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Prospective memory in autism: theory and literature review

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ABSTRACT

Objective: The current article set out to review all research conducted to date investigating prospective memory (PM) in autism. **Method**: All studies on PM in autism are first described, followed by a critical review and discussion of experimental findings within the multiprocess framework. PM in autism is then considered through an embodied predictive-coding account of autism. **Results**: Overall, despite somewhat inconsistent methodologies, a general deficit in PM in autism is observed, with evidence mostly in line with the multiprocess framework. That is, for tasks that are high in cognitive and attentional demand (e.g. time-based tasks; event-based cues of non-focality or low salience) PM performance of autistic participants is impaired. Building upon previous work in predictive-coding, and the way in which expected precision modulates attention, we postulate mechanisms that underpin PM and the potential deficits seen in autism. Furthermore, a unifying predictive-coding account of autism is extended under embodied predictive-coding models, to show how a predictive-coding impairment accounts not only for characteristic autistic difficulties, but also for commonly found differences in autistic movement. **Conclusions**: We show how differences in perception and action, core to the development of autism, lead directly to problems seen in PM. Using this link between movement and PM, we then put forward a number of holistic, embodied interventions to support PM in autism.

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General introduction

Autism spectrum conditions (ASC; henceforth, autism) are characterized by impairments in social communication, restricted interests, and activities and, most recently, atypical reactivity to sensory input (American Psychiatric Publishing [APA], 2013). The clinical picture and cognitive skills of autistic[1] people may differ in severity (Hill, 2004). However, even autistic adults of average or above average cognitive ability find everyday life problematic (e.g. housekeeping, financial matters). They have, for example, difficulties obtaining and

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maintaining employment that corresponds to their intellectual ability (Howlin, 1998) and coordinating social activities, e.g. organizing appointments with peers (Häußler, 2003) and living independently (Anderson, Shattuck, Cooper, Roux, & Wagner, 2014). Autistic children often have problems in school due to poor time management and organization, e.g. homework is often left at school (Mackinlay, Charman, & Karmiloff-Smith, 2006). These apparent organizational difficulties in autism are supported by empirical work revealing problems with prioritizing, coordinating and sequencing activities and hence, with planning ahead (Mackinlay et al., 2006; Ozonoff et al., 2004); such difficulties have been related to deficits in prospective memory (Altgassen, Koban, & Kliegel, 2012; Mackinlay et al., 2006). PM describes the ability to remember to execute intentions after a delay at a certain time (time-based tasks; TBPM) or event (event-based PM tasks, EBPM, Einstein & McDaniel, 1996), such as remembering to go to the hairdresser at 3 pm, or to buy batteries in the corner shop on the way home. Many occupational and social demands require PM, and PM is essential for the development and maintenance of autonomy and independence. Frequent failures to remember to complete planned activities may endanger professional careers, social relationships or even impose serious risks on physical well-being (Kliegel, Jäger, Altgassen, & Shum, 2008).

Prospective remembering is complex, and comprises multiple processes and phases, across varying time-spans. First, the individual has to form the intention, and store it in (retrospective) memory while being engaged in other ongoing tasks (OT). This (filled) delay between encoding and retrieval of the intended action may range from seconds over minutes to several hours or days (Ellis & Kvavilashvili, 2000). When the appropriate moment for intention initiation arises, other ongoing activities have to be inhibited and the individual has to switch to the prospective action and execute it as planned (Kliegel, Martin, McDaniel, & Einstein, 2002). Research differentiates between a prospective (remembering 'that' you have to do something) and a retrospective component (remembering 'what' and 'when'). The prospective component is supported by attention demanding processes that are closely aligned with executive functioning which serve to monitor the environment for prospective cues (e.g. Smith & Bayen, 2004), inhibit performing the ongoing activity, and to switch to the prospective intention at the appropriate moment (Marsh, Hicks, & Watson, 2002; West, 2011). The retrospective component supports the encoding and subsequent retrieval of the intention when a target stimulus is encountered and shares many processes with explicit episodic memory in recognition and cued-recall tasks (Einstein & McDaniel, 1996; Smith & Bayen, 2004; West & Krompinger, 2005). Recently, episodic future thinking, the ability to mentally simulate and thus pre-experience future events (Atance & O'Neill, 2001), has been linked to the intention formation phase (Altgassen et al., 2014). In line with these behavioral data, imaging studies indicate an involvement of frontal and medial-temporal structures in prospective remembering (for a recent review see Burgess, Gonen-Yaacovi, & Volle, 2011). Frontally mediated (executive control) processes seem to influence PM performance more strongly than temporally mediated (retrospective memory) processes (Brunfaut, Vanoverberghe, & d'Ydewalle, 2000; Kliegel, Eschen, & Thöne-Otto, 2004). Most recently, Cona, Bisiacchi, Sartori, and Scarpazza (2016; Cona, Scarpazza, Sartori, Moscovitch, & Bisiacchi, 2015) further specified the underlying neural networks and involved cognitive processes in their 'Attention to Delayed Intention' model. Specifically, they state that a dorsal frontoparietal network supports top-down attentional and memory processes that are needed to monitor for the PM cue and to keep the intention in mind, whereas a ventral frontoparietal network (in addition to the insula and posterior cingulate cortex) is mainly involved in the retrieval phase and supports bottom-up attentional processes (externally by the PM cue and internally by the mental representation of the PM cue and the intended action).

Importantly, different PM tasks vary in the extent to which they require these cognitive resources. TBPM tasks have been assumed to put higher demands on individuals' executive control resources than event-based tasks; there is no external cue that may prompt retrieval of the intended action, and the individual has to actively keep track of the elapsing time (Einstein & McDaniel, 1996). However, depending on the specific task features, EBPM tasks may also put high demands on executive control processes. Specifically, with regard to EBPM, two prominent conceptual models have been developed that allow for theory-based predictions on factors that determine the involvement of executive control in PM; namely the *multiprocess framework*[2] (McDaniel & Einstein, 2000) and the *preparatory attention and memory processes theory* (PAM, Smith, 2003; Smith & Bayen, 2004). For the multiprocess framework, McDaniel and Einstein (2000) suggested a range of factors and contexts that can determine the extent to which an EBPM task invokes relatively effortful or automatic retrieval processes: task importance, the type of PM cue (e.g. salient vs. non-salient cues or cues that are more or less focal to the OT), the OT (e.g. more vs. less demanding), and individual differences (e.g. in cognitive resources, personality). Given that PM tasks are dual task situations consisting of an ongoing activity and the embedded PM task, both tasks compete for (limited) attentional and executive control resources (Einstein & McDaniel, 1996). Hence, characteristics of both task levels will affect the more or less controlled allocation of those resources (please see McDaniel, Umanath, Einstein, & Waldum, 2015, for a recent discussion of the multiprocess framework). In contrast, the PAM model posits that that *all* PM tasks require executive control resources for the PM cue to be detected, but that the extent to which these resources are needed depends on task characteristics.

