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Sustained and transient processes in event-based prospective memory in adolescence and adulthood

Revision 2

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## Abstract

Prospective memory (PM) refers to the cognitive processes associated with remembering to perform an intended action after a delay. Varying the salience of PM cues while keeping the intended response constant, we investigated the extent to which participants relied on strategic monitoring, through sustained, top-down, control, or on spontaneous retrieval via transient bottom-up processes. There is mixed evidence regarding developmental improvements in event-based PM performance after age 13. We compared PM performance and associated sustained and transient neural correlates in 28 typically developing adolescents (12-17 years) and 19 adults (23-30 years). Lower PM cue salience associated with slower ongoing task (OT) reaction times, reflected by increased  $\mu$  Ex-Gaussian parameter, and sustained increases in frontoparietal activation during OT blocks, both thought to reflect greater proactive control supporting cue monitoring. Behavioural and neural correlates of PM trials were not specifically modulated by cue salience, revealing little difference in reactive control between conditions. The effect of cue salience was similar across age groups, suggesting that adolescents are able to adapt proactive control engagement to PM tasks demands. Exploratory analyses showed that younger, but not older, adolescents were less accurate and slower in PM trials relative to OT trials than adults and showed greater transient activation in PM trials in an occipito-temporal cluster. These results provide evidence of both mature and still maturing aspects of cognitive processes associated with implementation of an intention after a delay during early adolescence.

Keywords: prospective memory, ex-Gaussian function, sustained and transient processes, adolescence, fMRI

## Introduction

Prospective memory (PM) enables the execution of intended actions after a delay, e.g. remembering to respond to an email after reading this paper (Meacham & Singer, 1977). Event-based PM refers to instances in which the action needs to be performed in response to a cue (event) in the environment, such as remembering to send the email *when you see your laptop* (Einstein et al., 1992). An event-based laboratory task typically embeds a PM task, in which participants are instructed to do a different action in response to a target cue, in an ongoing task, which already requires a certain response to stimuli. Event-PM can be split into two components: cue identification (e.g., the email icon on your computer) and intention retrieval (e.g., what to do in response to the cue – write and send email; Simons et al., 2006).

PM performance is influenced by the degree to which several task factors rely on more or less top-down executive control processes, as has been proposed by the Multiprocess framework (McDaniel & Einstein, 2000), the preparatory attentional and memory (PAM) processes model (Smith, 2003), and more recently the Dual Mechanisms of Control framework (DMC; Braver 2012). The PAM theory posits that intention retrieval is only possible with non-automatic monitoring of the PM cue (Smith, 2003). In contrast, according to the Multiprocess Framework (McDaniel & Einstein, 2000), PM is supported by both strategic monitoring, which includes top-down sustained processes of intention maintenance and monitoring to detect a PM cue (McDaniel & Einstein, 2000), and spontaneous retrieval, associated with more transient bottom-up processes in which intentions “pop to mind” (McDaniel & Einstein, 2007; Scullin et al., 2013). Scullin and colleagues (2013) have proposed an extension, the Dynamic Multiprocess Framework, whereby strategic monitoring and spontaneous retrieval could be both recruited in the same PM task, but at different times and/or in distinct contexts. The extent to which individuals rely on strategic monitoring or spontaneous retrieval depends on: (1) characteristics of PM cues, including salience (how perceptually distinct PM cues are), valence, or focality (whether PM cue features are also the focus of the ongoing task), (2) characteristics of the task, including cognitive load and importance, and (3) characteristics of the individual, such as cognitive capacity and personality traits (Cona et al., 2015; Einstein et al., 2005).

The DMC framework (Braver, 2012) separates proactive and reactive dimensions of cognitive control, which are associated with sustained and transient activity in the frontoparietal and salience networks respectively (Braver, 2012; Jiang et al., 2015). Mapping these aspects of cognitive control to prospective memory processes may generate predictions at the brain-level and lead to improved understanding of

the cognitive processes supporting PM (McDaniel et al., 2013). Proactive control supports the cognitively demanding active maintenance of goals in working memory and attending to the environment (Braver, 2012; Koslov et al., 2019). While it is resource consuming, proactive engagement of preparatory attentional and memory processes would allow monitoring of the environment to detect PM cues that are non-salient or less important (Einstein et al., 2005; McDaniel & Einstein, 2000; Smith, 2003). Reactive control would match with the less demanding retrieval of the intention from episodic memory (Koslov et al., 2019).

Salient PM cues facilitate performance (Altgassen et al., 2010; Brandimonte & Passolunghi, 1994; Einstein et al., 2005; Kliegel et al., 2013; Mahy et al., 2014; Smith et al., 2007), reducing monitoring demands by encouraging spontaneous, automatic retrieval (Mahy et al., 2014), which does not load as much on cognitive demands and relies on reactive control triggered by the cue. The first aim of the present study was to investigate the effects of manipulating cue salience on strategic monitoring, mapped onto proactive and reactive cognitive control processes (Braver, 2012; McDaniel et al., 2013), and how this relates to the facilitation effect of cue salience on performance.

#### PM in Adolescence

Age-related differences are apparent in PM performance across the lifespan. Most studies to date have focused on improvements in childhood and impairments in aging. Cross-sectional studies have found evidence of improvement in performance until age 13 -14 years, when performance appears to level off through early adulthood, and later worsens in older adulthood (Kliegel et al., 2008; Zimmermann & Meier, 2006; Zöllig et al., 2007). By age 4, PM capacity is evident (Kvavilashvili et al., 2001) and continues to increase during preschool years (Ford et al., 2012; Guajardo & Best, 2000; Kliegel et al., 2008; Mahy et al., 2014). In middle childhood, performance continues to improve (Kerns, 2000; Mackinlay, Kliegel, & Mäntylä, 2009; Smith, Bayen, & Martin, 2010; Voigt et al., 2014). Not many studies have focused on adolescent and young adulthood samples however, and the evidence regarding continued development in this age group is mixed. Some studies show further improvement of PM performance in adolescence (from 12 to 16 years) compared to adults (Altgassen et al., 2014, 2017; Bowman et al., 2015; Wang et al., 2006, 2011; Zöllig et al., 2007), particularly when PM cues are not focal to the processes involved in the ongoing task. In contrast, some studies do not find strong evidence for development after early adolescence (Bowman et al., 2015; Wang et al., 2011; Ward et al., 2005; Zimmermann & Meier, 2006) with adolescents (over 13 years) and adults performing similarly better than children, and later on quite stable performance in young to mid- adulthood (Kliegel et al., 2008).

Other executive control processes that could contribute to PM, such as working memory and inhibitory control, develop extensively during childhood and adolescence (Best & Miller, 2010; Humphrey & Dumontheil, 2016; Munakata et al., 2012; Zanolie & Crone, 2018). Performance in prospective tasks that are particularly demanding might therefore be specifically impaired in adolescents, compared to adults (Altgassen et al., 2014; Bowman et al., 2015; Kliegel et al., 2013; Mahy et al., 2014). For example, adolescents have poorer PM performance than adults on tasks that use non-focal cues (Altgassen et al., 2014; Wang et al., 2011; Zöllig et al., 2007). In contrast, manipulation of cue salience to lessen cognitive demands can reduce age-related differences as has been shown in children (Kliegel et al., 2013) and also older adults (Altgassen et al., 2010).

Specifically, developmental differences in PM performance might be related to an immature ability to sustain cognitive control in adolescence, as it has been suggested adolescent participants rely more on reactive strategies than do adults in some contexts (Andrews-Hanna et al., 2011; Munakata et al., 2012), although see Magis-Weinberg et al. (2019) for evidence of flexible reactive and proactive control engagement in adolescence. This imbalance might impact the ability to monitor for PM cues, as salient and non-salient cues may recruit reactive and proactive control differentially and particularly challenge developing adolescent cognitive resources. Another driver of developmental differences may be orientation towards the future, which matures during adolescence (Steinberg et al., 2009) and has previously been shown to enhance PM function in adolescents (Altgassen et al., 2017) and adults (Altgassen et al., 2014).

The second aim of this study was therefore to directly test whether adolescents differed from adults in their ability to flexibly recruit proactive and reactive control of prospective memory as a function of cue salience, and whether age-related differences may be accounted for by developmental differences in executive functioning or future orienting.

#### Neural bases of PM

In adults, PM performance is robustly associated with a series of frontoparietal regions (for a review see Burgess, Gonen-Yaacovi, & Volle, 2011; Cona et al., 2015). The rostralateral prefrontal cortex (RLPFC), approximating Brodmann area (BA) 10 has been the main region implicated in intention maintenance (Burgess et al., 2007; Gilbert et al., 2006). The dorsolateral prefrontal cortex (DLPFC) and precuneus have been associated with monitoring (Kalpouzos et al., 2010; McDaniel et al., 2013), while more ventral frontoparietal and temporoparietal networks have been related to PM cue attention capture and intention retrieval (Beck et al., 2014; Kalpouzos et al., 2010; McDaniel et al., 2013). Cue detection and

intention retrieval have been associated with transient activity in the anterior cingulate cortex (ACC), posterior cingulate cortex (PCC) and temporal cortex (Beck et al., 2014; Gilbert et al., 2006, 2012; Gonneaud et al., 2014; Rusted et al., 2011). The anterior insula is frequently associated with prospective memory, with reports of both sustained and transient activation (Beck et al., 2014; Gilbert et al., 2009; Rea et al., 2011; Simons et al., 2006), suggesting a role in cue monitoring as well as increased cue salience (Cona et al., 2015).

A few studies using electrophysiology across the life span report differences with age in behavioural measures of PM and differences in neural activity measured through electroencephalography (EEG) between children, adolescents and adults (Mattli et al., 2011; Zöllig et al., 2007). Event-related potentials (ERPs) generated in PM error trials have different sources in children and adolescents compared to adults. This suggests that various processes might have contributed to PM errors in younger participants (Mattli et al., 2011; Zöllig et al., 2007). Bowman and colleagues (2015) described development of two key PM ERP components (N300 and parietal positivity) across the whole range of adolescence (age 12 to 19 years) in an ongoing task of lexical decision with PM targets cued by different coloured stimuli. They did not find age differences in N300 amplitude, but the parietal positivity was higher for the youngest (12-13 years) compared to the oldest adolescent group (18 -19 years), suggesting that cognitive processes associated with parietal positivity, such as general cognitive control capacities and working memory, are still developing.

