prospective memory performance that is prone to developmental differences across the lifespan as well (e.g., Smith et al., 2010; West and Craik, 1999; Zöllig et al., 2007). The retrieval of the intention has been associated with an ERP component that is called parietal positivity and reflects a sustained positivity over parietal regions between 400 ms and 1200 ms (West, 2011). Different processes contribute to

the parietal positivity, that is the detection of a rare target in general (as a P3b; Polich, 2007), the recognition of the prospective cue (like an old-new memory effect) and the retrieval of the prospective intention (prospective positivity; West and Krompinger, 2005). In his seminal review, West (2011) distinguished the prospective positivity from the P3b. The P3b is associated with memory updating and processes that result in a memory-based stimulus evaluation (Kok, 2001; Polich, 2007). For prospective memory it reflects the evaluation of the relevance of the prospective memory cue (Hering et al., 2016). The prospective positivity occurs mainly for prospective cues and is sensitive to the intention load or the number of intentions (West et al., 2003b).

The amplitude of the parietal positivity decreases from childhood to old adulthood (Mattli et al., 2011; West and Covell, 2001; Zöllig et al., 2007). West et al. (2003a) did not find amplitude differences in younger and older adults for the parietal positivity. The authors concluded that prior efficient encoding in older adults supported later retrieval. A conclusion that awaits further corroboration.

1.5. Aims of the Present Study and Main Predictions

The aim of the present study was to investigate the entire processing stream of encoding, maintaining, and later retrieving intentions and to explore how these phases differ across the lifespan. To assess all three phases, we adopted the encoding/retrieval paradigm first published by West and Ross-Munroe (2002). During this task, participants have to work repeatedly on sequences where they encode the intention, then work on the ongoing task for some trials (retention phase) before the prospective cue indicates intention retrieval. In order to examine if expected performance differences early and later in life may be explained by differences in comparable or different underlying neuronal processes, we identified ERPs that have been related to encoding, retention and retrieval of intentions. *Table 1* gives an overview on the phases and the investigated neural correlates.

Of special interest for the present study were the intention encoding and intention retention phases, hence we manipulated encoding time (i.e., the time participants had to encode the intention(s): either four or eight seconds) and intention load (i.e., the number of intentions participants had to encode: either one or two intentions). From the episodic memory literature, we know that longer encoding time can foster retrieval (e.g., Craik and Tulving, 1975; Roberts, 1972). The manipulation of intention load not only allows comparing the processes at encoding and retrieval but also at the retention phase. We predicted that higher intention load should impair prospective memory performance in adolescents and older adults compared to younger adults (observable at the encoding and retention phase), whereas longer encoding time should boost performance observable at the retrieval phase.

We investigated the *FPSW* and the *TPSW* as neural correlates of intention encoding (cf., West et al., 2003a; Zöllig et al., 2010 for a similar paradigm). When encoding two intentions, the intention load is higher and thus, more elaborated processing should be necessary than for encoding just one intention. Based on findings from Zöllig et al. (2010), we predicted that the relevance of both ERP components for encoding should differ between age groups. We expected that both the *FPSW* and the *TPSW* would be modulated by the intention load manipulation in adolescents, whereas the intention load manipulation should only modulate the *FPSW* in younger adults and only the *TPSW* in older adults.

Regarding developmental differences in the retention phase of prospective memory, we investigated the *fronto-central sustained modulation* as a neural correlate of intention retention indicating maintenance of one or more prospective memory tasks. We expected that the load of two intentions should especially modulate the sustained activity in adolescents and older adults as compared to young adults given that the task should be more challenging with two intentions than with one intention to maintain.

Finally, we examined the *prospective positivity* and the following *parietal slow wave* as neural correlates for the intention retrieval phase. The prospective positivity contributes

together with the P3b to the parietal positivity. Although both components occur within the same time window (West et al., 2003b), the prospective positivity is especially associated with prospective cues (West et al., 2006; West and Wymbs, 2004).

The parietal slow wave activity has previously been linked to post-retrieval task coordination of the prospective memory task set (i.e., intention) and the ongoing task set (Bisiacchi et al., 2009; Cona et al., 2013). We expected that the number of intentions would modulate the prospective positivity and the parietal slow wave in adolescents and older adults given that these memory-related processes of prospective memory seem to be reduced in adolescents and older adults compared to younger adults. Furthermore, if encoding time benefits later retrieval, these components should also be modulated by encoding time showing a benefit for more time to encode in all three age groups.

2. Method

2.1. Participants

Sixty-six participants were included in the sample, among them 25 adolescents aged 12 to 15 years ($M = 13.50$; $SD = .82$; 16 female), 20 younger adults aged 21 to 30 years ($M = 25.50$; $SD = 2.70$; 10 female) and 21 older adults aged 62 to 72 years ($M = 68.43$; $SD = 2.42$; 10 female). All participants were native German speakers. Participants were only eligible for study participation (and were otherwise excluded) if they had normal or corrected-to-normal vision and hearing, if they did not have any history of neurological or major psychiatric diseases and were not currently taking any psychoactive medication (e. g., anti-depressive, anxiolytics). Our exclusion criteria were assessed with a questionnaire via telephone before the testing session to avoid unnecessary testing. To measure general cognitive abilities, we assessed crystallized intelligence using the vocabulary test and the matrices test from the German versions of the Wechsler intelligence batteries for children (HAWIK, Petermann and Petermann, 2007) and adults, respectively (WIE, von Aster et al., 2006). All participants scored within or higher than one standard deviation from the age-normative mean ($M = 10$,

$SD = 3$), participants outside of this range were excluded from all analyses reported.

Handedness of the participants was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971) where values smaller than -40 indicate left-handedness, between -40 and 40 represents ambidextrousness and above 40 is right-handedness. All participants reported to be right-handed except for one adolescent who reported to be ambidextrous and another adolescent, where the data was missing (adolescents: $M = 71.84$; $SD = 21.15$; young adults: $M = 77.48$; $SD = 19.04$; older adults: $M = 92.55$; $SD = 16.42$). Participants were recruited through distribution of flyers at practices, sport gyms and the universities' senior academies. Furthermore, we used former contacts from the subject databases of the labs in Dresden and Dortmund (Germany). All participants signed an informed consent form prior to the beginning of the experimental session. The project was conducted in accordance with the Helsinki declaration (2004). Furthermore, a research committee of the German Research Foundation (DFG) approved the study protocol.

2.2. Material and Procedure

2.2.1. Prospective memory task

For the prospective memory task, we used an adapted version of an established encoding/retrieval paradigm (Hering et al., 2016; West and Ross-Munroe, 2002). The computerized task consisted of a semantic judgment ongoing task and a color-related prospective memory task. For the ongoing task, participants had to decide if two words belong to the same category (e.g., car and bus) or to different categories (e.g., rose and ball). Each ongoing task trial consisted of two words presented in the middle of the screen in lowercase letters. The word pairs were presented in four different colors (blue, red, white, yellow). To create the word material we used the category norms of the German language (Mannhaupt, 1983; Scheithe and Bäuml, 1995). In total, we included 43 different categories and used 1514 different words. Each word was used four times over the course of the experimental task, twice for same category stimuli and twice for different categories stimuli.