Thus, there is good evidence that strong executive control, episodic memory, and future thinking abilities are critical for successful PM, particularly so when PM tasks involve, for example, cues of low salience or low focality (EBPM) that are difficult to detect, or no environmental cues at all (TBPM). It is therefore of concern that problems with executive control and memory are well known in autism. Executive difficulties are typically seen in planning (Mackinlay et al., 2006; Ozonoff et al., 2004) and switching flexibly between different tasks or foci of attention (Corbett, Constantine, Hendren, Rocke, & Ozonoff, 2009; Kenworthy, Yerys, Anthony, & Wallace, 2008; Leung & Zakzanis, 2014; Ozonoff et al., 2004; but see Geurts, Corbett, & Solomon, 2009 for a critical review). Tasks assessing the inhibition of prepotent responses have resulted in more ambiguous findings (Corbett et al., 2009; Geurts, Verte, Oosterlaan, Roeyers, & Sergeant, 2004; Lopez, Lincoln, Ozonoff, & Lai, 2005; Pellicano et al., 2017). Evidence from retrospective (episodic) memory studies indicate impairments in free recall tasks that provide little memory support (Bowler, Gardiner, Grice, & Saavalainen, 2000), whereas more structured tasks that put lower demands on self-initiated processing, such as cued recall and recognition tasks (Barth, Fein, & Waterhouse, 1995; Bowler, Gardiner, & Grice, 2000), seem to be spared. In line with the well-documented deficits of autistic individuals in episodic memory and theory of mind (e.g. Baron-Cohen, Leslie, & Frith, 1985; Leekam & Perner, 1991; Perner, Frith, Leslie, & Leekam, 1989; see Baron-Cohen, 2000 for a review), reduced episodic future thinking has been reported in autism (e.g. Lind & Bowler, 2010; Lind, Bowler, & Raber, 2014; Lind, Williams, Bowler, & Peel, 2014; Terrett et al., 2013). It may be that these memory deficits are in some way related to impaired executive functioning, given the correlations found in other clinical populations between executive functions and episodic memory (Baudic et al., 2006; Greene, Hodges, & Baddeley, 1995) as well as future thinking (de Vito et al., 2012)

Furthermore, it is possible that these executive functions, seen as important to PM, are driven by attentional processes (Garon, Bryson, & Smith, 2008; Posner & Rothbart, 2000), processes which have also been shown as impaired in autism (e.g. problems with disengagement, Landry & Bryson, 2004) visual attention (Mann & Walker, 2003), joint attention (e.g. looking at or listening to people, Klin, Jones, Schultz, & Volkmar, 2003; Schultz, 2005), and reduced divided attention (Althaus, De Sonneville, Minderaa, Hensen, & Til, 1996; Ciesielski, Knight, Prince, Harris, & Handmaker, 1995) (cf. a review, Allen & Courchesne, 2001). Indeed, problems with attending to relevant sensory information have even been situated as core to autism (Lawson, Rees, & Friston, 2014; Pellicano & Burr, 2012; Van de Cruys, Van der Hallen, & Wagemans, 2017; Van de Cruys et al., 2014). Such problems would thus have a profound impact on PM performance in autism.

In summary, PM represents a ubiquitous daily process, critical to independent living. Successful execution of PM tasks requires the recruitment and coordination of several (socio) cognitive processes, processes that may rely fundamentally on effective attentional and executive control processes. Given the weight of evidence demonstrating autistic impairment in such processes, and the potentially debilitating PM failures this may lead to, it is vital to better understand prospective remembering in autism, its underlying mechanisms and the environmental conditions that best support it.

Therefore, the first section of the current review will summarize all literature directly investigating PM in autism to date, arriving at the conclusion that, relative to the non-autistic population, PM in autism appears to be impaired. Then, in an attempt to better understand why autistic individuals in particular may demonstrate such difficulties, we will consider the complex dynamic nature of PM, the environment in which it is situated, and the demands this puts on individuals to coordinate and act under such an environment. With this in mind, we will build upon the cognitive explanations of the PM process offered by the multiprocess framework (McDaniel & Einstein, 2000) by considering PM as embedded within a complex dynamic environment, and, as such, apply and further develop an existing account of autism, namely the Bayesian predictive-coding account of Van de Cruys et al. (2014, 2017). Finally, we will describe how this account, and the multiprocess framework, leads to useful, embodied interventions, many of which are already widely implemented in practice.

PM in autism – literature review

A literature search was conducted on the Web of Science for all papers including the terms 'autism' and 'prospective memory', in the title, published up until December 2016. The search returned 36 studies. After the inclusion of 2 of the current authors' unpublished works, and subsequent screening, 13 studies were available for review (see Figure 1). The following section will review each of the studies, beginning with three studies demonstrating spared PM ability, followed by five studies demonstrating a PM deficit, and ending with five studies revealing mixed results (e.g. preserved EBPM but diminished TBPM). For brevity, the studies will only be summarized, with key points highlighted. A full description of the methods and results is presented in Table 1, but for an in-depth description and critique of all studies, including further statistical data (such as effect sizes), we refer to the recently published meta-analysis of Landsiedel, Williams, and Abbot-Smith (2017) on PM in autism. Finally, an

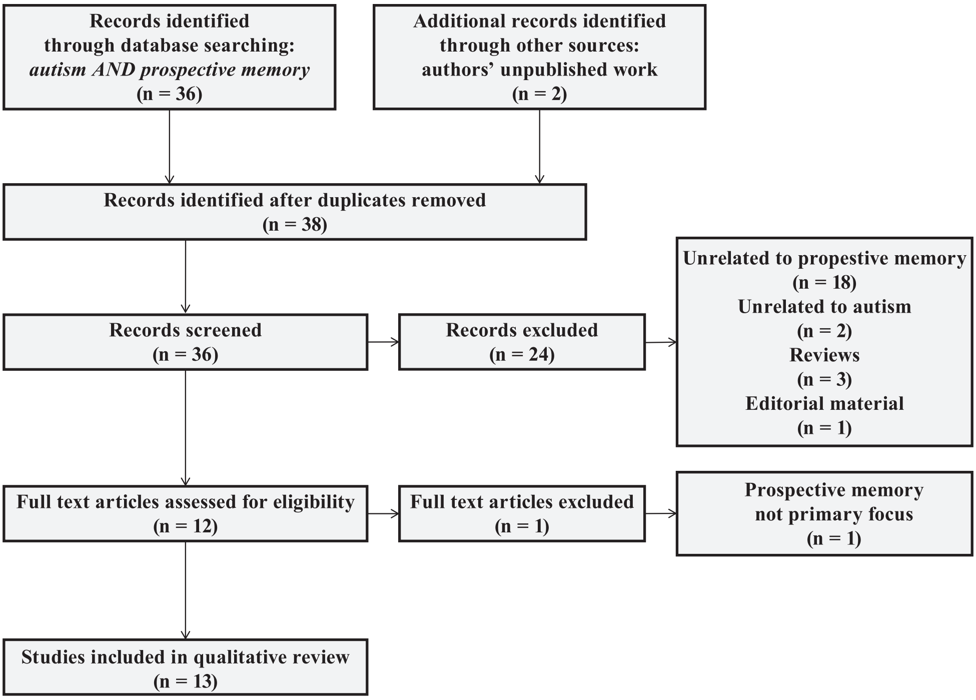

Figure 1. PRISMA flow-chart (Moher, Liberati, Tetzlaff, Altman, & Group, 2009) illustrating literature search process.

overall summary will be presented, describing patterns or commonalities evident between the studies to help elucidate variations in performance, and to discern possible cognitive functions that may contribute to the variation in PM performance.