Functional magnetic resonance imaging (MRI) neural correlates of PM function in adolescence remain insufficiently investigated (Dumontheil, 2014). However, studies investigating other aspects of cognitive control related to PM, such as abstract processing, integration and coordination of information have shown protracted development of their neural correlates in the RLPFC and parietal cortex during adolescence (Dumontheil, 2014; Dumontheil et al., 2008). This led us to hypothesise that adolescents would show poorer PM performance and associated differences in brain activity compared to adults. As for the behavioural measures, we further investigated whether developmental differences in PM may be related to developmental differences in executive function, using tasks previously shown to be sensitive to development during adolescence (Digit Span task for working memory, Go/No Go task for inhibitory control).

The present study

Here, we adapted an event-based PM paradigm designed by Simons et al. (2006) to focus on cue identification. In this version of the task, we kept intention retrieval demands constant, but manipulated

cue salience, which is thought to modulate the degree of strategic, proactive monitoring, to investigate proactive and reactive processes in PM. The DMC framework ties behavioural strategic monitoring with neural traces of proactive sustained cognitive control processes, and automatic retrieval to reactive transient cognitive control. Participants performed an ongoing task in which they indicated whether a triangle was to the left or right of another shape. Infrequent PM trials required pressing a different key if the shapes were the same colour (salient cue condition), or if they were a chess knight move apart (non-salient cue condition). Our aims were to (1) investigate the effects of manipulating the salience of the cue on strategic monitoring and recruitment of proactive vs. reactive control, and (2) to test whether adolescents differed from adults in behavioural and neural measures of prospective memory, and in their ability to flexibly recruit proactive and reactive control as a function of cue salience. Behavioural data were analysed with a distribution modelling technique using Ex-Gaussian functions, which has been used to characterize sustained and transient PM-induced cost effects (Abney et al., 2013; Ball & Brewer, 2017; Loft et al., 2014). A mixed block-event functional MRI (fMRI) design allowed us to investigate sustained and transient changes in blood oxygen-level dependent (BOLD) signal associated with intention maintenance across the task block and PM trials execution, respectively (Magis-Weinberg, Custers & Dumontheil, 2019).

We predicted that non-salient PM cues would be associated with worse PM performance than salient cues (McDaniel & Einstein, 2000). In the neuroimaging data, we expected activations associated with prospective memory in the RLPFC, dorsolateral PFC and parietal cortex in adults (in line with Simons et al., 2006), and modulation of sustained and transient activity by cue salience, with greater sustained activation in the low cue salience condition, associated with greater proactive monitoring, and reversely greater transient activation during PM trials in the high cue salience condition, reflecting reactive control and bottom-up target detection processes. We predicted age-related differences in PM performance, with better performance in adulthood than adolescence. We explored to what extent age group differences in Ex-Gaussian parameters related to overall reaction time ( $\mu$  parameter), variability ( $\sigma$  parameter) and abnormally slow responses ( $\tau$  parameter) contributed to reaction time interference costs associated with maintaining an intention. We explored whether adolescents exhibited different patterns of sustained and transient activation. We expected adolescents may show greater engagement of reactive control than adults, reflected in greater transient activation in PM trials. Adults were further expected to show greater differences in proactive control as a function of cue salience, which would reflect greater flexibility in proactive control engagement as a function of task demands. Finally, we explored whether lab-based behavioural and neural indices of prospective memory associated with



“real-life” subjective reports of PM and retrospective memory (RM) (Smith, Del Sala, Logie, & Maylor, 2000) and executive function failures (Buchanan et al., 2010), and whether neural and behavioural developmental differences in PM could be accounted for by developmental differences in executive functioning or future thinking.

## Method

### Participants

Nineteen adults (9 females, 22 – 30 years old,  $M = 27.1 \pm 1.9$  years ( $SD$ )) and 28 adolescents (15 females, 12 – 17,  $M = 14.6 \pm 1.4$ ) participated in the study. Data from two additional adolescents were not included in the analyses as they had less than three correct PM trials, and data from one additional adult participant were discarded due to technical problems with stimuli presentation during scanning. Participants did not have any developmental or neurological disorders and were recruited through advertising, social media, word of mouth and local participant volunteer databases. Participants were reimbursed £20 and their travel expenses for taking part in the study. This study was approved by the University College London Research Ethics Committee. Consent was obtained according to the Declaration of Helsinki, adults and the parents of adolescents provided written consent while adolescent themselves gave verbal consent. Adolescents and adults did not differ in their age-normed scores on the Vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence II (WASI; Wechsler, 2011) ( $M_{adolescents} = 67.2 \pm 4.8$  ( $SD$ );  $M_{adults} = 65.0 \pm 7.7$ ;  $t(27.5) = 1.1$ ,  $p = .29$ ).

### Design and materials

#### *Shapes PM task*

We adapted the “shapes” experimental task from Simons et al. (2006). All prospective memory trials were given the same intention retrieval demands whereas the cues remained either salient or non-salient. On each trial, two coloured shapes, a triangle and another shape, appeared in various positions in a  $4 \times 4$  grid (**Figure 1A**). Each shape had one of six possible colours. In the ongoing task (OT), participants had to indicate whether the triangle shape was located to the left or the right of the other shape. In the salient cue PM condition, if the shapes were the same colour, participants had to press a third key (Colour PM). In the non-salient cue PM condition, participants had to press the third key if the shapes were one chess knight’s move away from each other (Knight PM). Responses were indicated by pressing one of three buttons on a handheld response box (right index finger = left, right middle finger = right, right thumb = PM trial). Shapes were never the same colour in the Knight PM condition, nor in a knight configuration in the Colour PM condition, to avoid competing cues and confusion for the participants. Each trial started with 500 ms of a fixation cross, followed by presentation of the stimulus

(the two shapes in the 4x4 grid) for a maximum of 3000 ms, followed by 250 ms of a fixation cross at the inter-trial interval. The tasks were self-paced to prevent instruction rehearsal (Burgess et al., 2003).

An unrelated X task was used as an active baseline across all scanning runs (as in Simons et al., 2006). In this task, participants were asked to indicate as quickly as possible whether a series of X's were shown on the 4x4 grid along a vertical or horizontal axis (**Figure 1A**). Responses were given using the right index and middle finger keys. Vertical and horizontal X's stimuli alternated. Each trial presented the stimulus (the row of X's) until a response was made or for a maximum of 2000 ms. A fixation cross was shown during the inter-trial intervals, which varied randomly along a uniform distribution between 0 and 400 ms. The tasks were programmed in Cogent ([www.vislab.ucl.ac.uk/cogent\\_graphics.php](http://www.vislab.ucl.ac.uk/cogent_graphics.php)) running in MATLAB (The MathWorks, Inc., Natick, MA).

**Insert Figure 1 about here**

#### *Procedure*

The tasks were administered in three runs (**Figure 1B**). All runs were preceded by instructions and a practice round. The first run consisted of "uncontaminated" OT trials without any expectation of a PM trial, as the PM conditions were not mentioned in the instructions of this first run. Two PM runs followed, one run containing "contaminated" OT trials and Colour PM trials (salient cue), and one run containing "contaminated" OT trials and Knight (non-salient cue) PM trials. The order of the PM runs was counterbalanced between subjects. Each run consisted of five blocks of approximately 29 s of the shapes task alternating with approximately 14 s of the unrelated X task, with a 2 s pause between blocks which displayed an indication of the nature of the upcoming block ("Triangle task", "X task", "Colour task" or "Knight task"). Given the self-paced nature of the design, participants differed in total number of completed ongoing trials. Blocks of the two PM runs included up to two PM trials, which appeared no earlier than after 10 s of OT, to ensure that the participant would be fully engaged in the ongoing task and to control for the time between PM trials of successive blocks. In total, 10 PM trials were presented per run for both adolescents and adults. On average, adolescents completed 110 OT trials in the uncontaminated run, 94 OT trials in the Colour run, and 84 OT trials in the Knight run. Adults completed 113 OT trials in the uncontaminated run, 97 OT trials in the Colour run, and 88 OT trials in the Knight run.

#### *Other behavioural measures*

Participants completed the (1) Prospective and Retrospective Memory Questionnaire (PRMQ; Smith et al., 2000), (2) Future Orientation and Delayed Discounting Scale (FOS; Steinberg et al., 2009), and (3)

Webex, a web-based short self-report of executive functions (Buchanan et al., 2010). Participants also completed a computerised simple Go/No Go task (Simmonds et al., 2008) in which a “Go” stimulus (green square) is presented in high frequency and requires a rapid, dominant, response, which needs to be inhibited when a less frequent “No Go” stimulus (red square) is shown (Humphrey & Dumontheil, 2016). Lastly, participants were administered the Forward and Backward Digit Span task in which they were required to listen to a sequence of numbers and repeat them in the same or reversed order.<sup>1</sup>

#### *Image acquisition*

Functional data were acquired using the Center for Magnetic Resonance Research multiband echo planar imaging sequence (Xu et al., 2013) 2x acceleration, leak block on (Cauley et al., 2014) with BOLD contrast (44 axial slices with a voxel resolution of  $3 \times 3 \times 3$  mm covering most of the cerebrum; repetition time = 2 s; echo time = 45 ms; acquisition time = 2 s) in a 1.5 T MRI scanner with a 30-channel head coil (Siemens TIM Avanto, Erlangen, Germany). Functional images were acquired in three scanning runs lasting approximately 4 min each in which around 125 volumes were obtained (time and number of volumes varied per participant given the self-paced nature of the task). The first four volumes of each run were discarded to allow for T1 equilibrium effects. A T1-weighted Magnetization Prepared - Rapid Gradient Echo (MPRAGE) with 2x GeneRalized Autocalibrating Partial Parallel Acquisition (GRAPPA) acceleration anatomical image lasting 5 min 30 s was acquired before the acquisition of the three shapes task functional runs for each participant.