For the unrelated word pairs, we randomly regrouped the words between the different categories. For the related word pairs, we randomly combined two words within the same category. Responses were collected using a response box with two buttons labeled with an equal sign (=) for the same category and unequal sign ($\neq$) for different categories. Participants were asked to use the index and middle finger of their right hand to respond.

The prospective memory task was embedded within the ongoing task and included 192 encoding as well as retrieval trials. The *encoding trials* consisted of two lines of the letter “C” and the letter “V” in the colors green and magenta. The combination of letters and colors varied depending on the intention load condition (see below). When these stimuli were presented, participants had to encode and store the combination of letters and colors and then continue working on the ongoing task until the *retrieval trial* occurred. The retrieval trial presented the prospective cue: if a word pair was displayed in the previously learned color (e.g., green) participants had to remember to press the letter associated with the font color instead of responding to the ongoing task (e.g., “C”). Prospective memory responses were collected using a second response box with two buttons labeled with “C” and “V”. Participants used the left index finger for pressing “C” and their left middle finger for pressing “V”. Between encoding and retrieval trials there were 6 to 10 ongoing task trials. One exemplary sequence of the paradigm used is presented in *Figure 1*.

Memory load was manipulated by varying the number of intentions to encode. Depending on the intention load condition, participants had to encode and learn either one letter-color association (one intention) or two letter-color associations (two intentions). In the *one intention* condition, the encoding trials depicted one of the two letters in one of the two colors (e.g., “C” in green) in two lines. Therefore, the next time a word pair was shown in this color (e.g., green) participants had to press the corresponding letter (e.g., “C”). In the *two intentions* condition, the encoding trials showed two lines of different letter-color combinations (e.g., one line of “C” in green and one line of “V” in magenta). Participants had

to encode and learn both combinations. Thus, the next time a word pair appeared in one of the two memorized colors they had to press the corresponding and previously learned letter (e.g., for a word pair in magenta font color, participants had to press “V”). After the retrieval trial, participants worked on ongoing task trials without an intention present until the next encoding trial occurred.

In addition to the number of intentions, we varied the amount of encoding time. The encoding trials were either four or eight seconds long. During the encoding trials, participants did not have to respond but they were encouraged to carefully encode and memorize the letter-color combination(s). Intention load and encoding time were manipulated between blocks. There were four blocks of one intention shown for four seconds during encoding, four blocks of one intention shown for eight seconds, four blocks of two intentions shown for four seconds and four blocks of two intentions shown for eight seconds.

The entire experiment consisted of 16 blocks that were split into two sessions. Blocks were of counterbalanced order for both the number of intentions and encoding time. In each of the 16 blocks, we presented 190 trials in total, including 12 encoding trials, 12 retrieval trials and 166 ongoing task trials. Encoding trials were presented for either four or eight seconds, the ongoing task trials and the retrieval trials were presented for three seconds. Before working on the 16 experimental blocks, participants performed a practice block for only the ongoing task consisting of 70 word pairs, followed by two practice blocks (of 32 trials each) for the complete paradigm including two encoding and retrieval trials. Participants had to respond correctly for at least one retrieval trial; otherwise the practice block was repeated to ensure participants completely understood the task instructions. At the beginning of the second testing session, the experimenter repeated the task instructions and participants worked on the practice block for the two intentions condition to remind them of the task instructions.

2.2.2. Procedure

The experiment consisted of two sessions to avoid fatigue and an overlong procedure for the participants. The first session started with signing the informed consent and cognitive background testing.¹ Afterwards participants could take a break and were prepared for the EEG session. Application of electrodes took approximately 15 minutes. After receiving instructions for the experimental task and practice blocks, participants had a short break during which they filled in the questionnaire about their handedness. Participants worked on the first eight blocks of our paradigm. The prospective memory task lasted for approximately 1 hour and 30 minutes (each block took approximately 11 minutes). After each block, there was a short break of 1 to 2 minutes and after half of the experimental session, participants had a break of 5 minutes. In total, the first experimental session lasted 3.5 to 4 hours. The second session was scheduled within the next 7 days. Participants started with the practice block and the instruction of the task. Afterwards the experimenter again applied the electrodes and started the experimental blocks. Participants worked on the remaining eight blocks with short breaks between blocks similar to session 1. The second session took approximately 2 to 2.5 hours. After completing the entire experiment participants were reimbursed with 10€ per hour for their participation and travel expenses.

2.3. Recording of Electrophysiological Data

The EEG was continuously recorded while participants performed the prospective memory task. We used an Active-Two BioSemi system with 32 Ag/AgCl active scalp electrodes. Electrodes were distributed on the head according to the 10-20 system using head caps with plastic electrode holders (Fp1, Fpz, Fp2, F7, F3, FZ, F4, F8, FC3, FCZ, FC4, T7, C3, CZ, C4, T8, CP3, CPZ, CP4, P7, P3, PZ, P4, P8, PO3, POZ, PO4, O1, OZ, O2) as well as at the two mastoids. Additionally, six facial electrodes (LO1, LO2, IO1, IO2, SO1, SO2) were applied near the outer canthi, below and above the pupils at both eyes to assess eye movements. They were affixed to the skin with an adhesive patch. Data was recorded with the ActiView BioSemi software (BioSemi Active-Two, V.O.F., Amsterdam, the Netherlands) and

digitized at a sampling rate of 2048 Hz in a bandwidth filter of 0–417 Hz. All electrode offsets were held between ± 20 microvolt. Processing of collected data was accomplished with Brainvision Vision Analyzer Software 2.0 (Brain Products, Munich, Germany). Data were down-sampled to 1000 Hz. VEOG and HEOG were derived from the facial electrodes. Data were bandpass-filtered between 0.05 Hz and 20 Hz. Segmentation was conducted relative to the marker position and stimulus driven in a time window of -200 ms to 2000 ms. To correct for eye movements we used the Gratton and Coles approach, that is a regression based algorithm using VEOG and HEOG (Gratton et al., 1983). Artefact rejection was applied within the time window of interest between -100 ms and 2000 ms. The criterions for artefact rejection were: amplitudes exceeding -150 μV or 150 μV , voltage steps above 50 $\mu\text{V}/\text{ms}$, lower activity than 0.5 μV and differences of values above 300 μV . The data was then re-referenced offline using an averaged mastoid reference electrode. Data were baseline-corrected during the preprocessing procedure.

Averages were computed for events of interest that were the correct responses (i.e., hit) to different trial types: encoding trials preceding a correct prospective memory hit, prospective memory hits (PM hits), ongoing task hits (OT hits) that occurred outside of an encoding-retrieval sequence (i.e., without an additional prospective memory intention) as well as between encoding trials and subsequent retrieval (i.e., with an additional prospective memory intention). Time windows and electrode sites for the ERP components were selected based on existing literature (West, 2011; West et al., 2003a; Zöllig et al., 2010; Zöllig et al., 2007) and visual inspection of the grand averages.