Intact PM in autism

The three papers to find intact PM in autism investigated EBPM in children of around 10 years old (Altgassen, Schmitz-Hübsch, & Kliegel, 2010; Sheppard, Terrett, Rendell, & Altgassen, 2017) and young adults (Altgassen & Koch, 2014). All three studies employed a typical Einstein–McDaniel computer-based EBPM paradigm in which participants first completed a single, computer-based task (OT). They were then informed they would work on the task again in the near future, but it would contain an additional task (PM), which they completed after a short, filled delay,

No main group effects for EBPM emerged, a result in support of intact EBPM in autism. With the exception of the 'low salience' condition in Sheppard et al. (2017), all PM cues were rather salient (distinctive, as compared to the OT) being either a change of target word color to blue (Altgassen & Koch, 2014), a change of border color from black to red (Sheppard et al., 2017) or a whole screen color change to yellow (Altgassen, Schmitz-Hübsch, & Kliegel, 2010b). PM cues were focal for the Altgassen and Koch (2014) study non-focal for the other two studies.

No group effects were found in OT performance (differences in Altgassen & Koch, 2014; were limited by ceiling effects). Two studies showed adverse effects of the additional PM

Table 1. Overview of all studies on prospective memory in autism.

	Participant information					PM				OT				
Intact PM	Sample size (mean age)	Gender	Intellectual ability measures	Severity of ASC symptoms	Diagnostic and exclusion criteria	Task description	(Filled) delay length	Main effects	Interactions	Task description	Number of trials	Main effects	Interactions	Control variables
Altgassen, Schmitz-Hubsch, and Kliegel (2010)	19 ASC children ($M = 10.6$) 19 controls ($M = 10.6$)	ASC: 18 m, 1 f Controls: 16 m, 3 f	WISC-III vocabulary test: ASC $M = 9.6$ Controls $M = 11.8$ Block design: ASC $M = 10.1$ Controls $M = 11.0$	High-functioning ASC (IQ > 85)	Diagnoses established with ADI-R* and ADOS** No exclusion criteria mentioned	Non-focal EBPM: • press specific key when background turns yellow (5 PM trials)	~10min filled delay (other cognitive tests)	No effects for accuracy and reaction times	–	Computerized visuo-spatial working memory task	• single task block: 10 • dual-task block: 100	Accuracy • no group effect • effect of task block: single OT > dual-task No effects for reaction times	No significant interaction	DEX: ASC < controls ASC: DEX correlates negatively with PM hits
Altgassen and Koch (2014)	22 ASC adults ($M = 25.8$) 22 controls ($M = 25.6$)	ASC: 20 m, 2 f Controls: 20 m, 2 f	WASI matrices: ASC $M = 10.5$ Controls $M = 10.2$	9 high-functioning ASC (IQ > 85) 13 Asperger's syndrome	Expert clinical evaluation according to DSM-IV criteria Exclusion criteria: other psychiatric or neurological disorders, drug or alcohol abuse	Non-focal EBPM: • press specific key when color of words turns blue (4 PM trials per inhibitory load block)	~10min filled delay (other cognitive tests)	No effects for accuracy	No significant interaction	Computerized word categorization task Within-subject manipulation of inhibitory load (high, low)	• single OT: 20 • single inhibition task (high or low): 20 • dual-task: OT plus inhibiton task (high or low): 46 • triple task: OT plus inhibition task (high or low) plus PM: 96	Accuracy OT • group effect: controls > ASC • task block effect: single OT > dual-task low inhibitory load > dual-task high inhibitory load > both triple task blocks Accuracy inhibition • no group effect • inhibitory load effect: single task conditions > dual- and triple-tasks low inhibitory load > dual- and triple-tasks high inhibitory load	No significant interactions	–

Sheppard et al. (2017)	24 ASC ($M = 11.3$) 23 controls ($M = 11.1$)	ASC: 24 m, 0 f Controls: 7 m, 16 f	WISC-III & WNV vocabulary test: ASC $M = 11.7$ Controls $M = 10.4$ Matrices: ASC $M = 61.6$ Controls $M = 53.8$	High-functioning ASC (IQ > 85) SRS T score: ASC > Ctrl $M_{ASC} = 72.86$ $M_{ctrl} = 43.95$ SSP – visual: ASC > Ctrl $M_{ASC} = 18.19$ $M_{ctrl} = 23.85$ SSP – auditory: ASC > Ctrl $M_{ASC} = 14.29$ $M_{ctrl} = 25.35$	Expert clinical evaluation according to DSM-IV criteria Exclusion criteria: other psychiatric or neurological disorders	Focal EBPM: • press specific key on presentation of PM targets 3 conditions, within-subjects, each with 4 different PM cues • low salience • high Visual • high auditory	~8 min (vocabu-lary, matrices, digit span tests)	No effects for accuracy Reaction times: • no group effect • salience effect: low salience > high salience	Reaction times: • for both groups low salience > high visual salience, but only ASC: low salience > high auditory salience	Computerized picture-based categorization task	• single task block: 20 • dual-task block: 70	No effects for accuracy Reaction times • no group effect • task block effect: single OT < dual-task blocks; low salience > high salience (visual and auditory)	No significant interactions	–
Altgassen et al. (2009)	11 ASC children ($M = 9.6$) 11 controls ($M = 10.6$)	ASC: 9 m, 2 f Controls: 6 m, 5 f	WISC-III vocabulary test: ASC $M = 9.4$ Controls $M = 11.6$ Block design: ASC $M = 12.9$ Controls $M = 11.0$	High-functioning ASC (IQ > 85)	Diagnoses established with ADOS and 3di Exclusion criteria: other psychiatric or neurological disorders	TBPM: Press specific key every 2min (5 PM trials) Press other specific key for clock check	~10 min (other cognitive tests)	Correct PM responses: ASC < controls Clock checks: • group effect: ASC < controls • interval effect: increased time monitoring when target times approached	Interaction ($p < .06$): controls checked time more frequently as target time approached	Computerized visuo-spatial working memory task	• single task block: 10 • dual-task block: 85	Accuracy • group effect: ASC< controls in the dual task No effects for reaction times but: cost to OT by adding PM task: controls > ASC	No significant interactions	–

(*Continued*)

Table 1. (*Continued*).