#### Data Analysis

##### *Behavioural data*

##### Mean RT and accuracy analyses

Mean accuracy and RT data were analysed using mixed repeated measures ANOVA (rmANOVA). In all RT analyses we only used correct ongoing trials within 2.5 SDs of each participant’s mean, and excluded two trials after PM trial presentation, since participants might have still been engaged in PM processes (Ball & Brewer, 2017). First, the OT trials of the three runs were compared, using Run (Uncontaminated, Colour, Knight) x Age group (Adolescents, Adults) mixed rmANOVAs, to assess age group differences in ongoing task performance. Second, OT and PM trials of the PM runs were analysed with two within-subjects factors (Run: Colour, Knight; Condition: OT, PM) and Age group (Adolescents, Adults) as a

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<sup>1</sup> In the scanner, participants completed the shapes task following the administration of two 8 min runs of a working-memory and reward task, for an unrelated study (Magis-Weinberg, Custers, & Dumontheil, 2019). Associated with the working memory and reward task study, participants completed computerised versions of the Behavioural Activation Scale (Carver & White, 1994) and Sensitivity to Punishment and Sensitivity to Reward Questionnaire (Torrubia et al., 2001).

between-subjects factor. This allowed us to assess whether age groups differed in PM trials performance, accounting for differences in ongoing task performance. Models were fitted in R (R Development Core Team, 2020) using the *afex* package (Singmann et al., 2020). Where necessary, Greenhouse-Geisser correction was employed for violation of sphericity and Tukey correction for multiple comparisons.

#### Distributional RT analyses

In addition to typical analyses of RT means, modelling RT distribution has been proposed as a useful technique to better characterize underlying profiles of cognitive control dynamics related to different processes (for details see Ball et al., 2015; Ball & Brewer, 2017). In PM, Ex-Gaussian parameters can help investigate processes underlying monitoring and better reflect whether slower RTs are observed across task conditions (e.g., continuous monitoring, associated with the  $\mu$  parameter), or whether a particular task condition has greater relative frequency of slower RTs (e.g., transient monitoring, associated with the  $\tau$  parameter). We applied the Ex-Gaussian model to the ongoing task trials RT data, using Quantile Maximum Probability Estimation (QMPE) software (Heathcote et al., 2004) to obtain parameters estimates ( $\mu$ ,  $\tau$ ,  $\sigma$ ) for each participant, separately for Uncontaminated, Colour and Knight runs, using the maximum possible number of quantiles ( $N-1$ ). Acceptable model fits were obtained within 30 iterations for all participants. Parameters estimates were then analysed using Run (Uncontaminated, Colour, Knight) x Age group (Adolescents, Adults) mixed rmANOVAs. Visualization of the differential impact of Ex-Gaussian parameters on RT can be achieved with vincentile plots of the raw RT distribution (Andrews & Heathcote, 2001; Balota & Yap, 2011). These plots were obtained separately for each run (Uncontaminated, Colour and Knight) by rank ordering raw RTs from shortest to longest for each individual and calculating the mean of the first 20%, the second 20%, and so forth.

#### Individual differences analyses

Exploratory Spearman correlations partialling out age were ran across age groups to assess whether measures of performance on the PM task (PM accuracy, PM RT, OT  $\mu$ , OT  $\tau$  and OT  $\sigma$ ) were associated with experimental executive function measures and questionnaire measures of PM failures and future orientation using the *psych* package (Revelle, 2019). In addition, to assess whether age-related differences in PM may be related to developmental differences in executive functioning or future orientation, original rmANOVAs were repeated with the inclusion, separately, of the forward digit score, backwards digit score, No Go accuracy or future orientation score as a mean centred covariate.

### *MRI data*

#### MRI data preprocessing

MRI data were preprocessed and analysed using SPM12 (Statistical Parametric Mapping, Wellcome Trust Centre for Neuroimaging, <http://www.fil.ion.ucl.ac.uk/spm/>). Images were realigned to the first analysed volume with a second-degree B-spline interpolation to correct for movement during the run. The bias-field corrected structural image was coregistered to the mean, realigned functional image and segmented based on International Consortium for Brain Mapping (ICBM) tissue probability maps using Montreal Neurological Institute (MNI) coordinates. Resulting spatial normalisation parameters were applied to the realigned images to obtain normalised functional images with a voxel size of 3 x 3 x 3 mm, which were smoothed with an 8-mm full width at half maximum Gaussian kernel.

Realignment estimates were used to calculate framewise displacement (FD) for each volume, which is a composite, scalar measure of head motion across the six realignment estimates (Siegel et al., 2014). Volumes with an FD > 0.9 mm were censored and excluded from general linear model estimation by including a regressor of no interest for each censored volume. No run met criteria for exclusion, which were more than 10 % of volumes censored or a root mean square (RMS) movement over the whole run greater than 1.5 mm. Adolescent and adult participants did not differ significantly in mean RMS rotational movement (adolescents =  $0.17 \pm 0.01$  (SE), adults =  $0.18 \pm 0.01$ ;  $p = .605$ ). There were however age group differences in the mean number of censored scans ( $M_{\text{adolescents}} = 0.61 \pm 0.16$ ,  $M_{\text{adults}} = 0.14 \pm 0.08$ ;  $p = .013$ ), and mean FD ( $M_{\text{adolescents}} = 0.11 \text{ mm} \pm 0.01$ ,  $M_{\text{adults}} = 0.09 \text{ mm} \pm 0.01$ ;  $p = .023$ ), and mean RMS translational movement ( $M_{\text{adolescents}} = 0.17 \text{ mm} \pm 0.02$ ,  $M_{\text{adults}} = 0.24 \text{ mm} \pm 0.03$ ;  $p = .042$ ), with more censored scans and greater mean FD, but lower RMS of translations in adolescents than adults.

### *fMRI general linear model*

The volumes acquired during the three sessions were treated as separate time series. For each series, the variance in the BOLD signal was decomposed with a set of regressors in a general linear model (GLM) that examined sustained (block-related) and transient (event-related) activity during task performance. Three boxcar regressors represented sustained ongoing task activity during the five blocks of each run: Uncontaminated OT, OT in Colour PM run ("Colour OT"), and OT in Knight PM run ("Knight OT"). Two event-related regressors represented transient PM activity in correct trials only: Colour PM, Knight PM. Two additional event-related regressors represented transient activity in ten randomly selected OT trials in each session (two per block, occurring before the PM trials), to serve as a comparison for the PM trials. Other regressors included for each run in the GLM were: an event-related

regressor representing the start instructions of each block and another representing the end of each block (Dumontheil et al., 2011); a boxcar regressor representing blocks of the X task, which served as the baseline for comparison across runs; regressors representing censored volumes as covariates of no interest; and the mean over scans. Both block and event-related regressors were convolved with the canonical haemodynamic response function. The data and model were high-pass filtered to a cut-off of 1/128 Hz.

Second-level whole-brain analyses were performed to assess sustained and transient PM-related brain activation. A first set of analyses investigated the sustained effects of maintaining intentions and compared the [OT block – X task block] contrasts from each of the three runs: Uncontaminated, Colour and Knight. A second set of analyses investigated transient effects in PM trials and analysed the Colour PM trials and Knight PM trials event-related first-level contrasts using the randomly selected OT trials as baseline: [Colour PM trials – OT trials] and [Knight PM trials – OT trials]. These contrasts were then entered into two flexible factorial random-effects analyses using two factors of interest with the design Subject x Age group (Adolescent, Adult) x Run type (Uncontaminated OT, Colour OT, Knight OT) or Trial type (Colour PM, Knight PM), modelling Subject as a main effect (to account for the repeated-measure nature of the data) and the Age group x Block type or Age group x Trial type interaction.

Sustained activation in Colour and Knight OT blocks compared to Uncontaminated OT blocks, transient activation in Colour and Knight PM trials, and differences between Colour and Knight tasks and the interactions with Age group were determined using the *t* statistic on a voxel-by-voxel basis. Statistical contrasts were used to create SPM maps thresholded at  $p < .001$  uncorrected at the voxel level and whole-brain cluster family-wise-error (FWE) correction at  $p < .05$  (corresponding to a minimum cluster size of 60 voxels for event-related analyses and 91 voxels for block-related analyses). Voxels surviving whole-brain FWE correction  $p < .05$  at the voxel-level are also reported. All coordinates are given in MNI space. Region labelling was done using automatic anatomical labelling (Tzourio-Mazoyer et al., 2002). BA labelling of peak of activations was done using MRICron (Rorden & Brett, 2000) (. Statistical maps for all whole-brain, voxel-wise analyses are available at: <https://neurovault.org/collections/6073/>.

Whole-brain correlations were run using two sample *t*-tests with a single covariate in SPM. In a first series of analyses, the contrast images were the average of [Colour OT block – X task block in Colour run] and [Knight OT block – X task block in Knight run], representing sustained activation associated with PM in the contaminated run, and the covariates were mean accuracy and RT in PM trials, FOS and PRMQ (PM), and  $\mu$ . In a second series of analyses, the contrast images were the average of [Colour PM trials –

OT trials] and [Knight PM trials – OT trials], representing transient activation associated with PM, and the covariate was  $\tau$ .

Exploratory analyses

As other studies suggest improvement in performance until 13 to 14 years (Altgassen et al., 2014; Bowman et al., 2015; Wang et al., 2006, 2011; Zöllig et al., 2007), two series of exploratory analyses were carried out. First, the adolescent sample was split into fourteen younger adolescents from 12 to 14 years ( $M = 13.1$ ,  $SD = 0.7$ ) and fourteen older adolescents from 15 to 17 years ( $M = 15.5$ ,  $SD = 0.5$ ) and their behavioural and fMRI data were compared with those of adults. Second, associations with age as a continuous measure were assessed within the adolescent sample.