For the encoding phase, the FPSW and the TPSW were measured by using mean amplitudes at electrodes Fp1, Fpz and Fp2 for the FPSW and P7 and P8 for the TPSW, electrode sites were chosen based on Zöllig et al. (2010). Time windows for the two components were based on prior visual inspection of the grand averages and peak detection measures. The FPSW showed a biphasic activity that started with a positive deflection

between roughly 400 and 800 ms and turned into a negative going slow wave. To capture this shift in the waveform, we analyzed the mean amplitudes for the positive deflection of the FPSW (FPSW_{pos}) in a time window of 400–700 ms and the negative deflection of the FPSW (FPSW_{neg}) in a time window of 850–1650 ms. The TPSW was analyzed in a time window of 800–1600 ms.

We analyzed the FPSW and the TPSW for the encoding trials that elicited a later correct prospective memory response. Whereas previous studies compared the later-realized intention encoding trials to later-unrealized intention encoding trials (West et al., 2003a) or ongoing task trials (Zöllig et al., 2010), we decided to use only the later-realized intention encoding trials. Therefore, direct comparisons across results of the present study with previous work are to some extent limited. There were not enough artefact-free trials of later un-realized intentions per participant available to replicate the analyses described by West et al. (2003a). Moreover, the ongoing task trials did not represent an appropriate baseline for the encoding trials. For the encoding trials, participants just saw letter-color associations instead of actual words. Additionally, they did not respond to the encoding trials, whereas there was a motor response towards the ongoing task trials.

For the retention phase, fronto-central sustained activity was measured by using mean amplitudes within a time window of 400–900 ms at FCz. We compared the slow wave activity from ongoing task trials that occurred between encoding and retrieval trials (i.e., with intention instruction) with ongoing task trials after the retrieval trial until the next encoding trial (i.e., without intention instruction).

For the retrieval phase, the prospective positivity and the following parietal slow wave were measured by using mean amplitudes at Pz within a time window of 400–700 ms and of 800–1200 ms, respectively. We compared mean amplitudes between PM hits and OT hits without intention instruction to isolate the prospective memory specific processing from the ongoing task.

2.4. Data Analysis

2.4.1. Behavioral data

The behavioral data was analyzed separately for prospective memory task performance and ongoing task performance. We conducted mixed ANOVAs with age group (3: adolescents, young adults, old adults) as the between-subjects factor and intention load (2: one intention, two intentions) and encoding time (2: four seconds, eight seconds) as within-subject factors separately for accuracy of PM hits and OT hits. The significance level for main effects and interactions was set at $\alpha = .05$. Significant main effects and interactions were explored using post-hoc *t*-tests for contrasts between specific conditions. Post-hoc tests were corrected for multiple testing using the Bonferroni correction. To do so, the *p*-values for follow-up *t*-tests were multiplied the number of comparisons made in that follow-up family (indicated as p_{adj}).

2.4.2. Electrophysiological data

For the analyses of the electrophysiological data we had to exclude from the sample four adolescents, one young and one older adult, because they provided less than seven artefact-free trials for averaging the ERPs, especially for the rare encoding and retrieval trials. The final sample for the electrophysiological data analyses comprised 21 adolescents, 19 younger adults and 20 older adults (mean trial numbers across the condition pairings for intention load and encoding time: Adolescents: PM hits: $M = 32.00$, $SD = 9.50$; OT hits_{with intention}: $M = 236.16$, $SD = 52.05$; OT hits_{without intention}: $M = 172.37$, $SD = 37.43$; Encoding trials for PM hits: $M = 31.19$, $SD = 8.32$; Younger adults: PM hits: $M = 41.28$, $SD = 5.93$; OT hits_{with intention}: $M = 298.17$, $SD = 40.79$; OT hits_{without intention}: $M = 220.05$, $SD = 27.84$; Encoding trials for PM hits: $M = 39.16$, $SD = 5.49$; Older adults: PM hits: $M = 38.74$, $SD = 5.73$; OT hits_{with intention}: $M = 319.23$, $SD = 32.07$; OT hits_{without intention}: $M = 234.80$, $SD = 24.42$; Encoding trials for PM hits: $M = 37.71$, $SD = 5.74$). We conducted mixed ANOVAs separately for the different ERP components with age group as between-subjects factor (3:

adolescents, younger adults, older adults) and intention load (2: one intention, two intentions) and encoding time (2: four seconds, eight seconds) as within-subjects factors. For the encoding phase, the within factor electrode was included as well (FPSW: 3: Fp1, Fpz, Fp2; TPSW: 2: P7, P8). For the retention phase and the retrieval phase, we included the within-subject factor trial type (2: OT hits with intention instruction, OT hits without intention instruction for retention; 2: PM hits, OT hits without intention instruction for retrieval). For clarity, we prioritized on presenting significant effects only. All conducted analyses for the different ERP components can be found in the *Supplementary material*. Significant main effects and interactions were further explored using post-hoc comparisons, except for the factor electrode, as we did not have specific hypotheses regarding electrode site. To correct for multiple testing, we again used Bonferroni adjustment. To do so, the p-values for follow-up tests (*t*-tests or ANOVAs) were multiplied the number of comparisons made in that follow-up family (indicated as p_{adj}).

3. Results

3.1. Behavioral Results

Table 2 gives an overview of the descriptive results of prospective memory task and ongoing task performance.

3.1.1. Prospective memory task performance

We found significant main effects of age group ($F(2, 63) = 10.302$; $p < .001$; $\eta^2_p = .246$) and intention load ($F(1, 63) = 24.279$; $p < .001$; $\eta^2_p = .278$) on prospective memory accuracy. Both adult groups performed better than adolescents (all $p_{adj} < .010$), whereas younger and older adults did not differ from each other ($p_{adj} = .639$). Accuracy for remembering one intention was better than for remembering two intentions. Encoding time did not influence prospective memory accuracy ($p = .459$). None of the interactions reached significance (all $p > .108$).

3.1.2. Ongoing task performance

For ongoing task accuracy, we found significant main effects of age group ($F(2, 63) = 26.404$; $p < .001$; $\eta^2_p = .456$) and encoding time ($F(1, 63) = 10.250$; $p = .002$; $\eta^2_p = .140$). Both adult groups performed better than adolescents (all $p_{adj} < .001$), whereas younger and older adults did not differ from each other ($p_{adj} = .330$). When participants had four seconds to encode the prospective memory intention, they performed the ongoing task more accurately than with eight seconds of encoding time. The number of intentions to remember did not influence ongoing task accuracy ($p = .099$) and all interactions failed to reach significance (all $p > .245$).

3.2. Electrophysiological Results

3.2.1. Intention encoding

Figure 2 depicts the grand averages at electrode Fpz for the three age groups, showing the FPSW. *Figure 3* shows the grand averages for the TPSW at electrodes P7 for the different age groups.