	Participant information		PM							OT				
Intact PM	Sample size (mean age)	Gender	Intellectual ability measures	Severity of ASC symptoms	Diagnostic and exclusion criteria	Task description	(Filled) delay length	Main effects	Interactions	Task description	Number of trials	Main effects	Interactions	Control variables
Brandimonte et al. (2011)	Study 1: 30 ASC (*M* = 8.3) 30 controls (*M* = 8.3) Study 2 focuses on ADHD instead of ASC and will not be discussed here	ASC: 21 m, 9 f Controls: 21 m, 9 f	WISC-III Full Scale IQ: ASC *M* = 87.0 Controls *M* = 89.0	CARS: M_{ASC} = 35.5 → mild to moderate ASC	Diagnoses according to DSM-IV criteria Exclusion criteria: other behavioral disorders, learning deficits, chromosomal or neurological conditions	Focal EBPM: press specific key on presentation of PM target Go/NoGo: press nothing on presentation of target EBPM + Go/NoGo 2 cues; each 4× Single OT: no additional task	No filled delay	Accuracy • group effect for PM hits: ASC < controls • no group difference in the Go/NoGo condition Reaction times for the PM task: ASC> controls	–	Computerized categorization task; between-subjects	• single OT: 80 • dual-task block: 80 • OT plus Go/NoGo task: 80	Accuracy • group effect: ASC < controls • no category effect • costs to OT by adding PM task only for controls: single OT > dual-task Reaction times • group effect: ASC> controls • no category effect	No significant interactions	–
Yi et al. (2014)	25 ASC (*M* = 7.7) 25 age-matched controls (*M* = 7.7) 28 ability-matched controls (*M* = 5.8)	ASC: 19 m, 6 f Age-matched controls: 19 m, 6 f Ability-matched controls: 19 m, 6 f	PPVT-R: ASC *M* = 4.56 Age-matched controls N/A Ability-matched controls *M* = 4.75 Raven test: ASC *M* = 21.1 Age-matched controls *M* = 31.8 Ability-matched controls *M* = 21.4	No information	Expert clinical evaluation, diagnoses according to DSM-IV criteria Exclusion criteria: other developmental or psychiatric disorders, intellectual disability, congenital deafness	Non-focal EBPM: • hand card with heart shape to experimenter (5 PM trials)	No filled delay	Accuracy ASC < controls (age- and ability-matched); age-matched controls > ability-matched controls	–	Card naming game	5 sets of 10 cards	–	–	ASC: PM predicted by Raven Test and Block Span Ability-matched controls: PM predicted by Day–Night Stroop Age-matched controls: no correlations

Altgassen et al. (2012)	25 ASC ($M = 21.8$) 25 controls ($M = 21.8$)	ASC: 20 m, 5 f Controls: 19 m, 6 f	WASI Vocabulary test: ASC $M = 9.2$ Controls $M = 10.2$ Matrices: ASC $M = 11.0$ Controls $M = 11.4$	High-functioning ASC (IQ > 85) or Asperger's syndrome	Expert clinical evaluation, diagnoses according to DSM-IV criteria Diagnoses established with ADI-R and ADOS	EBPM: prepare tea when water is boiling and kettle changing color; switch off egg cooker when it is beeping TBPM: remove tea bag after 3min; put butter on table 6min prior to guests' arrival Red Pencil: repeat 'red pencil' after experimenter	~10 min (digit ordering, trail making test, Tower of Hanoi)	EBPM accuracy: ASC < controls TBPM accuracy: ASC < controls Red pencil: ASC < controls	–	Real-life breakfast task: participants had to prepare breakfast for 4 people following certain rules and time constraints	–	ASC < controls on all measures (rule adherence; planning; plan adherence; efficiency) except switching	–	EBPM and TBPM correlates with planning, task completion, rule adherence, switching, efficiency TBPM (but not EBPM) correlates with Red Pencil, DEX, trail making test, digit ordering, and marginally Tower of Hanoi
Kretschmer et al. (2014)	17 ASC ($M = 35.6$) 17 controls ($M = 39.9$)	ASC: 14 m, 19 f Controls: 4 m, 31 f	PPVT-4: ASC $M = 212.1$ Controls $M = 210.1$ Raven: ASC $M = 40.8$ Controls $M = 40.6$	High-functioning ASC (IQ > 80)	Expert clinical evaluation Diagnoses established with ADI-R and ADOS Exclusion criteria: neurological or psychiatric disorders, present or past drug or alcohol abuse	EBPM: e.g. take medication at dinner TBPM: e.g. use inhaler at 11 am EBPM & TBPM each day 4 tasks (2 regular, 2 irregular); total PM=24 2 conditions, between-subject: • implementation intentions • standard instructions	No filled delay	Accuracy • group effect: ASC < controls • PM cue effect: EBPM > TBPM • regularity effect: regular > irregular • no effect of encoding	• regularity: group x irregular ASC < controls; ASC regular > ASC irregular; no effect controls • regularity x PM cue: both conditions EBPM > TBPM; TBPM regular > TBPM irregular; EBPM no difference • Encoding x PM cue: both conditions EBPM > TBPM • no other interaction	Virtual week (computerized; 3 days)	–	–	–	–

(*Continued*)

Table 1. (*Continued*).

	Participant information					PM				OT				
Intact PM	Sample size (mean age)	Gender	Intellectual ability measures	Severity of ASC symptoms	Diagnostic and exclusion criteria	Task description	(Filled) delay length	Main effects	Interactions	Task description	Number of trials	Main effects	Interactions	Control variables
Henry et al. (2014)	30 ASC (M = 10.1) 30 controls (M = 10.0)	ASC: 24 m, 6 f Controls: 19 m, 11 f	WASI Full Scale IQ: ASC M = 112.9 Controls M = 115.3 Verbal IQ: ASC M = 110.3 controls M = 114.9 Performance IQ: ASC M = 114.5 controls M = 118.3	Highfunctioning ASC or Asperger's syndrome	Expert clinical evaluation, diagnoses according to DSM-IV criteria Exclusion criteria: other psychiatric or neurological disorders	EBPM: e.g., take medication at dinner TBPM: e.g., use asthma inhaler at 11 am EBPM & TBPM each 4 tasks per day (2 regular, 2 irregular); total PM=24	No filled delay	Accuracy - group effect: ASC < control - PM cue effect: EBPM > TBPM - absorption: Low > High - no effect of regularity	- group x PM cue: TBPM: ASC < controls; EBPM: ASC = controls - regularity x PM cue: EBPM: regular = irregular; TBPM: regular > irregular - no other interaction	Virtual week (computerized; children's version, 3 days) within-subjects: high absorption: specific die rolls before moving on, manual movement low absorption: any die roll, auto movement	–	–	–	ASC: TBPM correlates with Full Scale IQ, ABAS, Stroop switching; no correlations for EBPM Controls: TBPM with semantic switching, ABAS; EBPM with semantic switching Williams,
Williams et al. (2013)	21 ASC (*M* = 10.6) 21 controls (*M* = 10.6)	Not reported	WASI Verbal IQ: ASC *M* = 103.6 Controls *M* = 106.5 Performance IQ: ASC *M* = 110.2 Controls *M* = 107.5	13 autistic disorder, 8 Asperger's syndrome	Diagnoses established according to conventional criteria	Focal EBPM: press specific key when passing a lorry (max 6) TBPM: refuel car by pressing key (6 trials), check fuel by pressing other specific key	No filled delay	PM accuracy • EBPM: no group effects • TBPM: ASC< controls Fuel checks • linear increase per interval • no group effect	ASC: TBPM< EBPM, controls: TBPM=EBPM	Video game of driving car (collecting tokens and avoid hitting hazards)	–	Accuracy • no group effect • effect of condition: TBPM block < EBPM	No significant interactions	ASC: TBPM failures with mentalizing Controls: TBPM failures with Wisconsin Card Sorting test (approaching significance)