## Results

### Behavioural results

#### *Accuracy and RT analyses of trial type and cue salience*

First analyses compared the OT trials of the three runs (Uncontaminated, Colour, Knight) in Run x Age group mixed rmANOVAs (**Table 1**). Adolescents ( $M = 93.7\%$  ( $SE = 0.8$ )) were less accurate than adults ( $M = 96.7\%$  ( $0.8$ )) (**Figure 2A**) but accuracy was not affected by the PM tasks. In contrast, RTs were slower in OT trials in the Knight run ( $M = 762$  ms ( $16$ )) than the Colour run ( $M = 650$  ms ( $16$ );  $t(36) = 5.8$ ,  $p < .0001$ ) and fastest in the Uncontaminated run ( $M = 584$  ms ( $16$ );  $t(36) = 9.9$ ,  $p < .0001$ ) (**Figure 2B**). There was no main effect of Run on accuracy, main effect of Age group on RT, or Run x Age group interaction on either accuracy or RT. Exploratory analyses indicated that the difference in accuracy between age groups was driven by trend-level poorer performance in younger ( $M = 94.6\%$  ( $1.0$ ),  $t(44) = 2.2$ ,  $p = .08$ ) and older adolescents ( $M = 93.9\%$  ( $1.1$ ),  $t(44) = 2.4$ ,  $p = .05$ ) than adults ( $M = 97.5\%$  ( $1.0$ )). There was no significant effect or interaction of age (as a continuous predictor) within the adolescent sample for either accuracy or RT (all  $F$ 's  $< 0.2$  and  $p$ 's  $> .15$ ).

**Table 1:** Statistical results of the behavioural age group analyses. Non-significant effects are put in square brackets. OT = ongoing task; PM = prospective memory.

Measure	Effects	Age group: Adolescents, Adults	Age group: Younger adolescents, Older adolescents, Adults
<b>Ongoing task trials: Run (Uncontaminated, Colour, Knight) x Age group</b>			
Accuracy	Age group	$F(1,45) = 7.3$ , $p = .01$ , $\eta^2 = .11^a$	$F(2,44) = 3.7$ , $p = .03$ , $\eta^2 = .12^a$
	Run	$[F(1.5,67.4) = 1.6$ , $p = .33]$	$[F(1.5,66.1) = 0.8$ , $p = .43]$
	Age group x Run	$[F(1.5,67.4) = 0.5$ , $p = .55]$	$[F(3,66.1) = 0.4$ , $p = .76]$
RT	Age group	$[F(1,45) = 2.6$ , $p = .11]$	$[F(2,44) = 1.5$ , $p = .25]$
	Run	$F(1.2,51.6) = 96.1$ , $p < .001$ , $\eta^2 = .31$	$F(1.2,50.4) = 102.2$ , $p < .001$ , $\eta^2 = .33$
	Age group x Run	$[F(1.5,51.6) = 1.3$ , $p = .26]$	$[F(2.3,50.4) = 0.9$ , $p = .44]$
<b>Run (Colour, Knight) x Trial type (OT, PM) x Age group</b>			
Accuracy	Age group	$F(1,45) = 8.9$ , $p = .005$ , $\eta^2 = .06^a$	$F(2,44) = 6.9$ , $p < .002$ , $\eta^2 = .09^a$
	Trial type	$F(1,45) = 135.4$ , $p < .001$ , $\eta^2 = .43$	$F(1,44) = 148.5$ , $p < .001$ , $\eta^2 = .44$
	Age group x Trial type	$[F(1,45) = 1.4$ , $p = .25]$	$F(2,44) = 4.2$ , $p = .02$ , $\eta^2 = .04$
	Run	$[F(1,45) = 2.9$ , $p = .10]$	$[F(1,44) = 2.9$ , $p = .09]$
	Age group x Run	$[F(1,45) < 0.1$ , $p = .86]$	$[F(2,44) < 0.1$ , $p = .98]$
	Trial type x Run	$[F(1,45) = 2.0$ , $p = .25]$	$[F(1,44) = 2.0$ , $p = .17]$
	Age group x Run x Trial type	$[F(1,45) < 0.1$ , $p = .97]$	$[F(2,44) < 0.1$ , $p = .99]$
RT	Age group	$F(1,45) = 4.5$ , $p = .04$ , $\eta^2 = .07^b$	$[F(1,44) = 2.6$ , $p = .09]$
	Trial type	$F(1,45) = 183.1$ , $p < .001$ , $\eta^2 = .17$	$F(1,44) = 200.1$ , $p < .0001$ , $\eta^2 = .18$
	Age group x Trial type	$F(1,45) = 5.5$ , $p = .02$ , $\eta^2 = .006^a$	$F(2,44) = 4.2$ , $p = .02$ , $\eta^2 = .009^a$



Run	$F(1,45) = 59.9, p < .001, \eta_G^2 = .19$	$F(1,44) = 61.9, p < .001, \eta_G^2 = .21$
Age group x Run	$[F(1,45) = 0.7, p = .41]$	$[F(2,44) = 0.3, p = .71]$
Trial type x Run	$F(1,45) = 12.8, p < .001, \eta_G^2 = .008$	$F(1,44) = 9.9, p = .003, \eta_G^2 = .006$
Age group x Run x Trial type	$[F(1,45) = 0.2, p = .64]$	$[F(2,44) = 1.3, p = .30]$

<sup>a</sup> Effect remained significant when forward digit score, backwards digit score, No Go accuracy or future orientation score were included as a centred covariate.

<sup>b</sup> Effect became non-significant when forward digit score, backwards digit score, No Go accuracy or future orientation score were included as a centred covariate.

The second set of analyses compared PM and OT trials in the two PM runs in Run (Colour, Knight) x Trial type (PM, OT) x Age group mixed rmANOVAs. Participants were more accurate on OT trials ( $M = 95.5\%$  (1.2)) than PM trials ( $M = 76.5\%$  (1.2)), and adolescents ( $M = 83.2\%$  (1.3)) were again overall less accurate than adults ( $M = 88.5\%$  (1.3)) (**Table 1**), but there was no main effect of run or significant two or three-way interaction (**Figure 2A**). Exploratory analyses comparing younger and older adolescents to the adult group demonstrated that the main effect of age group was driven by younger adolescents ( $M = 81.8\%$  (1.5)), who were less accurate than adults ( $M = 89.0\%$  (1.4);  $t(44) = 3.7, p = .0017$ ), while older adolescents had intermediary accuracy ( $M = 86.6\%$  (1.6)) and did not differ from younger adolescents or adults ( $p$ 's  $\geq .10$ ). In addition, there was a significant Trial type x Age group interaction indicating that younger adolescents were less accurate in PM trials than older adolescents ( $\Delta M = 9.9\%$  (3.0),  $t(87) = 3.3, p = .003$ ) and adults ( $\Delta M = 11.2\%$  (2.6),  $t(87) = 4.2, p = .0001$ ) but did not differ from older adolescents on OT trials ( $p$ 's  $> .43$ ). Older adolescents and adults did not differ on either PM or OT trials ( $p$ 's  $> .41$ ). Consistent with these age group analyses, exploratory analyses within the adolescent group showed a significant linear increase in accuracy with Age ( $F(1,26) = 5.09, p = .03, \eta_p^2 = .05$ ), however the Trial type x Age interaction was not significant ( $F(1,26) = 0.02, p = .89$ ).

For RT data (**Table 1**) participants were faster on OT trials ( $M = 709$  ms (18)) than PM trials ( $M = 834$  ms (18)), and faster in the Colour ( $M_{Colour} = 703$  ms (19)) than the Knight run ( $M = 839$  ms (19)). In addition, the interaction between Trial type and Run was significant: the difference between Knight and Colour runs was greater for PM trials ( $\Delta M = 159$  ms (19)) than for OT trials ( $\Delta M = 111$  ms (18)) (**Figure 2B**).

Adolescents ( $M = 809$  ms (25)) were slower than adults ( $M = 733$  ms (25)); but a significant Trial type x Age group interaction indicated that the age group difference was driven by PM trials ( $\Delta M = 97$  ms (37),  $t(51.1) = 2.6, p = .01$ ), with no difference in OT trials ( $\Delta M = 53$  ms (37),  $t(51.1) = 1.5, p = .15$ ) (**Figure 2B**).

Neither the interaction between Run and Age group nor the three-way interaction was significant.

Exploratory analyses with the split adolescent groups showed similar results. While the main effect of Age group did not reach significance (**Table 1**), the interaction between Trial type and Age group showed

that younger adolescents were significantly slower than adults on PM trials ( $\Delta M = 120$  ms (41),  $t(49.7) = 2.9$ ,  $p = .02$ ) but not on OT trials ( $\Delta M = 61$  ms (41),  $t(49.7) = 1.5$ ,  $p = .31$ ). Older adolescents did not differ from either age group on either type of trials (all  $p$ 's  $> .38$ ). Exploratory analyses within the adolescent group revealed no main effect of age (as a continuous predictor) or interactions with age (all  $F$ 's  $< 3.1$  and  $p$ 's  $> .09$ ).