FPSW. Mean amplitudes for the FPSW_{pos} differed between the three age groups ($F(2, 54) = 37.94$; $p < .001$; $\eta^2_p = .584$). The FPSW_{pos} was largest in older adults, intermediate in younger adults and smallest in adolescents (all $p_{adj} < .007$). Furthermore, mean amplitudes varied between encoding one or two intentions ($F(1, 54) = 4.20$; $p = .045$; $\eta^2_p = .072$) and also interacted with the age groups (interaction age group by intention load: $F(2, 54) = 12.60$; $p < .001$; $\eta^2_p = .318$; see *Figure 2*). Further analyses indicated that younger and older adults showed no significant differences when encoding one intention compared to encoding two intentions (younger adults: $t(18) = 1.376$; $p_{adj} = .558$; older adults: $t(19) = .491$; $p_{adj} > .999$). In contrast, adolescents showed greater negative (i.e., smaller) mean amplitudes when encoding one intention vs. two intentions ($t(20) = -5.044$; $p_{adj} < .001$). Additionally, the four-way interaction of age group by intention load by encoding time by electrode reached significance ($F(3.04, 82.13) = 3.71$; $p = .014$; $\eta^2_p = .121$). Following up on this interaction, we conducted three ANOVAs on intention load, encoding time and electrode separately for each

age group. None of the subsequent three-way interactions was significant ($p_{adj} > .137$). The only significant effect found was the earlier reported difference of intention load in the adolescents.

Mean amplitudes for the FPSW_{neg} were more negative when encoding for eight seconds than for four seconds ($F(1, 54) = 5.444$; $p = .023$; $\eta^2_p = .092$). Additionally, there was a significant four-way interaction of age group by intention load by encoding time by electrode ($F(3.61, 97.56) = 2.57$; $p = .048$; $\eta^2_p = .087$). Following up on this interaction, we conducted three ANOVAs on intention load, encoding time and electrode separately for each age group. None of the subsequent three-way interactions turned significant in none of the age groups ($p_{adj} > .155$).

TPSW. Intention load influenced the mean amplitude of the TPSW differently for the three age groups (interaction age group by intention load: $F(2, 54) = 3.79$; $p = .029$; $\eta^2_p = .123$, see *Figure 3*). Adolescents and younger adults showed no significant differences when encoding one intention compared to encoding two intentions (adolescents: $t(20) = 1.075$; $p_{adj} = .885$; younger adults: $t(18) = .251$; $p_{adj} > .999$). Older adults showed greater negative mean amplitudes when encoding one intention vs. two intentions ($t(19) = -2.846$; $p_{adj} < .030$). Additionally, there was a significant interaction of age group by intention load by electrode ($F(2, 54) = 4.23$; $p = .020$; $\eta^2_p = .136$). As we did not have specific assumptions regarding electrode site, we did not follow up on this interaction.

3.2.2. Intention retention

Fronto-central sustained modulation. The grand average showed negative sustained activity at FCz, that differed between OT hits that occurred between encoding and retrieval trials (i.e., with the need to retain the intention) and OT hits after the retrieval trial until the next encoding trial (i.e., without the need to retain the intention). When participants had to retain the intention (vs. no intention) their sustained activity was less negative ($F(1, 54) = 32.19$; $p < .001$; $\eta_p^2 = .373$). Fronto-central sustained activity differed further between the

three age groups ($F(2, 54) = 6.29$; $p = .004$; $\eta_p^2 = .189$, see *Figure 4*): Adolescents showed greater negative activity than older adults ($p_{adj} = .003$). Activity of younger adults was intermediate but did not differ significantly from either adolescents ($p_{adj} = .067$) or older adults ($p_{adj} = .794$).

Fronto-central sustained activity was modulated by intention load and encoding time indicated by a significant main effect of intention load ($F(1, 54) = 9.21$; $p = .004$; $\eta_p^2 = .146$) and further significant interactions of trial type by intention load by encoding time ($F(1, 54) = 6.27$; $p = .015$; $\eta_p^2 = .104$), trial type by intention load ($F(1, 54) = 5.11$; $p = .028$; $\eta_p^2 = .086$) and trial type by encoding time ($F(1, 54) = 6.48$; $p = .014$; $\eta_p^2 = .107$). Following up on the interactions, we analyzed the influence of intention load and encoding time separately for OT hits with an additional intention instruction and without. In OT hits after retrieval without intention load, we found a significant interaction of intention load by encoding time ($F(1, 56) = 5.78$; $p_{adj} = .040$). Post-hoc paired t -tests showed that mean amplitude was the smallest in the condition with two intentions to retain and eight seconds encoding time. Thus, amplitudes differed between four and eight seconds encoding time when retaining two intentions ($t(58) = -2.466$; $p_{adj} = .034$) but there were no differences between four and eight seconds encoding time when retaining one intention ($t(57) = .808$; $p_{adj} = .446$). Findings suggested that the condition of having two intentions to maintain after an eight-second encoding phase differed from the other three conditions.

Fronto-central sustained activity for OT hits after encoding differed depending on the intention load ($F(1, 56) = 12.93$; $p_{adj} = .002$). The negative sustained mean activity decreased—and amplitudes were less negative—when the number of intentions was increased from one to two. The effects on encoding time did not persist the subsequent post-hoc analyses.

3.2.3. Intention retrieval

Prospective Positivity. To analyze the prospective positivity, we compared PM hits with OT hits for ongoing trials without the intention present. Mean amplitudes varied between PM hits and OT hits indicating the presence of the prospective positivity ($F(1, 54) = 98.69$; $p < .001$; $\eta_p^2 = .646$). Mean amplitudes were significantly greater in PM hits than in OT hits. Mean amplitudes also varied between age groups ($F(2, 54) = 5.26$; $p = .008$; $\eta_p^2 = .163$); adolescents showed significantly greater mean amplitudes than older adults ($p_{adj} = .006$), mean amplitudes of younger adults were intermediate and did not differ from adolescents ($p_{adj} = .463$) or older adults ($p_{adj} = .235$).

Furthermore, we found a significant interaction of trial type by age group ($F(2, 54) = 5.45$; $p = .007$; $\eta_p^2 = .168$). Subsequent analyses showed that the prospective positivity was present in all three age groups (see *Figure 5*), with greater amplitudes for PM hits than OT hits, it was the largest in younger adults and the smallest in older adults (adolescents: $t(20) = 6.560$; $p_{adj} < .001$; younger adults: $t(18) = 8.511$; $p_{adj} < .001$; older adults: $t(19) = 3.946$; $p_{adj} = .003$).

Parietal slow wave. To analyze the parietal slow wave, we compared PM hits to OT hits for ongoing trials without the intention present. Mean amplitudes varied between PM hits and OT hits indicating the presence of the prospective memory specific modulation of the parietal slow wave ($F(1, 54) = 60.09$; $p > .001$; $\eta_p^2 = .527$). Mean amplitudes were significantly smaller in PM hits than in OT hits. Furthermore, we found a significant interaction of trial type by age group ($F(2, 54) = 6.47$; $p = .003$; $\eta_p^2 = .193$, see *Figure 5*). Subsequent analyses showed that the parietal slow wave was only present in adolescents and younger adults (adolescents: $t(20) = -6.45$; $p_{adj} < .001$; younger adults: $t(18) = -4.54$; $p_{adj} < .001$), but not in older adults ($t(19) = -2.12$; $p_{adj} = .141$).