Williams et al. (2014)	17 ASC (M = 31.1) 17 controls (M = 31.9)	ASC: 14 m, 3 f Controls: 14 m, 3 f	WASI Full Scale IQ: ASC M = 114.1 Controls M = 117.7 Verbal IQ: ASC M = 111.4 Controls M = 114.6 Performance IQ: ASC M = 113.5 Controls M = 116.9	4 autistic disorder, 13 Asperger's syndrome	Diagnoses established according to conventional criteria (13 with ADOS) Exclusion criteria: psychotropic medication, illegal drugs. neurological or psychiatric disorders-	Non-focal EBPM: press 'm' every time a musical instrument appeared in list TBPM: press 'P' every 2mins; spacebar for clock	No filled delay	PM accuracy • no group effect • effect of cue: TBPM < EBPM PM RT/precision • group effect: ASC > controls • no effect of cue Clock checks • linear increase per interval • no group effect	PM accuracy ASC < controls in TBPM, but not EBPM PM RT/precision • no interaction Clock checks • no interaction	Computerized presentation of single words (N=7) for 1s followed by all 7 words for 4s: final list same or different?	40 lists for EBPM and 40 for TBPM	Accuracy • no main effects no response times reported	No significant interactions	ASC: EBPM correlates with verbal storage span, verbal processing No correlations for TBPM Controls: EBPM correlates with visual storage span No correlations for TBPM
Sheppard et al. (2016)	14 severe ASC (M = 9.3) 14 mild ASC (M = 10.1) 26 controls (M = 5.1)	ASC: 27 m, 1 f Controls: 14 m, 3 f	No information; measures of reading, writing and number skills	CARS: Severe ASC M = 42.3 mild ASC M = 30.9	Diagnoses according to DSM-IV criteria	EBPM: 1) clap when hear music (2 trials); 2) don't feed puppet grapes (2 trials); 3) get reward at end (1 trial) memory: name of puppet	Distractor game (60s)	Accuracy • Total PM: Severe ASC < Mild ASC = controls (same for clapping & feeding tasks) • Reward: no group effect • Name recall: no group effect	–	Feed puppet food	–	–	–	Correlation between PM and CARS scores approaching significance

Notes: ABAS = Adaptive Behavior Assessment Scale; ADI-R = Autism Diagnostic Interview – Revised; ADOS = Autism Diagnostic Observation Scale; ASC = Autism Spectrum Condition; CARS = Childhood Autism Rating Scale; DEX = Dysexecutive Questionnaire; 3di = Developmental, Dimensional and Diagnostic Interview; EBPM = Event-Based Prospective Memory; PM = Prospective Memory; PPVT = Peabody Picture Vocabulary Test; OT = Ongoing Task; SRS = Social Responsiveness Scale; SSP = Short Sensory Profile; TBPM = Time-Based Prospective Memory; WASI = Wechsler Abbreviated Scale of Intelligence; WISC-III = Wechsler Intelligence Scale for Children – Third Edition; WNV = Wechsler Non-Verbal scale of ability.

task on OT performance, which is in line with the premised central role of the allocation of limited attentional resources in the PM process, as posited by the multiprocess framework. This notion was particularly supported by Sheppard et al. (2017) in that the costs to OT performance were significantly reduced when the additional PM task involved cues of high salience, and thus, facilitated more automatic (less attentionally demanding) retrieval processes.

A further result of note from the Sheppard et al. (2017) study involved their novel addition of an auditory cue (beep) condition. The PM hits were higher in this condition, for both groups, compared to the control condition, as they were for the visual salience condition. However, perhaps more interestingly, while both groups were also faster to respond in the visual salience condition, compared to the control condition, only the autistic group were also faster in the auditory condition. This was particularly interesting given that the autistic group, but not the control group, were reported to exhibit atypical and hypersensitive reactivity to visual and auditory sensory information, as measured by the Short Sensory Profile (SSP; McIntosh, Miller, Shyu, & Dunn, 1999), a behavioral characteristic commonly seen in autism (Ashburner, Ziviani, & Rodger, 2008; Tomchek & Dunn, 2007).

Taken together, these three studies suggest that EBPM is intact in autism, while also identifying certain characteristics of the process, particularly cue salience, that may be of particular importance and benefit to the PM ability of autistic individuals. All studies employed simple and/or calibrated OTs, and focal and/or rather salient cues, which arguably resulted in a net reduction of cognitive load. In contrast to these papers, the studies discussed in the next section found impaired PM in autism, and employed EBPM and/or TBPM tasks.

Impaired PM in autism

Two of the studies to find impaired PM in autism investigated only TBPM (Altgassen, Sheppard, & Hendriks, 2017; Altgassen, Williams, Bölte, & Kliegel, 2009). Both studies employed a standard Einstein–McDaniel computer-based TBPM paradigm, the primary difference between versions being that participants press a button at given target times, rather than on presentation of a cue. Participants' time-monitoring behavior is recorded as the frequency with which they check the clock (via key press), thought to be a measure of strategic, attention switching processes.

Overall, both studies saw TBPM deficits in autistic children and adolescents, compared to non-autistic controls. Furthermore, while all participants in both studies increased their time monitoring as the target time approached, the autistic participants in Altgassen et al. (2009) checked the time less frequently overall. While this time-monitoring behavior was spared in the autistic participants in Altgassen et al. (2017), the autistic participants of both studies appeared to check the time less frequently in the critical time interval closest to the target time, although this difference was only close to significance in the study of Altgassen et al. (2009, $p = .06$).

Altgassen et al. (2017) went further by investigating the role of motivation, manipulated via the PM instructions. Results revealed that performance was better for all participants of both groups in the 'personal motivation' condition ('If you also manage to press this button every minute, you will receive 5 euros'), compared to the social ('It would really help me out if you could remember to press this button every minute') and the low (standard instruction) motivation conditions; the performance within the latter two groups did not differ. Planned comparisons, however, revealed this effect to be driven by the control group only.

Regarding OT performance, controls in the Altgassen et al. (2009) study were more accurate than autistic participants, while groups did not differ in response times. In contrast, there were no group differences in terms of accuracy in the Altgassen et al. (2017) study and autistic participants responded faster to OT stimuli than controls. Moreover, the cost to OT of the additional PM task, seen in both groups in Altgassen et al. (2017) was only evident in the control group in Altgassen et al. (2009).

Taken together, these results demonstrate that when PM tasks rely primarily on strategic retrieval processes (as is the case with TBPM), and comprise OTs with high demands on attentional control resources (visuo-spatial working memory task and two-back task, respectively), autistic individuals perform less well than non-autistic controls. The lack of any motivation effect on PM in the autistic participants could be a result of a general lower level of motivation for the tasks, possibly linked to a less-developed sense of self (discussed in more detail later in the current paper). However, given that OT performance was also impacted, and time monitoring was less frequent and/or less strategic, it may be that attentional resources were at capacity, rendering the ability of the manipulation to influence attention less effective.

However, reduced PM performance is also possible from EBPM paradigms, as demonstrated by the studies of Brandimonte, Filippello, Coluccia, Altgassen, and Kliegel (2011) and Yi et al. (2014). While both studies saw impaired EBPM in the autistic group, they varied considerably in methodology. Brandimonte et al. (2011) employed a standard EBPM computer-based paradigm and found the autistic children to respond slower, and with less success, to the black and white PM target pictures than non-autistic controls. Yi et al. (2014), on the other hand, applied the same card-naming paradigm as employed in the landmark study of Kvavilashvili, Messer, and Ebdon (2001) in which young children named a stack of cards (OT), passing any cards that had a heart in one corner to the experimenter (PM). Yi and colleagues compared the performance of the autistic children to that of age-matched controls and to ability-matched controls, with the latter group being significantly younger than the two other groups. Results showed that the autistic children remembered to pass significantly less PM target cards to the experimenter than both control groups, an indication that EBPM is difficult for young autistic children, even in the face of a very simple OT.