**Insert Figure 2 about here**

#### *Ex-Gaussian analyses*

Ex-Gaussian analyses focused on the ongoing task RT data (**Table 2**). Run (Uncontaminated, Colour, Knight) x Age group (Adolescents, Adults) mixed rmANOVA revealed a main effect of Run for all three estimates (**Table 2**), but with different patterns.  $\mu$  estimates were higher in the Knight than the Colour run ( $t(90) = 7.2$ ,  $p = .007$ ), and higher in both Knight ( $t(90) = 10.3$ ,  $p < .0001$ ) and Colour ( $t(90) = 3.1$ ,  $p < .0001$ ) than in the Uncontaminated run. There was therefore a modal shift of the overall RT distribution ( $\mu$ ) in ongoing trials of the PM runs that was greater in the Knight task than the Colour task (**Figure 3**).  $\tau$  was higher in the Knight than the Uncontaminated run ( $t(90) = 2.6$ ,  $p = .025$ ), and there was a trend for higher  $\tau$  for the Colour than the Uncontaminated run ( $t(90) = 2.3$ ,  $p = .054$ ), but no difference between Knight and Colour runs ( $t(90) = 0.31$ ,  $p = .94$ ). Colour and Knight tasks were therefore associated with a similar increased frequency of slow RTs (**Figure 3**).  $\sigma$  estimates were higher in the Knight run than the Uncontaminated ( $t(90) = 7.3$ ,  $p < .0001$ ) and Colour runs ( $t(90) = 6.9$ ,  $p < .0001$ ), with no difference between Colour and Uncontaminated runs ( $t(90) = 0.3$ ,  $p = .93$ ), suggesting increased overall variability in the Knight ongoing task. There were no significant main effects of Age group or Run by Age group interaction ( $p$ 's  $> .08$ ), except for the  $\tau$  estimate. A main effect of Age group ( $F(1,45) = 7.7$ ,  $p = .008$ ,  $\eta_p^2 = .08$ ) indicated that adolescents had more frequent slow RTs (higher  $\tau$  estimates,  $M = 115$  ms ( $SE = 7$ )) than adults ( $M = 87$  ms ( $7$ )). Exploratory analyses with the split adolescent groups indicated age group differences were driven by the younger adolescents. There was a main effect of Age group ( $F(2,44) = 7.1$ ,  $p = .002$ ,  $\eta_p^2 = .14$ ): younger adolescents had overall higher  $\tau$  estimates ( $M = 125$  ms ( $8$ )) than older adolescents ( $M = 96$  ms ( $8$ );  $t(90) = 3.7$ ,  $p = 0.001$ ) and adults ( $M = 82.2$  ( $7.9$ );  $t(90) = 2.3$ ,  $p = 0.05$ ), while older adolescents and adults did not differ ( $t(44) = 1.2$ ,  $p = .47$ ). Exploratory analyses within the adolescent group revealed no significant main effect of age or interaction between Run and Age (all  $F$ 's  $< 4.1$  and  $p$ 's  $\geq .05$ ), although, consistent with the three age groups analyses, the effect of age on  $\tau$  was at trend level ( $F(1,26) = 4.1$ ,  $p = .05$ ).

**Table 2.** Results of the Ex-Gaussian analyses of the ongoing trials RT data.

	Uncontaminated run Mean (SE)	Colour run Mean (SE)	Knight run Mean (SE)	Main effect of Run
RT (ms)	584 (16)	650 (16)	762 (16)	$F(1.2,51.6) = 96.2, p < .001, \eta^2 = .31$
$\mu$ (ms)	497 (15)	544 (15)	653 (15)	$F(1.2,53.7) = 55.9, p < .001, \eta^2 = .29$
$\tau$ (ms)	87 (7)	106 (7)	109 (7)	$F(1.4,60.9) = 4.2, p < .03, \eta^2 = .04$
$\sigma$ (ms)	51 (5)	52 (5)	96 (5)	$F(1.3,58.2) = 33.6, p < .001, \eta^2 = .27$

Insert Figure 3 about here

*Other behavioural measures of executive function, prospective memory failures and future orientation*

Adults had higher backwards digit span scores than adolescents and there was a trend for greater future orientation in adults than adolescents. The other measures did not show age group differences (**Table 3**). Spearman correlation analyses partialling out age showed that PM accuracy was negatively associated with Webexec ( $r = -.34, p = .02$ ) and PRMQ (PM) ( $r = -.32, p = .03$ ) scores, which are indices of executive functioning and PM failures in daily life, respectively. Correlations between PM RT, OT  $\mu$ , OT  $\tau$ , and OT  $\sigma$  and questionnaire measures of executive functioning and PM and future orientation were not significant (all  $p$ 's > .21).

**Table 3.** Behavioural measures of executive functions, prospective memory and future orientation. Summary statistics of measures collected in adolescent and adult participants. The possible range for each measure is given in brackets. FOS: Future Orientation Scale; PM: prospective memory; PRMQ: Prospective and Retrospective Memory Questionnaire; RM: retrospective memory.

	Adolescents Mean (SE)	Adults Mean SE)	Age group comparison
Prospective memory <sup>a</sup>			
PRMQ (PM subscale) (8 – 40)	22.0 (0.7)	20.6 (0.8)	$t(45) = 1.4, p = .17$
PRMQ (RM subscale) (8 – 40)	19.1 (0.9)	19.4 (0.9)	$t(45) = 0.3, p = .76$
Future orientation			
FOS (1 – 4) <sup>b</sup>	2.9 (0.1)	3.1 (0.1)	$t(43)^d = 1.9, p = .06$
Executive functions			

Webexec (6 – 24) <sup>c</sup>	13.5 (0.5)	12.8 (0.7)	$t(45) = 0.9, p = .42$
Forward digit span score (1 – 22)	16.8 (0.7)	18.2 (0.8)	$t(45) = 1.4, p = .18$
Backward digit span score (1 – 22)	9.0 (0.6)	12.2 (0.8)	$t(44) = 3.5, p = .001$
No Go accuracy (%)	87.7 (1.7)	91.2 (2.1)	$t(45) = 1.4, p = .16$

<sup>a</sup> Higher scores indicate more prospective and retrospective memory failures

<sup>b</sup> Higher scores indicate stronger future orientation

<sup>c</sup> Higher scores indicate more executive functioning failures

<sup>d</sup> One adolescent participant did not complete the backwards digit span task

To assess whether observed developmental differences in PM task measures may have been related to developmental differences in executive functioning or future orientation, the rmANOVAs ran above which showed significant main effects or interactions with age group (Adolescents, Adults) were repeated with the inclusion, separately, of the forward digit score, backwards digit score, No Go accuracy or future orientation score as a centred covariate. Results showed that the significant main effects of age on accuracy and interactions of age group with Run and Trial type on RT remained significant when these covariates were included. However, the main effect of age group on RT in contaminated runs, which indicated slower RTs in adolescents than adults across OT and PM trials, became non-significant when forward digit score, backwards digit score, No Go accuracy or future orientation were entered as a covariate (**Table 1**).

## Neuroimaging results

### *Intention maintenance*

Sustained activation during the ongoing task blocks were compared between runs, using blocks of the X task, common across runs, as a baseline, for all comparisons. Compared to OT blocks in the Uncontaminated run, ongoing task blocks in the Colour run were associated with higher BOLD signal in a large cluster in the right hemisphere with peak activation in the insula, extending into the right lateral middle frontal gyrus cluster and rostrally into the frontal pole. The left insula/frontal operculum also showed increased BOLD signal in this contrast, as well as the left fusiform gyrus and the left cerebellum. The other observed clusters were bilateral and located in the inferior parietal lobules and along the medial wall in the pre-supplementary motor area (pre-SMA) (**Table 4, Figure 4A**).

Ongoing task blocks in the Knight run exhibited similar but greater overall activation than in the Colour run when compared to the Uncontaminated run. The right frontal and bilateral parietal clusters were larger and the latter extended to the medial wall and into the middle occipital gyri. There was also an additional cluster in the left precentral gyrus (**Table 4, Figure 4B**).

Comparing Colour OT blocks to Knight OT revealed higher activation in bilateral angular gyri, left supramarginal gyrus and in a cluster in the superior medial frontal cortex, reflecting less decreases in BOLD signal compared to X-task baseline blocks in the Colour run than the Knight run (**Table 4, Figure 4C**). Comparing Knight OT blocks to Colour OT revealed higher activations of the right superior frontal gyrus and bilateral superior and inferior parietal lobules, in regions that showed overall greater activation in the contaminated than the uncontaminated runs, and greater activation in OT task blocks than X task blocks (**Table 5, Figure 4D**).

**Table 4.** Sustained neuroimaging results across age groups. Coordinates and *t*-values are listed for regions showing a significant difference in sustained BOLD signal for [Colour ongoing task (OT) block > Uncontaminated OT block], [Knight OT block > Uncontaminated OT block], and the comparison between the two. Blocks of the X-task were used as a baseline common across runs. BA = Brodmann area; L/R = left/right hemisphere; SMA = supplementary motor area.

Region	L/R	Extent	<i>t</i> -value	x	y	z	BA
<b>Colour OT &gt; Uncontaminated OT</b>							
Insula	R	1111 <sup>b</sup>	8.21 <sup>a</sup>	33	26	2	47
Inferior frontal gyrus (operculum)	R		7.16 <sup>a</sup>	42	8	29	44
Middle frontal gyrus	R		5.82 <sup>a</sup>	39	2	53	6
Pre-SMA	R	218 <sup>b</sup>	6.09 <sup>a</sup>	6	20	50	8
Inferior parietal lobule	L	505 <sup>b</sup>	5.90 <sup>a</sup>	-45	-37	50	40
Superior parietal lobule	L		5.32 <sup>a</sup>	-27	-64	56	7
Inferior parietal lobule	R	546 <sup>b</sup>	5.64 <sup>a</sup>	33	-55	53	7
Supramarginal gyrus	R		5.26 <sup>a</sup>	45	-34	44	40
Insula	L	147 <sup>b</sup>	5.45 <sup>a</sup>	-30	26	-1	47
Cerebellum	L	186 <sup>b</sup>	4.99 <sup>a</sup>	-6	-79	-19	
Cerebellum	L		4.87 <sup>a</sup>	-27	-73	-22	
<b>Knight OT &gt; Uncontaminated OT</b>							

Inferior parietal lobule	L	1515 <sup>b</sup>	10.56 <sup>a</sup>	-45	-37	47	40/2
Superior parietal lobule	L		9.92 <sup>a</sup>	-15	-67	56	7
Middle occipital gyrus	L		6.81 <sup>a</sup>	-27	-70	29	19
Supramarginal gyrus	R	1944 <sup>b</sup>	9.90 <sup>a</sup>	39	-37	44	40
Superior parietal lobule	R		9.26 <sup>a</sup>	27	-64	53	7
Middle occipital gyrus	R		5.87 <sup>a</sup>	33	-79	14	19
Insula	R	1703 <sup>b</sup>	9.79 <sup>a</sup>	33	26	2	47
Precentral gyrus	R		9.19 <sup>a</sup>	45	8	29	44
Middle frontal gyrus	R		6.54 <sup>a</sup>	33	2	59	6
Inferior frontal gyrus	L	162 <sup>b</sup>	7.38 <sup>a</sup>	-30	20	-1	47
Pre-SMA	R	295 <sup>b</sup>	7.21 <sup>a</sup>	6	20	50	8
Inferior frontal gyrus (operculum)	L	189 <sup>b</sup>	6.88 <sup>a</sup>	-42	5	26	44
Inferior temporal gyrus	R	751 <sup>b</sup>	6.75 <sup>a</sup>	48	-52	-7	37
Fusiform	L		6.42 <sup>a</sup>	-30	-73	-19	19
Cerebellum	L		5.91 <sup>a</sup>	-9	-79	-19	
Superior frontal gyrus	L	244 <sup>b</sup>	6.29 <sup>a</sup>	-24	2	62	6.