Additionally, there was a significant main effect of intention load ($F(1, 54) = 34.25$; $p < .001$; $\eta_p^2 = .388$), with greater mean amplitudes for one intention vs. two intentions and a significant interaction of trial type by intention load ($F(1, 54) = 35.68$; $p < .001$; $\eta_p^2 = .398$).

Following up on the interaction revealed that mean amplitudes were greater for OT hits than for PM hits for both intention load conditions (one intention: $t(59) = 5.28$; $p_{adj} < .001$; two intentions: $t(59) = 7.513$; $p_{adj} < .001$). Furthermore, mean amplitudes of the PM hits were smaller (i.e., more negative) for two intentions than for one intention ($t(59) = -6.24$; $p_{adj} < .001$); but there was no difference for OT between the one and the two intention condition ($t(59) = -.377$; $p_{adj} > .999$).

4. Discussion

The present study examined prospective memory as a multi-phasic process in adolescents, younger and older adults. The main goal was to investigate encoding, retention and retrieval of intentions to better understand how these phases differ across the lifespan, and thereby, to pinpoint underlying neural mechanisms that may drive developmental differences across the lifespan. Especially the phases of encoding and retention have only been scarcely studied so far.

4.1. Behavioral Results

Adolescents demonstrated the lowest performance for the prospective memory task and the ongoing task compared to the adult age groups. Somewhat unexpectedly, younger and older adults showed comparable performance rates for the prospective memory task and the ongoing task. While the reduced performance of the adolescents supports the notion of a steady increase in prospective memory performance across the first half of the lifespan, the high prospective memory performance of the older adults is only partly in line with previous research using a similar paradigm (Hering et al., 2016). However, looking closer at the ongoing task performance might help to explain this pattern. Descriptively, older adults showed the highest accuracy rate for the ongoing task, which is in line with other studies using a semantic judgment task as an ongoing activity (e.g., West et al., 2003a), and which supports the general intactness of crystallized intelligence and vocabulary until a very old age (Park et al., 2002). Adolescents showed the lowest accuracy rates for the ongoing task, a

result that supports previous studies using a similar paradigm (e.g., Mattli et al., 2014; Zöllig et al., 2007). The ongoing task might have been more challenging for adolescents due to its demands on vocabulary, hence capturing more cognitive resources and consequently reducing prospective memory performance in the adolescents. Thus, the relatively high prospective memory performance in our older adults could partly be explained by lower ongoing task absorption that might have freed attentional resources that would have otherwise been captured by the ongoing task (e.g., Rendell et al., 2007). Yet, these explanations have to remain speculative because we do not have experimental evidence in the current data set. The behavioral age differences also align well with neuroscientific findings on the development across the lifespan. A central area for prospective memory functioning is the prefrontal cortex (Cona et al., 2015b), which is still developing during adolescence (e.g., Casey et al., 2008; Crone, 2009). Indeed, findings on prospective memory development during adolescence are mixed. A few studies have shown no age differences between adolescents and young adults suggesting that prospective memory is already fully developed in this age (e.g., Kretschmer-Trendowicz and Altgassen, 2016; Ward et al., 2005). Most studies, however, report reduced prospective memory performance in adolescents compared to young adults indicating ongoing development (e.g., Altgassen et al., 2014; Bowman et al., 2015). The higher performance in the older adults could indicate compensatory mechanisms to support their prospective remembering such as more frontal activation via neural reorganization (Cabeza, 2002; Davis et al., 2008). Especially, assuming that the less demanding ongoing task might have freed resources for more top-down processing of the prospective memory task (McDaniel and Einstein, 2011).

The results revealed an interesting dissociation for intention load and encoding time which is of conceptual importance. Remembering one or two intentions influenced prospective memory performance. In contrast, having four or eight seconds to encode the prospective memory intention affected only ongoing task performance. The number of

intentions influenced prospective memory performance as predicted, with participants realizing their intentions less successfully overall when they had to remember two intentions compared to remembering one intention. However, this effect was not age-specific. Ongoing task performance was lower for longer (eight seconds) compared to shorter (four seconds) encoding times. It is possible that longer encoding time distracted participants, lead to mind-wandering and hampered resuming the ongoing task. Alternatively, the longer encoding time could have (implicitly) allocated more importance to the prospective memory task and thus reduced ongoing task performance (cf. Hering et al., 2014b). However, encoding time did not influence prospective memory accuracy, making this alternative explanation less likely. From the literature on episodic memory, it is known that encoding has to be meaningful to be helpful (for review see Craik and Rose, 2012), therefore longer encoding time itself (without externally providing strategies, for example) was possibly not sufficient for increasing later intention retrieval.

4.2. Neural Correlates of Intention Encoding

The FPSW and the TPSW were investigated as neural correlates of intention encoding. The FPSW represents encoding efficiency in prospective memory and was evidenced by greater negativity for later realized intentions compared to unrealized intentions (West et al., 2003a). Similarly, frontal slow wave activity was observed for episodic memory encoding with greater activity indicating more elaborated encoding (cf. subsequent memory effect; e.g., Friedman, 1990; Paller and Wagner, 2002).

In our lifespan study, older adults showed the largest positive mean activity of the earlier part of the FPSW, whereas adolescents showed the smallest activity (see *Figure 2*). Younger adults showed intermediate amplitudes for the positive deflection of the FPSW. Although it remains to be confirmed in future research, the larger activity in older adults could suggest that they have engaged in elaborated encoding for the prospective memory cues. This conclusion aligns with the behavioral performance pattern, where older adults

showed high prospective memory performance. Similarly, Zöllig et al. (2010) reported higher frontal activation in older adults compared to younger adults for the period of the FPSW. Possibly, the ongoing task was less demanding for the older adults, leaving them with more resources to encode the intentions. Alternatively, older adults may have simply treated the prospective memory task as more important, leading to more resource allocation to intention encoding (e.g., Hering et al., 2014b; Walter and Meier, 2014). Adolescents showed less effective encoding at the neurophysiological level, which is in line with their lower behavioral performance. One reason could be that the ongoing task was too absorbing for adolescents, withdrawing too many cognitive resources that would have been necessary for elaborated encoding of intentions.

Furthermore, the positive deflection of the FPSW showed an age-specific modulation by the numbers of intention to encode. In adolescents only, the amplitudes were more negative when encoding one intention compared to encoding two intentions. Two intentions were more demanding to encode than one intention, this pattern was also reflected by reduced behavioral performance for the two-intention condition. In younger and older adults, this difference on the neural level was not found. It could suggest that indeed the encoding process was not as challenging in these age groups as it was the case for the adolescents. This finding is in line with the reduced behavioral prospective memory in adolescents compared to the adult groups and aligns with findings by Zöllig et al. (2010) demonstrating more compensatory mechanisms in adolescents compared to younger adults. Interestingly, the behavioral and neural results for the older adults contrast previous studies by West et al. (2003a) and Zöllig et al. (2010) reporting less efficient encoding in older adults. Critically, although both previous studies used a similar paradigm, they did not experimentally manipulate the intention encoding phase. The manipulation of the number of intentions in the present study revealed age group-specific modulations for intention encoding. This interaction

supports the conceptually important conclusion that adolescents might have more difficulties in adapting or compensating for the varying demands during encoding.