In contrast to the previously described EBPM studies that saw preserved PM in autistic participants, these studies included PM cues of arguably low salience (line drawings in same format as OT picture trials and a small red heart in the corner of a card, in the Brandimonte et al. (2011) and Yi et al. (2014) studies, respectively. Thus, the task of controlling attention, identifying the relevant cue and retrieving the intention was, according to the multiprocess framework, necessarily more strategic, placing higher demands on attentional control resources, likely compounded by the younger age of the participants (around eight-years-old).

The study described henceforth examined both TBPM and EBPM within one sample by way of the Dresden Breakfast Task (Altgassen et al., 2012), a task designed to assess PM ability under naturalistic conditions. Participants were required to prepare the table for breakfast for their three friends' arrival. This was to be completed in a particular way, as per a given set of rules and a photograph, within seven minutes; participants were encouraged to plan their actions beforehand. Four PM tasks were embedded within the main task: two EBPM, and two TBPM (also see Table 2 for a description of the main assessment techniques).

Analysis of the video-recorded performance of the participants revealed that controls outperformed the autistic participants in *every* measure of the Dresden Breakfast Task, other than switching. That is to say, controls were better at forming plans and adhering to them, adhering to rules, executing plans fully and effectively, and performing all TBPM and EBPM tasks. Furthermore, controls outperformed autistic participants on a standard laboratory PM task, and scored better at self-report and computer-based executive function measures. This study therefore provides evidence that, under complex and naturalistic conditions, which require participants to coordinate themselves and their execution of several tasks, either sequentially or in parallel, PM performance is severely impaired in autistic individuals, even for EBPM. However, this was the first study to investigate both TBPM and EBPM in the same sample under such conditions, and so it is useful to compare the results with a study with similarly complex and multitask demands, namely with one employing the Virtual Week (Kretschmer, Altgassen, Rendell, & Bölte, 2014).

Kretschmer et al. (2014) employed a computerized version of Virtual Week (also see Table 2 for a description of the main assessment techniques), a board game that imitates daily PM task demands, originally devised by Rendell and Craik (2000). In brief, players roll virtual dice and move their tokens around the board a total of three times (three virtual days). When passing an event square, players must pick up a card and choose an activity from one of three options (e.g. have toast for breakfast), and are only permitted to move on once they roll the number corresponding to their chosen option (OT). EBPM and TBPM tasks are embedded within the game, equally split into either 'regular' tasks (e.g. take medication at breakfast – EBPM), or 'irregular' tasks (e.g. call plumber at 5 pm – TBPM). To perform the task, players press the 'perform task' button, which presents the task within a list of (distractor) tasks. The virtual time, which is linked to the movement of the tokens on the board, can be seen on a digital clock produced on-screen via key press.

Half of all participants were assigned to an 'implementation intention' condition in which they repeated 'if-then' statements on presentation of the PM task, such as 'when it is 5 pm I will press the "perform task" button and select "phone the number."' Implementation intentions have been posited to strengthen the task-cue association, thereby increasing the probability that the retrieval of the task would be more automatically triggered by presentation of the cue (Gollwitzer, 1999). Indeed, much of the previous work on implementation intentions in populations with reduced planning ability (e.g. older adults; Kliegel, Martin, McDaniel, Einstein, & Moor, 2007) has shown that this particular encoding strategy can be effective in improving PM performance (Chasteen, Park, & Schwarz, 2001), and so the authors hypothesized that this may also be important for their autistic participants.

The autistic participants performed less well than non-autistic controls across all PM tasks, replicating the PM difficulties experienced by autistic participants in multitask conditions, as seen in (Altgassen et al., 2012). Both groups performed better on the regular tasks than the irregular tasks, and a group x regularity interaction revealed the autistic participants to have performed worse than controls on the irregular tasks. Surprisingly, the implementation-intentions did not benefit either group.

PM in autism – mixed results

Thus far, studies reviewed have demonstrated either intact or impaired PM in autism, across both EBPM *and* TBPM paradigms. Three of the four following studies also included both event- and time-based cues, but, rather than showing a complete deficit, reveal only TBPM, but not EBPM deficits. The final study to be reviewed employed only a EBPM paradigm, but the results were mixed in that differences emerged between participants grouped according to a measure of autism severity. The first study discussed will be that of Henry et al. (2014) as it, like that of Kretschmer et al. (2014), employed the Virtual Week, but with children, rather than adults.

Other than participant age, the methodology employed by Henry et al. (2014) was much the same as Kretschmer et al. (2014), but was adapted to include tasks relevant to children. Also, rather than an implementation condition in this study, the authors included a 'low OT absorption' condition, which allowed children to move on from an event card with any dice roll, rather than the standard specific number; furthermore, participants were not required to move the token manually around the board as this was done automatically, further reducing overall cognitive demand.

In contrast to Kretschmer et al. (2014) the main group effect, whereby controls outperformed autistic participants, was qualified by a group by cue-type interaction, revealing that, while both groups performed better on EBPM than TBPM tasks, autistic participants only performed worse than controls on the TBPM tasks. This pattern was somewhat mirrored by a cue-type x regularity interaction, in that varying the regularity of the tasks did not result in differences in EBPM performance, but performance in irregular TBPM tasks was worse than that of the regular TBPM tasks.

This pattern again emerged in the studies by Williams, Boucher, Lind, and Jarrold (2013) and Williams, Jarrold, Grainger, and Lind (2014) which investigated both EBPM and TBPM in autistic children and autistic adults, respectively. In Williams et al. (2013) the PM of autistic children was investigated by way of an engaging computer game in which the children had to drive a car down a road, taking care to avoid obstacles and other vehicles (OT) while collecting gold coins (also see Table 2 for a description of the main assessment techniques). Using a within-subjects design, children's PM was assessed across two separate sessions in which they either had to remember to press a certain key when passing a lorry (EBPM), or to refuel after 80s (TBPM). Performance in the TBPM condition was further supported by the fuel gage turning red with 20s to go. Upon a fail, the car would stop, the OT score would be reset to zero, and a reminder presented on screen of 'Don't forget to refuel!'. In a fashion similar to that of previous TBPM studies, participants could press a certain key to check the fuel level.

No differences emerged between groups in OT performance, with both groups performing similarly on the car driving game. The PM results, however, revealed a TBPM deficit, but not an EBPM deficit, in the autistic children, compared to non-autistic children. Furthermore, only the autistic children fared better in their EBPM performance compared to their TBPM performance, although some caution is needed with interpretation as the autistic children were at ceiling in the EBPM task. Fuel-monitoring behavior showed the expected linear increase toward the TBPM target time, for both groups, indicating that strategic monitoring was intact in this autism group. Interestingly, measures of cognitive flexibility and mentalizing did show impairments in the autistic group, but only autistic mentalizing was associated with TBPM performance. The results of this study again confirmed that EBPM success is possible even for autistic children if PM cues are focal and salient; when external cues are absent, and strategic processes are necessary, as in TBPM tasks, performance may be impaired.

The study by Williams et al. (2014) found very similar results in autistic adults, though this was achieved using a more common computer-based paradigm. Specifically, participants had to remember to press a different key whenever a musical instrument appeared (EBPM) or every two minutes (TBPM), while judging whether the list presented on-screen was the same as the words previously presented one by one (OT). Again, participants could press a certain key at any moment to bring up a display of a digital clock.