#### Colour OT > Knight OT

Mid cingulate cortex	L	365 <sup>b</sup>	4.83 <sup>a</sup>	-12	-49	35	23
Mid cingulate cortex			3.97	0	-22	41	23
Mid cingulate cortex	R		3.93	12	-46	35	23
Angular gyrus	R	191 <sup>b</sup>	4.83 <sup>a</sup>	57	-58	35	39
Angular gyrus	R		4.07	45	-67	50	39
Superior frontal gyrus	L	108 <sup>b</sup>	4.68	-15	41	47	1
Angular gyrus	L	159 <sup>b</sup>	4.62	-45	-70	44	39
Supramarginal gyrus	L		3.71	-60	-55	32	40

#### Knight OT > Colour OT

Precuneus	L	2067 <sup>b</sup>	7.37 <sup>a</sup>	-15	-67	56	7
Superior parietal lobule	R		6.79 <sup>a</sup>	18	-61	56	7
Supramarginal gyrus	R		6.60 <sup>a</sup>	36	-40	44	40

Superior frontal gyrus      R                      95<sup>b</sup>      4.63      24      8      56      6/8

<sup>a</sup> Voxel significant at  $p_{FWE} < .05$ . <sup>b</sup> Cluster significant at  $p_{FWE} < .05$ , with a cluster-defining threshold of  $p < .001$  uncorrected at the voxel level.

**Insert Figure 4 about here**

*PM trial execution*

Transient effects during PM trials were investigated by contrasting event-related changes in BOLD signal during PM trials to a randomly selected subset of OT trials performed within the same run. Colour PM trials were associated with strong activation along the precentral and postcentral gyri bilaterally, extending into the supramarginal gyri, frontal activation in the left inferior and middle frontal gyri, and bilateral anterior insula, and activation along the medial wall in clusters in the mid-cingulate cortex and pre-SMA or SMA, as well as in the right middle temporal gyrus (**Table 5, Figure 5**). Knight PM trials were associated with a similar but broader network of brain regions, with additional clusters in the frontal cortex bilaterally and in the right parietal and temporal cortex. A more conservative threshold of  $p < .0001$  uncorrected at the voxel-level was used to differentiate the clusters observed in this contrast presented **Table 5** and **Figure 5**. There was bilateral activity in the frontal poles (RLPFC) which extended posteriorly into inferior and middle frontal gyri including DLPFC and VLPFC. There was activation of bilateral AI. On the medial wall, there was activation that extended from the anterior cingulate cortex to the SMA and mid-cingulate cortex. In the parietal lobes, bilateral superior and inferior activation was observed, as well as precentral and postcentral gyri activation. Finally, there was activation of the right middle temporal gyrus, as well as of subcortical structures: the caudate and putamen. No regions showed an impact of cue salience, i.e. differences in event-related BOLD signal between Colour PM and Knight PM trials, when controlling for contaminated OT trials.

**Insert Figure 5 about here**

**Table 5.** *Transient neuroimaging results across age groups.* Coordinates and *t*-values are listed for regions showing a significant difference in transient BOLD signal between Colour prospective memory (PM), Knight PM and ongoing task (OT) trials. BA = Brodmann area; L/R = left/right hemisphere; SMA = supplementary motor area

Region	L/R	Extent	<i>t</i> -score	x	y	z	BA
<b>Colour PM trials &gt; Colour OT trials</b>							
Postcentral gyrus	L	1489 <sup>b</sup>	7.45 <sup>a</sup>	-60	-22	41	3
Precentral gyrus	L		6.61 <sup>a</sup>	-33	-22	71	6

Postcentral gyrus	L		6.13 <sup>a</sup>	-48	-31	59	3/2
Insula	R	158 <sup>b</sup>	5.76 <sup>a</sup>	36	17	-1	48
Postcentral gyrus	R	574 <sup>b</sup>	5.60 <sup>a</sup>	57	-22	53	3
Postcentral gyrus	R		4.48	60	-16	32	43
Postcentral gyrus	R		4.43	42	-40	62	2
Mid cingulate cortex	L	274 <sup>b</sup>	4.98	-9	5	38	24
SMA	R		3.99	3	11	62	6
Superior frontal gyrus	R	94 <sup>b</sup>	4.95	33	-7	65	6
Mid temporal gyrus	R	166 <sup>b</sup>	4.84	48	-25	-7	21
Mid temporal gyrus	R		4.47	57	-43	2	22
Precentral gyrus	R	80 <sup>b</sup>	4.76	57	11	32	6/44
Middle frontal gyrus	L	99 <sup>b</sup>	4.46	-36	41	29	46
Mid cingulate cortex	L	72 <sup>b</sup>	4.23	-12	-28	47	23
SMA	R		3.96	9	-22	47	23

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**Knight PM trials > Knight OT trials**

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Insula	R	3243 <sup>b</sup>	7.82 <sup>a</sup>	39	17	-1	48
Mid temporal gyrus	R		6.87 <sup>a</sup>	57	-40	2	22
Middle frontal gyrus	R		6.61 <sup>a</sup>	42	50	8	46/10
Postcentral gyrus	L	1476 <sup>b</sup>	6.14 <sup>a</sup>	-45	-28	50	3
Postcentral gyrus	L		6.01 <sup>a</sup>	-57	-19	35	48
Precentral gyrus	L		5.25	-33	-22	71	6
Mid cingulate cortex	R	1379 <sup>b</sup>	6.35 <sup>a</sup>	9	29	32	32
Mid cingulate cortex	L		5.52 <sup>a</sup>	0	-10	32	23
SMA	R		4.87	6	17	56	6
Insula	L	700 <sup>b</sup>	9.40 <sup>a</sup>	-33	20	-7	47
Insula	L		5.44 <sup>a</sup>	-36	-1	2	48
Middle frontal gyrus	L	444 <sup>b</sup>	5.59 <sup>a</sup>	-33	47	17	5
Middle frontal gyrus	L		5.13	-39	32	35	46
Precentral gyrus	L		4.70	-45	5	44	6
Fusiform gyrus	R	269 <sup>b</sup>	5.27	24	-58	-16	37



Vermis			3.83	3	-67	-28
Caudate	R	100 <sup>b</sup>	5.61 <sup>a</sup>	12	2	17
Thalamus	R		3.84	9	-19	8

<sup>a</sup> Voxel significant at  $p_{FWE} < .05$ . <sup>b</sup> Cluster significant at  $p_{FWE} < .05$  at the cluster level, with a cluster-defining threshold of  $p < .001$  uncorrected at the voxel level for the Colour PM trials > Colour OT trials, and  $p < .0001$  uncorrected for the Knight PM trials > Knight OT trials contrast. This more stringent contrast was used to better differentiate the observed clusters.

#### *Age group differences*

Adolescents and adults did not show differences in patterns of activation in any of the sustained or transient BOLD signal changes contrasts. Exploratory analyses comparing the younger, older adolescent and adult groups showed greater activation in the young adolescent group compared to the adult group in PM trials than in contaminated OT trials in a posterior cluster (119 voxels) located in the right fusiform ([36, -52, -13], BA 37,  $t = 5.24$ ), inferior temporal gyrus ([48, -49, -7], BA 17,  $t = 4.54$ ) and inferior occipital gyrus ([36, -67, -10], BA 19,  $t = 3.99$ ) (**Figure 6**). There were no other significant differences between these age groups. Additional exploratory analyses assessed whether brain activation was associated with age as a continuous measure in the adolescent sample. No significant associations were observed.

**Insert Figure 6 about here**

#### *Covariate analyses*

Whole-brain analyses were performed to investigate correlations between the self-reported measure of FOS, PRMQ (PM) and  $\mu$  and sustained BOLD signal during contaminated trials in OT blocks (averaging across cue salience), and  $\tau$  and transient BOLD signal during PM trials. No significant association was observed.

## Discussion

We examined the impact of cue salience on event-based prospective memory and whether differences exist between adolescents and adults. To characterise sustained and transient processes associated with prospective memory, we supplemented analyses of mean indices of performance. We used Ex-Gaussian modelling of RT distribution to distinguish patterns of slowing associated with PM interference. We also used a mixed block/event-related fMRI design, which allowed the investigation of sustained effects associated with maintaining PM intentions, and transient effects associated with PM trial execution. We show that adults remember to execute delayed intentions better than young adolescents and provide some evidence that this ability develops somewhat across the adolescent age range in this study (12 – 17 yo). High cue salience facilitated prospective memory performance and influenced sustained activation during the ongoing task. However, contrary to predictions, cue salience did not interact with age. Adolescents and adults showed similar modulation of performance and neural activity by cue salience, and broadly similar behavioural and neural correlates of PM.