Mean activity for the negative going deflection of the FPSW was only sensitive to the encoding time manipulation, with activity being more negative for trials with eight seconds encoding time than four seconds encoding time. This result matches our findings for ongoing task accuracy, which was lower for the longer encoding time. Supporting our earlier conclusion, the neural differences for the encoding time manipulation could indicate that the longer time of eight seconds might have indeed been rather distracting for participants compared to the shorter four seconds condition.

The grand averages for the FPSW showed a biphasic component evolution in all three age groups starting with a positive deflection that turned into a negative deflection. We captured this shift by assessing mean activity in an earlier time window for the FPSW_{pos} and a later time window for the FPSW_{neg} for all three age groups. However, there seem to be pronounced latency shifts between adolescents and the two adult groups that might have led to some overlap between the positive and negative parts of the FPSW. The grand averages showed that the course of the FPSW is similar in all three age groups but that it is decreasing in negativity from adolescents to older adults, which is a general finding in developmental studies (cf. Dujardin et al., 1993; Polich, 1997; Zöllig et al., 2007). It is therefore possible that the FPSW_{pos} was reduced in the adolescents due to the onset of the FPSW_{neg}, which was more negative than in the other groups.

For the TPSW, we found an age-specific modulation for the mean activities that varied between encoding one or two intentions. More precisely, we did not find differences in mean activity for encoding one versus two intentions in adolescents and younger adults. However, in older adults, the TPSW was reduced in negativity for encoding two intentions compared to one intention. Thus, our findings deviate from Zöllig et al. (2010) who found that the TPSW supports encoding in adolescents but not in younger and older adults. It matches findings

from West et al. (2003a) showing that the TPSW is only relevant for encoding in older adults but not younger adults.

Taken together, we found different patterns in the neural correlates for elaborative encoding between adolescents and older adults. The FPSW was affected only in adolescents by the intention load manipulation, suggesting that this is a critical component for prospective memory development in the first half of the lifespan. Although we cannot draw firm conclusions on the spatial generators for the FPSW, it is line with the ongoing developmental maturation of the frontal cortex during adolescence (e.g., Casey et al., 2008) and it could explain the reduced prospective memory performance. In older adults, we found that the TPSW contributed to efficient encoding, matching the high prospective memory performance. The TPSW modulation could indicate compensatory mechanisms as they are supported by more frontal or bilateral activation in this age group (e.g., Cabeza, 2002; Davis et al., 2008). Future studies could follow up on these diverging patterns across the lifespan by using imaging techniques or source estimation.

4.3. Neural Correlates of Intention Retention

Previous studies have identified sustained positive modulations over frontal, parietal and posterior sides that could reflect monitoring for the prospective memory cue and maintenance of the intention (e.g., Cona et al., 2012a, b; Czernochowski et al., 2012; Mattli et al., 2011). For the retention phase, we identified a negative fronto-central sustained modulation that was sensitive to the presence versus absence of the intention instruction, similar to the previous findings. The prospective memory-specific sustained activity may represent the retrieval mode, which presents a state of preparation for the prospective memory cue to appear (Guynn, 2003; West et al., 2011). During the retention phase, participants maintain the intention and monitor the environment for the prospective memory cue while being engaged in the ongoing task. Given that cognitive resources are limited, these extra

demands of the prospective memory task may lead to costs to the ongoing task (e.g., reduced ongoing task performance or slower response times; Smith, 2003).

The number of intentions influenced the neural correlates for the ongoing task trials after encoding, which is of conceptual importance. More precisely, in ongoing task trials with a preceding intention instruction, the fronto-central sustained activity was less negative with increasing number of intentions, but this modulation was not found for ongoing task trials without an additional intention. For activity in ongoing task trials after retrieval, there were no differences between conditions except for the condition of maintaining two intentions with an eight seconds encoding time. For this condition, mean amplitudes were less negative compared to the three other conditions, which is in line with the lower behavioral ongoing task performance in the eight seconds encoding time condition. This supports our conclusion that the longer encoding time could have been distracting for participants (e.g., leading to mind wandering, etc.).

The increase in mean amplitudes for ongoing task trials after encoding might reflect costs to the ongoing task. Hence, when participants had to encode two compared to one intention they might have needed to engage in more attentional and mnemonic processes to maintain and monitor for the two intentions while working on the ongoing task. Similarly, Cona et al. (2013) found a greater sustained modulation for tasks that required more strategic monitoring than for tasks that required less or no monitoring. This higher engagement in maintaining the intentions and monitoring for the prospective memory cues seemed to have reduced the resources deployed to the ongoing task, which was indicated by the lower, more negative mean activity. Consequently, our findings demonstrate that participants are able to adapt their attentional resources to context (i.e., if intentions are present or not). Furthermore, a modulation by number of intentions indicated that resource allocation may be load- or content-dependent. Although our results demonstrated that the amount of information to maintain influences the retention phase, we cannot differentiate if participants rather passively

maintain intentions, if they actively monitor for the prospective cue or if they do a mix of both. Theoretical accounts suggest that participants monitor for the prospective cue (McDaniel and Einstein, 2000; Scullin et al., 2013; Smith and Bayen, 2004), which is supported by the present findings as well as previous results (e.g., Cona et al., 2013). Participants seem to monitor for the prospective memory cues and to adapt resources accordingly to the specific task demands. The exact nature of these processes needs to be addressed in future studies.

The sustained activity differed between age groups, being larger in adolescents and attenuated in older adults, a finding reported by other studies (e.g., Hering et al., 2016; Zöllig et al., 2007). However, there was no interaction with intention load or encoding time, indicating that the retention phase might be less relevant for prospective memory development. In contrast to our results, Mattli et al. (2011) did not find age differences in their lifespan sample for sustained activity associated with monitoring. The identification of developmental differences in the neural signature of maintaining and monitoring and their interaction with specific task demands needs to be further investigated by future research.

4.4. Neural Correlates of Intention Retrieval

For the retrieval phase, we focused on the prospective positivity and a subsequent negative parietal slow wave comparing mean activity for prospective memory cue trials and ongoing task trials (without intention load). Both potentials occurred within the time window of the parietal positivity, the neural correlate that represents intention retrieval in prospective memory (West, 2011). The prospective positivity was neither modulated by intention load nor by encoding time, however the mean amplitudes varied between age groups. Adolescents showed the greatest amplitude and older adults the lowest (cf. Zöllig et al., 2007). The mere activation of the prospective positivity might reflect the initiation of search processes after the prospective cue was detected and classified as task-relevant.

Compared to the prospective positivity, the parietal slow wave occurred rather late, starting at 800 ms after stimulus onset. We found an age-specific modulation of the parietal slow wave, showing that it was only present in adolescents and younger adults but not in older adults. Furthermore, the parietal slow wave was sensitive to intention load. When participants had to retrieve from two possible intentions, mean amplitudes were more negative than when participants had to retrieve only one intention. However, we did not find this difference for the ongoing task trials, indicating that it may be specific for prospective remembering. The increase in negativity for two intentions suggests that more coordination was required when having to select the correct response out of the two encoded intentions (Bisiacchi et al., 2009). The missing parietal slow wave modulation in older adults could indicate that they had more difficulties with the task coordination than the other groups. Meta-analytic evidence suggests that post-retrieval processes and task management contribute to age effects in prospective memory independently of pre-retrieval processes such as monitoring (Ihle et al., 2013).