With regard to OT performance, no group or cue differences emerged. With regard to PM accuracy, overall TBPM performance was worse than EBPM. Further, as in the previously described study, EBPM performance between the two groups was similar, whereas autistic TBPM performance was worse than that of controls. Analysis of the response precision of TBPM (i.e. the temporal distance to the target time) and the reaction time of the EBPM revealed no overall differences between TBPM and EBPM performance. However, the analysis did reveal that autistic participants were less precise in the TBPM task, but no slower in the EBPM task. The monitoring of the time did not differ between groups, showing the expected linear increase as the target time approached.

The final study to be summarized is that conducted by Sheppard, Kvavilashvili, and Ryder (2016), which investigated the relationship between autism symptom severity and PM performance. To accomplish this, the study included a group severely autistic children (as categorized by the Childhood Autism Rating Scale – CARS; Schopler, Reichler, DeVellis, & Daly, 1980), and adapted the methods (e.g. participant matching, task design) in novel ways accordingly. Children were engaged in three simple games, played with a hand puppet, which measured their EBPM. Recalling the puppet's name provided a measure of RM.

The inclusion of severely autistic children proved an important aspect, as, overall, only the severe, and not the mild autism group demonstrated poorer PM than the non-autistic controls. A group × task interaction revealed, however, that, remarkably, the severely autistic children performed as well as the non-autistic children on the task that involved picking up a spring toy when leaving the room.

This study, therefore, suggests that variation in autistic symptoms, a common occurrence in a population well known for its heterogeneity (Jeste & Geschwind, 2014), plays an important role PM performance. Furthermore, EBPM success is possible for severely autistic individuals if they are sufficiently motivated.

Literature summary and critique

At first glance, it is clear that very few of the reviewed investigations employed common methodologies. If, for instance, studies employed comparable age groups and OTs, they varied on cue-types and control variables, and yielded contrasting OT results (Altgassen et al., 2009 vs. Altgassen et al., 2010); if studies shared very similar paradigms, they varied on age group and yielded contrasting PM results (Kretschmer et al., 2014 vs. Henry et al., 2014). The current literature could, therefore, be considered inconsistent and unreliable and, to an extent, this is true. Thus, to provide clarity and reliability, future research must endeavor to consistently replicate findings. Importantly, the recent meta-analysis and review by

Landsiedel et al. (2017) came to a similar conclusion as the current paper, finding a reliable TBPM impairment, and a small (although less reliable), EBPM impairment. With this in mind, the apparent methodological inconsistency could also be viewed as a strength in that, across a broad range of ages and methodologies, patterns have emerged that provide important insight into PM in autism.

Firstly, of the 19 experiments conducted across the 13 studies, which included participants ranging in age from 8 to 41, 14 (73.7%) revealed a PM deficit, compared to controls. More specifically, all 7 TBPM experiments, and 6 of the 12 EBPM experiments, were suggestive of PM impairment. Considering the consistent TBPM results, it seems clear that when autistic individuals cannot depend on any external cue, but must instead rely on internal signals and self-generated and initiated strategies, such as regularly switching attention and inhibiting action without prompt, PM tasks are particularly difficult. This notion is further supported by those studies (e.g. Brandimonte et al., 2011) that did not find any cost to the OT of adding the PM task, suggesting that attention was not successfully diverted from the OT in order to monitor for and execute the PM task. Difficulty with strategically allocating attentional resources would also explain the poorer performance found in half of the EBPM studies; when cues were low in salience (e.g. Kretschmer et al., 2014) or non-focal (e.g. Yi et al., 2014), or the attention competing OT was high in cognitive demand (e.g. Altgassen et al., 2012, 2017), then autistic performance suffered, compared to non-autistic controls. In contrast, however, when these factors were reversed, and so dependence on self-initiated strategy was reduced, and automatic retrieval facilitated, then PM performance was spared. This pattern of results thus supports the multiprocess framework (McDaniel & Einstein, 2000).

When looking at the different phases of prospective remembering and keeping in mind the well-documented deficits of people with autism in attention, executive functioning, retrospective memory, and episodic future thinking, we expect to find reduced performance in virtually all phases of prospective remembering (namely, intention formation, intention retention, intention initiation and execution). So far, only one study on PM in autism has included a measure of intention formation (i.e. planning; Altgassen et al., 2012), and reported reduced autistic performance, and only one study tried to manipulate intention formation (i.e. implementation intentions; Kretschmer et al., 2014). All other studies have focused on the phases of intention initiation and execution (as has the vast majority of PM research in general), and have found the discussed mixed results (e.g. Henry et al., 2014; Sheppard et al., 2017) that are generally in line with the multiprocess framework. Intention retention has not been directly investigated, but first evidence points to retrospective memory load affecting PM in autism. Specifically, Kretschmer et al.'s study reported reduced autistic deficits with regular PM tasks that put less demands on retrospective memory as compared to irregular tasks. Similarly, Henry et al. (2014) found larger autistic PM deficits for irregular TBPM tasks.

However, an important limitation of the reviewed PM studies is that all but one (Sheppard et al., 2016) include only mildly to moderately autistic participants, of average to above average IQ. The PM evidence does not therefore fully represent the autistic population, a population known for its heterogeneity (Masi, DeMayo, Glozier, & Guastella, 2017), which is, indeed, an issue across the autism literature. The study by Sheppard et al. (2016) does highlight the importance of considering symptomatic variation in autism and how it relates to PM performance, revealing a difference in PM performance between 'severely' and 'mildly' autistic children. However, in this case, severity classification was made on the basis of a composite CARS score (Schopler et al., 1980), disguising the variation of behaviors that contributed to the total score. Thus, while the Sheppard et al. (2016) paper was an important step in the (PM) autism literature, much more needs to be done to more accurately represent the population. Therefore, while symptom severity and other aspects of the heterogeneous condition may have contributed to the PM performances seen in the literature, caution is needed when generalizing the conclusions to the entire autism population.

Taken together, despite the heterogeneous methodology of the conducted studies, and the relative homogeneity of the participants, a pattern emerges that suggests autistic individuals will likely find PM tasks that demand a high level of attentional control and strategic processing, such as those involving multiple sub-tasks and/or cues of low salience, very difficult. These findings are in line with the everyday difficulties of people with autism with planning ahead, and the organization and coordination of (complex) activities.

In terms of improving PM performance and reducing everyday difficulties, reducing the cognitive/strategic demand of PM tasks by increasing the automaticity of retrieval processes, would almost certainly be of benefit to autistic individuals, indeed, to all populations. However, all PM and autism studies conducted so far, with exception of the Dresden Breakfast Task, employed typical laboratory-based tasks that provide high experimental control, but low ecological validity, and which may not be able to reflect the complexity of real-life tasks.

The dynamic characteristics of PM

In reality, daily tasks are significantly more complex than the scenarios presented in typical laboratory-based dual-task PM paradigms. For instance, some tasks will only involve a short delay, with few competing tasks and no social interaction, such as remembering to check out with an electronic travel card when alighting the bus after a short journey. In contrast, others will involve long delays and human interaction, in the face of several other tasks and social and cultural expectations, such as passing on a message to a friend at the end of a busy academic conference. Importantly, therefore, PM is a variable, multitask process which demands the fluid and dynamic control of attentional control resources to facilitate the integration and execution of all aforementioned PM-critical cognitive mechanisms, the exact calibration of which depends heavily on context. This between- and within-PM task variability is to some extent recognized by the recent dynamic multiprocess framework proposed by Scullin, McDaniel, and Shelton (2013), which argues for the need for dynamic utilization of automatic and strategic retrieval processes over time, given the temporal variability of PM demands. Therefore, in practice, while investigating discrete cognitive mechanisms, such as executive function (e.g. reducing switching and inhibition demands by increasing cue salience) provides some indication as to the role of that specific mechanism, it ignores the interrelated, systemic and social characteristics of the PM process. One further critical factor in the dynamic PM process is individual difference, that is, how individuals are variably equipped to function in such a complex environment, a factor particularly important to consider for the autistic population who are known for their cognitive and behavioral heterogeneity (Georgiades, Szatmari, & Boyle, 2013; Jeste & Geschwind, 2014).