## Behavioural results

### *PM intention maintenance (OT trials)*

In comparison to the uncontaminated run, intention maintenance throughout contaminated runs was associated with slower mean RTs, but similar accuracy. We manipulated one of the main retrieval-based factors, cue salience, to explore the underlying cognitive processes related to its facilitation effect on performance. The two PM conditions were designed to elicit a greater need for proactive monitoring of the Knight PM cues than the Colour PM cues, and, reversely, the possibility to rely to a greater extent on reactive control for the detection of the salient Colour PM cues. Consistent with the task design, monitoring costs varied as a function of cue salience, with relatively slower RTs for ongoing trials of the Knight run, with non-salient PM cues, than the Colour run, with salient PM cues. There was no difference in OT accuracy between PM conditions. This suggests that non-salient cues had higher intention maintenance and cue monitoring demands that detracted from speed, but not accuracy, performance of the ongoing task. To the extent that perceptually salient cues can elicit an orienting response (Kliegel et al., 2013, McDaniel & Einstein, 2000) they can be more reliant on bottom-up attentional processes (Smith, 2003; Smith & Bayen, 2004), reducing the need for controlled monitoring. In contrast, low cue salience can cause shifts towards the use of proactive above reactive control mechanisms, as more strategic monitoring (versus automatic retrieval) is needed for successful performance.

Mean RT interference costs have been well documented in PM paradigms (Smith, 2003) and can be interpreted as evidence for monitoring activities in the context of competition for limited cognitive control resources (Altgassen et al., 2017). Alternative interpretations posit that increased latencies can be related to target-checking strategies before and after the ongoing decision (Horn & Bayen, 2015), or that they could relate to lapses in attention (Ball & Brewer, 2017).

Standard RT cost analyses were followed up with Ex-Gaussian distribution modelling, which has been suggested to differentiate between sustained (associated with the  $\mu$  parameter) and transient PM-induced cost effects (associated with the  $\tau$  parameter) (Abney et al., 2013; Ball & Brewer, 2017; Loft et al., 2014). Intention maintenance was associated with an overall shift in the distribution ( $\mu$ ) which was highest for the condition with non-salient PM cues, and is reflective of the increased RTs described above. A  $\mu$  cost has been proposed as an important indicator of slowing due to PM processes (Ball & Brewer, 2017), which suggests that sustained monitoring is particularly increased in ongoing trials of the Knight task, when the PM cue is less salient. However, the  $\mu$  parameter was not correlated with sustained BOLD activity in the contaminated runs. A second parameter,  $\sigma$ , which captures variability of the normal distribution (Gmehlin et al., 2016; Vaurio et al., 2009), was increased in the Knight run compared to the Colour and Uncontaminated runs, which did not differ. This increased variability may reflect fluctuations in recruitment of proactive control and cue monitoring in this more demanding task. Increased  $\sigma$  has previously been observed in children with and without attention deficit and hyperactivity disorder (ADHD) when the complexity of a Go/No-go inhibitory control task was increased (Vaurio, et al. 2009). Sigma is also increased in ADHD vs. typically developing children, which has been interpreted as reflecting impaired response preparation (Vaurio et al., 2009). In contrast,  $\tau$  was increased in the contaminated runs, but not sensitive to cue-salience, and not associated with transient BOLD changes. The greater frequency of slower RTs may be related to transient increases in periodical checking (Guynn, 2003; Scullin et al., 2013), or the fact that participants needed extra time on ambiguous trials to check whether the position of the two shapes matched a chess knight's move. Tau has also been associated with lapses in attention both in children (Vaurio et al., 2009) and in adults with ADHD (Gmehlin et al., 2014). These Ex-Gaussian analyses suggest that a variety of mechanisms, related to proactive anticipation, lapses in attention, and reactive processes triggered by the cue are underlying differences in RT between uncontaminated and PM runs varying in PM cue salience.

#### *PM execution (PM trials)*

Participants were slower and less accurate for PM trials than OT trials, in line with similar performance differences observed by Simons et al. (2006). This pattern is consistent with the additional demands of

PM trials including cue identification, intention retrieval, inhibition of the ongoing task, and branching into subtasks necessary for successful performance. The slowing down observed for OT trials in the Knight run relative to the Colour run was larger for PM trials, i.e. participants were relatively slower to respond to non-salient PM cues than salient PM cues. There was no difference in accuracy. The current results align with reports of strong influence of cue manipulations on PM (Kliegel et al., 2013; McGann et al., 2003). For example, high PM cue salience has been demonstrated to enhance PM in younger adults (Brandimonte & Passolunghi, 1994; Einstein et al., 2005; Einstein & McDaniel, 1990), older adults (Altgassen et al., 2010), and children (Kliegel et al., 2013). Overall, our results are consistent with the well-documented facilitation effect of salient cues and suggest a variety of cognitive mechanisms underlie this effect, including strategic monitoring as well as spontaneous retrieval.

Across age groups, PM accuracy was negatively correlated with PRMQ (PM), which assesses PM failures in daily life (Smith et al., 2000). Similarly, PM accuracy was negatively correlated with Webexec, indicating that more executive function failures were associated with lower PM accuracy. While these exploratory correlation analyses would need to be replicated in a larger sample, our results suggest that general executive functioning might be important individual traits associated with PM performance, as has been reported in adolescents (Robey et al., 2014) and adults (Gonneaud et al., 2011).

#### *Adolescent performance*

Adolescents were overall less accurate on the task, both on OT and PM trials, and had a greater frequency of particularly slow responses, as is indicated by higher  $\tau$  in OT trials across conditions. These results were mostly driven by the younger adolescents in the sample. Combined, these results may reflect lapses in attention leading to a higher frequency of slower RTs and a higher frequency of errors in adolescents than in adults. This is consistent with findings that sustained attention continues to improve during adolescence (Brocki & Bohlin, 2004).

Focusing on ongoing task trials, our results showed that adolescents and adults showed similar patterns of RT costs related to the maintenance of the PM intention, and PM cue salience effects on RT. These results suggest that the capacity to flexibly engage proactive and reactive control to maintain PM intentions and monitor for salient vs. non-salient PM cues are similar in adolescents than adults. High PM cue salience has been demonstrated to enhance PM in pre-school (Kliegel et al., 2013) and school-aged children (Mahy et al., 2014) as well as in young and older adults (Brandimonte & Passolunghi, 1994; Einstein & McDaniel, 1990, Altgassen et al., 2010). Here, we demonstrate similar enhancement effects of salient cues for both adolescents and adults. Contrary to our hypothesis, the interaction

between cue salience and age was not significant. Thus, the current study appears to suggest that there may be similar facilitation mechanisms driven by cue salience across adolescence and into adulthood. In line with results in children (Kliegel et al., 2013), cue salience might not be the key mechanism underlying prospective memory development.

Previous studies did observe age differences in ongoing task performance. For example, lower accuracy in a contaminated ongoing task was reported in adolescents (13 – 16 years) compared to adults when the OT task had high, but not low cognitive demand (Ward et al., 2005). Similarly, 12 to 13-year-olds and 14 to 15-year-olds had lower accuracy than 18 to 19-year-olds in a contaminated ongoing lexical decision task, where 12 to 13-year-olds were also slower than other age groups (Bowman et al., 2015). Exploratory analyses across the adolescent age range indicated that accuracy, but not RT, increased linearly with age in the contaminated runs. Integrating the results of the present study to this previous research suggests that differences in performance on contaminated ongoing task trials between adolescents and adults may only be observed when the demands of the ongoing task are high. Such a pattern of greater developmental differences in most challenging conditions has been observed for example in working memory tasks with greater developmental differences for greater working memory loads (De Luca et al., 2003).

Looking at PM trials performance, again effects of cue salience on PM trials RT were similar in adolescents and adults. However, across cue salience conditions, adolescents, and specifically younger adolescents aged 12-14 years, showed lower accuracy and slower RT in PM trials, relative to OT trials. Previous studies investigating differences in PM performance between adolescents and adults have found mixed findings. There have been reports of increased PM performance with age between adolescence and adulthood in terms of accuracy (Altgassen et al., 2014; Wang et al., 2006, 2011; Zöllig et al., 2007) and RTs (Bowman et al., 2015), but also of improvements between childhood and adolescence, with no further maturation of PM after adolescence, especially for focal cues (Ward et al., 2005; Zimmermann & Meier, 2006), and particularly after age 13 (Bowman et al., 2015). Our results are broadly in line with this literature and suggest that adult PM performance is reached in mid-adolescence.

PM and OT performance are usually not directly compared in other developmental studies. Although PM and OT trials are not directly equivalent, we believe comparing PM trials performance to OT trials may be useful to distinguish between general (e.g. changes in processing speed) and PM-specific

improvements with age and suggest that future studies could benefit from including this analysis. We did not find differences in self-reported prospective memory failures in real-life settings between adolescents and adults. However, to our knowledge, the PRMQ has only been used in adult populations in the past (Smith et al., 2000). Although the PRMQ was piloted in adolescent participants, and the questions were screened for age-appropriateness, further studies could more systematically investigate how suitable the PRMQ is to detect developmental differences. There was a trend for adolescents to score lower in the FOS compared to adults. These results are in the direction of the pattern typically observed in the literature (Steinberg et al., 2009), in which adults are more oriented towards the future than adolescents.

Differences in executive functioning (forward and backwards digits span, No Go accuracy) and future orientation were found to partially explain non-specific RT differences between adolescents and adults on contaminated Runs across OT and PM trials. However, age group differences in accuracy and specific differences in RT and accuracy on PM compared to OT trials between adolescents and adults remained significant when accounting for these variables, suggesting that there are specific mechanisms of PM that are still maturing, independent of the maturation of working memory, inhibitory control and future orientation.

#### Neuroimaging findings

##### *Sustained changes in BOLD signal: PM intention maintenance*

Intention maintenance was associated with sustained activity in regions implicated in PM, with activation in similar regions, but to varying strength, for salient and non-salient PM cues conditions. The current findings are robustly aligned with reports of regions which respond in a sustained fashion in PM task blocks, notably RLPFC, DLPFC, ACC, and inferior parietal lobe (McDaniel et al., 2013, 2015; Reynolds, West, & Braver, 2009). Administration of PM instructions, which leads to the maintenance of an internal representation of the delayed intention as well as cue monitoring, was associated with sustained higher BOLD signal in the right rostral aspects of the lateral PFC, including BA 46 and extending into BA 10, the key region implicated in PM (Burgess et al., 2003; Gilbert et al., 2006; Momennejad & Haynes, 2012; Simons et al., 2006).