Against our assumptions, longer encoding time did not benefit intention retrieval. Although the three age groups differed for both components in mean amplitudes, these differences were not linked to the memory-related processes, as we did not obtain any interactions with intention load or encoding time. This supports conclusions from previous studies that also have observed only a limited role of memory-related aspects for age-related differences in prospective memory retrieval (Cohen et al., 2003; Mattli et al., 2014).

4.5. Limitations

The present findings have to be considered in light of some limitations. The ongoing task seemed to have been more demanding for the adolescents than the two adult groups, which might have also influenced their prospective memory performance. However, performance rates were still relatively high (on average more than 75% correct responses in

adolescents) and comparable to other studies using a similar task and population (Hering et al., 2016; Zöllig et al., 2007).

Secondly, although we aimed to follow a lifespan approach, our study included only three distinct age groups. To better understand prospective memory development, it would be desirable to assess performance with a continuously increasing age range. So far, information on middle-aged adulthood is rather scarce and studies often focus on rather extreme groups of younger (20 to 30 years of age) and older adults (60 years of age and older).

Thirdly, to be able to analyze neural correlates of the encoding phase in light of our experimental manipulations of encoding time and number of intentions, our paradigm comprised 192 encoding trials and retrieval trials, respectively. This number may appear higher than in other (behavioral) studies on prospective memory, but it still represented only 6 % of all trials per block, which is in line with recommendations for ERP research (West, 2008) and comparable to other paradigms.

Lastly, we have to note that after the ERP data processing our final sample sizes for the different age groups were smaller than it is usually the case for behavioral studies, thus reducing statistical power to detect effects. However, our samples are comparable to similar ERP studies (Cona et al., 2012a; Zöllig et al., 2007). We encourage future studies to include larger sample sizes or to integrate the empirical findings with meta-analytical techniques to further investigate age differences across the lifespan.

5. Conclusions

The study set out to understand the neural correlates of prospective memory and their differences in adolescents, younger, and older adults. The aim was to identify at which stage in the process of prospective remembering (i.e., intention encoding, retention and retrieval) age differences are present and how ERPs could contribute to explaining such age differences. Our findings emphasize the role of *intention encoding* for understanding the prospective memory process in general and its lifespan development in particular. There are age-specific

contributions of the FPSW and the TPSW for differences in prospective memory encoding. Whereas the FPSW seemed mainly relevant for encoding efficiency in adolescents, the TPSW contributed to encoding in older adults, suggesting compensatory mechanisms. In our study, we used a quantitative manipulation of intention load by varying the number. Future studies could apply more qualitative manipulations such as providing encoding strategies to vary levels of encoding processes. Similarly, the fronto-central sustained activity during the retention phase did not show age-related differences that would contribute to prospective remembering. However, it could be shown that participants were able to adapt resource allocation depending on the intention load to maintain. Finally, the components investigated during the retrieval phase showed age-specific modulations, but the age differences were not modulated by the manipulations of intention load or encoding time. This may suggest that the components of the retrieval phase are relevant for prospective memory development, but that the influence of memory-related aspects seemed less relevant for explaining developmental differences at this stage. Other aspects of intention retrieval (e.g., cue detection) might be more suitable to explain age differences in prospective remembering during this phase (Hering et al., 2016). However, present results suggested that post-retrieval processes including task coordination are interesting candidates for revealing age-related differences. In sum, intention encoding seems to be a crucial but neglected parameter that influences not only later prospective memory performance, but also seems to be a driving factor for age differences between adolescents, younger and older adults. Elaborated encoding might be the key to successful realizing delayed intentions.

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Footnotes

¹The cognitive assessment included the following tests: digit-symbol-test, vocabulary test and matrices test from the Wechsler test batteries (Petermann and Petermann, 2007; von Aster et al., 2006) , a German verbal learning and memory test (Helmstaedter et al., 2001) and the Trail-making test (Reitan, 1979). The tests were not included in data analysis for the present study and therefore not further mentioned.

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Table 1.

Overview of prospective memory phases and associated neural correlates.

Phase	Investigated event-related potentials	Associated process
Intention encoding	Fronto-polar slow wave Temporal-parietal slow wave	Efficiency of encoding
Intention retention	Fronto-central sustained modulation	Maintaining a prospective retrieval mode that is adaptive to the context
Intention retrieval	Prospective Positivity	Initiation of search processes after cue detection
	Parietal Slow wave	Coordination between prospective memory task and ongoing task

Table 2.

Mean accuracy rates for the prospective memory task.

Intention load was manipulated by varying the number of intentions (one versus two intentions) and encoding time varied between four and eight seconds.

	Adolescents		Younger adults		Older adults	
	<i>N</i> = 25		<i>N</i> = 20		<i>N</i> = 21	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<i>Prospective memory accuracy</i>						
One intention						
4 seconds encoding	.82	.24	.96	.04	.92	.08
8 seconds encoding	.80	.23	.97	.04	.93	.07
Two intentions						
4 seconds encoding	.73	.23	.94	.04	.88	.09
8 seconds encoding	.73	.22	.94	.05	.87	.09
<i>Ongoing task accuracy</i>						
One intention						
4 seconds encoding	.77	.07	.86	.05	.89	.04
8 seconds encoding	.76	.07	.86	.05	.89	.04
Two intentions						
4 seconds encoding	.77	.08	.86	.06	.89	.06
8 seconds encoding	.76	.07	.85	.06	.88	.05

Figure 1.

Experimental paradigm.

Participants had to encode either one color-letter combination (low load) or two color-letter combinations (high load). Encoding trials were presented for either 4 seconds or 8 seconds. Each encoding trial was followed by six to ten ongoing task trials (semantic judgment task on the two words presented) lasting three seconds each. When on one trial the encoded color appeared as font color for the word pairs (e.g., green), participants had to retrieve the corresponding letter (e.g., C) and respond accordingly instead of performing the ongoing task (retrieval trial).

Figure 2.

Topographic maps and grand averages at Fpz separately for the three age groups showing the FPSW_{pos} and FPSW_{neg} for encoding trials that were followed by a prospective memory hit for encoding one versus two intentions. Encoding time conditions were collapsed. Note, the interaction between age group and intention load for the FPSW_{neg} did not reach significance ($p = .223$).

Figure 3.

Topographic maps and grand averages at P7 separately for the three age groups showing the TPSW for encoding trials that were followed by a prospective memory hit for encoding one versus two intentions. Encoding time conditions were collapsed.

Figure 4

Topographic maps and grand averages at FCz separately for the three age groups showing fronto-central sustained activity for ongoing task hits after retrieval and after encoding. Intention load and encoding time conditions were collapsed. Note, the interaction between age group and trial type did not reach significance ($p = .064$).

Figure 5.

Topographic maps and grand averages at Pz separately for the three age groups showing the prospective positivity (Pros. Positivity) and the parietal slow wave for prospective memory hits and ongoing task hits after retrieval. Intention load and encoding time conditions were collapsed.

Supplementary Material.

Inferential statistics for the electrode physiological measures.

	<i>F</i>	<i>df</i>	<i>p</i>	η_p^2
<i>Encoding</i>				
FPSW _{pos} at Fp1, Fpz, Fp2 (Mean amplitude in μV)				
Age	37.942	2, 54	< .001	.584
Intention Load	4.204	1, 54	.045	.072
Encoding Time	.075	1, 54	.785	.001
Electrode	1.602	1.9, 104.2	.207	.029
Age $\times$ Intention Load	12.597	2, 54	< .001	.318
Age $\times$ Encoding Time	.497	2, 54	.611	.018
Age $\times$ Electrode	1.412	3.9, 104.2	.236	.050
Intention Load $\times$ Electrode	.129	1.6, 84.0	.828	.002
Encoding Time $\times$ Electrode	.538	1.9, 103.1	.577	.010
Intention Load $\times$ Encoding Time	.017	1, 54	.897	.000
Age $\times$ Intention Load $\times$ Encoding Time	.555	2, 54	.577	.020
Age $\times$ Intention Load $\times$ Electrode	.260	3.1, 84.0	.861	.010
Age $\times$ Encoding Time $\times$ Electrode	.239	3.8, 103.1	.916	.009
Intention Load $\times$ Encoding Time $\times$ Electrode	2.898	1.5, 82.1	.075	.051
Age $\times$ Intention Load $\times$ Encoding Time $\times$ Electrode	3.713	3.0, 82.1	.014	.121
FPSW _{neg} at Fp1, Fpz, Fp2 (Mean amplitude in μV)				
Age	.633	2, 54	.535	.023
Intention Load	.748	1, 54	.391	.014
Encoding Time	5.444	1, 54	.023	.092
Electrode	.273	1.9, 100.0	.745	.005
Age $\times$ Intention Load	1.545	2, 54	.223	.054
Age $\times$ Encoding Time	.689	2, 54	.506	.025
Age $\times$ Electrode	1.635	3.7, 100.0	.176	.057
Intention Load $\times$ Electrode	.844	2.0, 107.2	.432	.015
Encoding Time $\times$ Electrode	3.216	1.8, 95.2	.051	.056
Intention Load $\times$ Encoding Time	.011	1, 54	.918	.000
Age $\times$ Intention Load $\times$ Encoding Time	2.378	2, 54	.102	.081

Age × Intention Load × Electrode	.384	4.0, 107.2	.818	.014
Age × Encoding Time × Electrode	1.385	3.5, 95.2	.249	.049
Intention Load × Encoding Time × Electrode	3.048	1.8, 97.6	.057	.053
Age × Intention Load × Encoding Time × Electrode	2.566	3.6, 97.6	.048	.087

TPSW at P7, P8 (Mean amplitude in μ V)

Age	.182	2, 54	.834	.007
Intention Load	1.462	1, 54	.232	.026
Encoding Time	2.562	1, 54	.115	.045
Electrode	.005	1, 54	.946	.000
Age × Intention Load	3.787	2, 54	.029	.123
Age × Encoding Time	.090	2, 54	.914	.003
Age × Electrode	1.047	2, 54	.358	.037
Intention Load × Electrode	1.843	1, 54	.180	.033
Encoding Time × Electrode	1.554	1, 54	.281	.028
Intention Load × Encoding Time	.905	1, 54	.346	.016
Age × Intention Load × Encoding Time	1.531	2, 54	.225	.054
Age × Intention Load × Electrode	4.233	2, 54	.020	.136
Age × Encoding Time × Electrode	2.217	2, 54	.119	.076
Intention Load × Encoding Time × Electrode	.706	1, 54	.404	.013
Age × Intention Load × Encoding Time × Electrode	2.454	2, 54	.096	.083

*Retention*Fronto-central sustained modulation at FCz
(Mean amplitude in μ V)

Age	6.289	2, 54	.004	.189
Intention Load	9.210	1, 54	.004	.146
Encoding Time	.573	1, 54	.452	.010
Trial Type	32.189	1, 54	< .001	.373
Age × Intention Load	1.123	2, 54	.333	.040
Age × Encoding Time	2.256	2, 54	.115	.077
Age × Trial Type	2.893	2, 54	.064	.097
Intention Load × Trial Type	5.111	1, 54	.028	.086
Encoding Time × Trial type	6.479	1, 54	.014	.107
Intention Load × Encoding Time	1.839	1, 54	.181	.033

Age × Intention Load × Encoding Time	.439	2, 54	.647	.016
Age × Intention Load × Trial Type	.877	2, 54	.422	.031
Age × Encoding Time × Trial Type	.373	2, 54	.691	.014
Intention Load × Encoding Time × Trial Type	6.266	1, 54	.015	.104
Age × Intention Load × Encoding Time × Trial Type	2.122	2, 54	.130	.073
<i>Retrieval</i>				
Prospective Positivity at Pz (Mean amplitude in μV)				
Age	5.259	2, 54	.008	.163
Intention Load	2.230	1, 54	.141	.040
Encoding Time	.014	1, 54	.906	.000
Trial Type	98.689	1, 54	< .001	.646
Age × Intention Load	.633	2, 54	.535	.023
Age × Encoding Time	1.884	2, 54	.162	.065
Age × Trial Type	5.452	2, 54	.007	.168
Intention Load × Trial Type	1.434	1, 54	.236	.026
Encoding Time × Trial type	.012	1, 54	.914	.000
Intention Load × Encoding Time	.015	1, 54	.903	.000
Age × Intention Load × Encoding Time	.251	2, 54	.779	.009
Age × Intention Load × Trial Type	.472	2, 54	.626	.017
Age × Encoding Time × Trial Type	.219	2, 54	.804	.008
Intention Load × Encoding Time × Trial Type	1.158	1, 54	.287	.021
Age × Intention Load × Encoding Time × Trial Type	1.217	2, 54	.304	.043
Parietal Slow wave at Pz (Mean amplitude in μV)				
Age	.407	2, 54	.668	.015
Intention Load	34.245	1, 54	< .001	.388
Encoding Time	.589	1, 54	.446	.011
Trial Type	60.090	1, 54	< .001	.527
Age × Intention Load	1.808	2, 54	.174	.063
Age × Encoding Time	.129	2, 54	.879	.005
Age × Trial Type	6.471	2, 54	.003	.193
Intention Load × Trial Type	35.678	1, 54	< .001	.398
Encoding Time × Trial type	1.433	1, 54	.237	.026

Intention Load × Encoding Time	.003	1, 54	.955	.000
Age × Intention Load × Encoding Time	.491	2, 54	.614	.018
Age × Intention Load × Trial Type	1.297	2, 54	.282	.046
Age × Encoding Time × Trial Type	.168	2, 54	.845	.006
Intention Load × Encoding Time × Trial Type	2.820	1, 54	.099	.050
Age × Intention Load × Encoding Time × Trial Type	.829	2, 54	.442	.030

Note. Significant findings in bold. FPSW = Fronto-polar Slow wave. TPSW = Temporal-parietal Slow wave.