In addition, there was activation of the ACC, and of the DLPFC (BA 46) extending into superior frontal cortex (BA 44) as well as VLPFC (BA 47/45). These results are in line with the increased recognition of involvement of more extended frontoparietal networks in PM processes (Cona et al., 2015; McDaniel et

al., 2013). The anterior insula was also recruited in both hemispheres. Activity in these regions has been reported in other PM studies in non-focal tasks (Beck et al., 2014; Burgess et al., 2001; Gilbert et al., 2006, 2009; Rea et al., 2011) suggesting a role of the anterior insula in cue monitoring (Cona et al., 2015; McDaniel et al., 2015). Overall, and in line with previous accounts, activation of DLPFC, bilateral anterior insula, and superior parietal lobule, may relate to preparatory processes that include maintaining the task set (e.g. instructions for PM trial) in anticipation of cues to enable goal pursuit in the dual-mechanisms of control framework (Braver, 2012; Jiang et al., 2015; Magis-Weinberg et al., 2019).

There was considerable overlap in neuroimaging results between the salient and non-salient PM cues conditions, consistent with behavioural evidence of interference costs in both runs. However, contamination with non-salient cues did recruit more extensive regions overall. There were greater increases in BOLD signal during OT Knight run than OT Colour run blocks in the superior parietal lobules bilaterally (BA 7 and BA 40), a region which has been implicated in encoding and maintenance/retrieval of PM intentions (Gilbert, 2011; Poppenk et al., 2010; Reynolds et al., 2009). The reverse contrast revealed a set of regions, namely the angular gyri, superior frontal gyrus and mid-cingulate cortex, which showed greater decreases in BOLD signal during OT Knight run than OT Colour run blocks. These regions are typically considered as part of the default mode network, which shows decreases in BOLD signal when task demands increase (Raichle, 2015), which fits with the results observed here. We did not find an association between either PRMQ or FOS and average activity in contaminated runs across cue salience.

#### *Transient changes in BOLD signal: PM trials execution*

The RLpFC exhibited transient changes in BOLD signal during PM trials as has been described in previous fMRI studies, which have reported higher activity in RLpFC when participants either anticipate or encounter PM cues (Burgess et al., 2003; Reynolds et al., 2009; Simons et al., 2006). Additional transient activation for salient and non-salient PM trials was observed in ACC, bilateral anterior insula, precentral gyrus, middle frontal gyri, and superior parietal lobe, results that are in line with transient activations in a non-focal PM task that investigated proactive and reactive strategies (McDaniel et al., 2013). Along with activity in VLPFC (BA 45) and anterior insula (BA 47), these results might speak to the involvement of bottom-up attention processes captured externally by the PM cue (Cona et al., 2015).

While Knight PM trials overall seemed to elicit more widespread changes in BOLD signal than Colour PM trials, no significant differences emerged, which may reflect that, although the PM cues differed, the PM intention (pressing the thumb button) was the same for both. These results are in contrast with the

behavioural findings of slower RTs in Knight PM trials than Colour PM trials. Importantly however, OT trials served as a baseline for these contrasts, and RTs were also slower in Knight OT trials than Colour OT trials. Although this difference was greater in PM trials, this was by only 58 ms, a difference unlikely to be picked up by fMRI measures of neural activity. Overall these results indicate that cue salience was associated with differences in sustained activation, with greater sustained activation in the low cue salience condition in the right superior frontal gyrus and bilateral superior and inferior parietal lobules, but cue salience did not impact transient changes in activation associated with PM trials.

The left anterior insula, right superior parietal lobule, DLPFC and precentral gyri and frontal eye fields (FEF), as well as middle aspect of ACC exhibited a mixed pattern of sustained and transient differences in BOLD signal as a function of the PM context or PM trials execution. The anterior insula has previously been found to show sustained and transient changes in a PM task (Cona et al., 2015; Gilbert et al., 2009), suggestive of a role both in sustained task control as well as in increasing the salience of the cue (Cona et al., 2015). McDaniel et al. (2013) also found a mixed pattern of activation in precentral gyrus (BA 44) and FEF in the middle frontal gyrus (BA 6) for a non-focal PM task. More generally, these regions have been previously implicated as neural correlates of the Dual Mechanisms of Control (Jiang et al., 2015; Magis-Weinberg et al., 2019), where temporal dynamic within some regions, in addition of activation of distinct brain networks, would enable the shift between modes of proactive and reactive cognitive control. The anterior insula has been suggested to monitor current control demands and sustain task control, and rostral ACC reactively monitors level of conflict and then signals DLPFC and dorsal ACC to mediate trial-by-trial conflict driven adjustments in control (Jiang et al., 2015; Magis-Weinberg et al., 2019). When PM cues are detected, conflict may arise between the goal of continuing to perform the ongoing task and the retrieval of the relevant PM intention followed by execution of the PM response, giving rise to transient activity during PM trial (Hashimoto et al., 2011).

#### *Age-related differences*

No differences were observed in the planned analyses comparing sustained and transient BOLD signal changes between adolescents (12 – 17 years) and adults (23 – 31 years). Given that developmental investigations of PM using fMRI are limited, we further explored age differences between younger, older adolescents, and the adults. Age differences emerged for PM trials in which younger adolescents had higher transient BOLD signal in occipital regions than adults, with no differences with the older adolescents. These results indicate that overall adolescents recruit similar brain networks to adults, and to a similar extent, during event-related PM tasks, which is in line with the mostly similar behavioural



correlates of PM observed between the two age groups in the present study. The finding with the younger adolescents is consistent with the behavioural results of the current study, which revealed that younger, but not older, adolescents, showed lower accuracy and slower RTs in PM trials relative to OT trials than adults, as well as with previous research suggesting that PM performance stabilises by mid-adolescence, around 13-14 years (Bowman et al., 2015; Ward et al., 2005; Zimmermann & Meier, 2006). While we expected to observe differences in prefrontal cortex functioning, possibly in the RLPFC, a region that has consistently been associated with PM and which continues to mature during adolescence (Dumontheil, 2014), we instead found increased recruitment of posterior regions in younger adolescents, in addition to commonly recruited brain regions, as has previously been observed in a Go/No-Go task (Jonkman et al., 2007). In this case the results were interpreted as reflecting the fact that younger children may bolster their performance with basic stimulus processing and attention mechanisms. A study in adults found that occipital areas show greater activation during event-based than time-based PM, and this was interpreted as reflecting target-checking (Gonneaud et al., 2014). Our results may therefore suggest that younger adolescents engaged in more extensive target-checking.

#### Limitations and Future directions

PM tasks are also dual tasks paradigms which require participants to execute the ongoing task and the PM task in parallel. In this view, behavioural and neural correlates of PM tasks might be reflecting general dual task demands and associated cognitive processes (Dumontheil, 2014). There is also a cognitive branching component (Hyafil et al., 2009), in which participants disengage momentarily from the ongoing task and switch to the internal representation of the PM intention. These explanations are in line with other proposed interpretations of RLPFC function (Koechlin, 2016) and ultimately PM processes cannot be entirely dissociated from branching performance processes with the current design.

There was evidence for strategic monitoring for both salient and non-salient cues. This might be because the current paradigm employed a non-focal PM task, which has been shown to elicit strategic monitoring in previous studies (see McDaniel et al. 2015 for a review). Alternatively, as has been identified by McDaniel et al. (2015), isolating spontaneous retrieval is difficult in traditional laboratory settings. Contextual factors in the way experiments are set up and delivered might encourage monitoring even with focal cues. Monitoring which responds to instruction framing or high number of PM target cues could mask discovery of bottom-up spontaneous retrieval processes.

Exploratory analyses comparing the youngest with the oldest adolescents and adults hinted at maturation of prospective memory in early adolescence. Accuracy, but not RT, increased linearly with age in the adolescent group. Our sample size, however, might limit our ability to detect age-related changes. To fully capture age-related differences, future studies should include a larger number of participants and sample across a wider age range to include late childhood. In the current task, it seems that varying cue salience did not require high enough levels of monitoring that developmental differences were apparent. To further understand which aspects of controlled processes are targeted by cue salience during adolescence, it might be important to systematically manipulate complexity and cognitive demands. In addition, manipulations around cue-salience that align with adolescent sensitivities (such as socio-emotional processes) might be an interesting route going forward, especially since positively-valenced cues have been shown to improve prospective memory in adults (Altgassen et al., 2010; Hostler et al., 2018).

## Conclusion

Our results show that when intention retrieval demands are matched, prospective memory cue salience modulates performance and sustained activation during the ongoing task. While accuracy did not vary as a function of cue salience, the low cue salience PM condition was associated with slower reaction times, with a shift in the mean distribution of RT, and greater sustained activation in the right superior frontal gyrus and bilateral superior and inferior parietal lobules. We add to the nascent body of literature of neural markers of different strategies, in the proactive/reactive control framework, in relation to maintaining intentions and task retrieval. We show that beyond the recruitment of regions typically implicated in PM, such as the RLPFC, regions that are typically associated with proactive control are recruited for intention maintenance, for both adolescents and adults. We found that neural correlates of PM trials were not specifically modulated by cue salience, revealing little difference in reactive control between conditions. These results underscore how retrieval and cue detection are separate processes that map onto different cognitive control strategies. Finally we show, for the first time, that adolescents and adults share similar modulation of performance and neural activity by cue salience. However, the younger adolescents showed specifically lower accuracy and slower RT on PM trials, as well as increased activation in a posterior occipito-temporal cluster, providing evidence that PM maturation continues during early adolescence.

## Acknowledgements

L. M. W. was funded by the Mexican National Council on Science and Technology (CONACYT). The authors would like to thank Dr. Hunter B. Ball for his helpful advice and comments.

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