Thus, to properly understand PM, and so devise the most effective interventions, it is important to consider any processes that may be fundamental to the development of the cognitive and behavioral functions needed for prospective remembering and their dynamic integration and utilization, while also recognizing the dynamic and contextual requirements of PM as demanded from an ever changing physical and social environment. With this in mind, the following section will briefly examine the potentially fundamental role of predictive coding in the PM process. Furthermore, via the predictive-coding account of account by Van de Cruys et al. (2014), we will show how these predictive-coding deficits that may be primary to autism would result in the cognitive and PM deficits seen in the literature.

In recognition of the dynamic agent–environment interactions inherent to PM, we extend the role of predictive coding in PM, and the account of autism, to not just include perception, but also movement and affect, as is the case in predictive models formulated under active inference (Clark, 2015; Joffily & Coricelli, 2013; Kiverstein & Miller, 2015; Pezzulo, Rigoli, & Friston, 2015). In this way, the notions put forward in the current paper will shed light not only on processes fundamental to PM, but also on the underlying causes of autism. In addition, by better understanding fundamental atypicalities in perception, action and movement, the development of better targeted interventions is supported that not only improve daily PM performance, but also inform clinical practice and help target specific learning to improve autistic individuals' lives as a whole.

A unifying predictive-coding account of autism

Simply described, predictive coding is an account of perception in which the main task of the perceptual system is to minimize the prediction-error between predicted and actual sensory input (Clark, 2013; Rao & Ballard, 1999). Under this account, the brain continuously generates predictions about future incoming sensory information (top-down), based on the current context and associated prior experiences, which are subsequently compared with input received (bottom-up). While predictions serve to minimize prediction-error, a resulting prediction-error can be used to optimize the prediction, which in turn minimizes prediction-error, a process that cycles in perpetuity. Through prediction-errors and their minimization, the brain gradually comes to learn the statistical structure of the environment, i.e. how distal structures in the environment give rise to proximal sensory input (for more detailed introductory accounts to predictive coding, see Clark, 2013, 2015; Hohwy, 2013).

However, as Van de Cruys et al. (2014) note, due to the 'fluctuating nature of regularities in the world, and the stochastic and noisy biological system through which we experience it […]' (p.1) there is a limit to what can be predicted and hence there will always be some residual prediction-error. Therefore, a critical ability is to learn which prediction-errors are behaviorally relevant, and so should be attended to and used to update predictions, and which can be ignored.

For instance, upon entering a café, one may be surprised by the weight of the door when opening. This is a useful prediction-error, and should update the future prediction of *that particular door*. Once inside, one would expect, and so predict, to hear the sound of the milk steaming machine. If a familiar café, one would even be able to predict well the location of the sound, and have some idea of the sound's particular characteristics. However, it would be practically impossible to predict the exact time, and the exact volume and clarity as experienced by the perceiver (influenced, for example, by talking, head cold, a particularly loud/busy moment). Therefore, the sound of the steam machine would almost always generate an error. However, this error could never be reduced and should thus receive minimal attention, and should not update the model of what to expect in a café; that is, nothing further could be learnt from this experience (irreducible uncertainty, Van de Cruys et al. (2014), so the error should be assigned low confidence (*precision*) that it is attention worthy.

Thus, within an optimal prediction model of a steam machine in a café, the occurrence of the sound at any given moment will essentially be surprising, but not unexpected.

Clearly, then, being able to flexibly and context-sensitively vary the precision of prediction-errors is critical for optimal learning and attention allocation (Feldman & Friston, 2010). An understanding of the errors that still offer reducible uncertainty facilitates the efficient direction of attention toward errors that can be further reduced, i.e. real learning opportunities. Conversely, assigning equal and high weight to each and every error would result in attention being drawn to errors which will always occur and cannot be reduced, thus depleting valuable and limited cognitive processing power, and needlessly updating prediction models. Precision, therefore, is seen as the fundamental mechanism of learning and attention (Van de Cruys et al., 2014) and has a clear and important role in PM.

If, as posited by the multiprocess framework (McDaniel & Einstein, 2000) the allocation of attentional resources is central to the PM process, then an optimum precision weighting mechanism is essential to successful PM performance. Selectively attending to relevant information and ignoring the high volume of other information would facilitate time monitoring, or the monitoring for and identification of PM cues (particularly for those of low salience and non-focality), or the switching of attention from one task to another. Furthermore, attenuating the relentless barrage of irrelevant sensory information is important for the development and application of other, higher level cognitive processes critical to PM, such as planning, retrospective memory, episodic future thinking and critical thinking and reasoning (regarding, say, the context and environment within which the PM is likely to be situated).

Using the previous example of a café, it is easy to see the importance of precision to PM. One would rely on the high-level concept of a café to form a 'café-prediction', from which one would expect, and thus assign low precision to, the tumultuous stream of relatively lower level errors (e.g. sudden bursts of laughter, or cups being dropped to the floor) allowing them to be ignored within (and thus not update) my 'café-prediction' model. This would free up attentional resources, which would be particularly important for demanding PM tasks within the café, such as monitoring the time in order to call your boss at a certain time, or to monitor for a cue indicating your coffee is ready, after which you might stop your conversation (OT) and pick up the coffee which has been placed at the end of the counter.

Pertinently for the current review, Van de Cruys et al. (2014), in their unifying account of autism, put forward the selective and contextual weighting of precision, a mechanism essential to attentional control and so to PM, as the core deficit of the condition. Specifically, they situate the core deficit in the High, Inflexible Precision of Prediction-Errors in Autism (HIPPEA). This means that impaired precision allocation results in attention often being drawn to what is effectively noise, thus demanding valuable and limited cognitive resources, drawing attention away from real and important learning opportunities, and needlessly updating prediction models. The authors posit that this uniformly high precision, irrespective of context, accounts for the characteristic impairments and difficulties commonly seen in autism, such as atypical sensory processing (Ashburner et al., 2008; Ben-Sasson et al., 2009; Robertson & Baron-Cohen, 2017; Tomchek & Dunn, 2007), social communication difficulties, and insistence on sameness and repetitive behaviors, as efforts to reduce confusing and unpleasant environmental uncertainty (American Psychiatric Publishing, 2013). Specifically, high sensory precision may result in a constant barrage of seemingly unfamiliar, attention grabbing signals, each of which would arguably be at best surprising and distracting; at worst, shocking and frightening. Importantly, prediction itself is not impaired in autism, as is evidenced by superior performance in situations with high consistency and predictability, for example in structured visual search tasks (O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001).

Assuming the validity of the Van de Cruys et al. (2014) account, the deficit of HIPPEA leads directly to the PM impairments seen in the population. It would explain, for example, poor PM performance, relative to non-autistic participants, when PM cues were low in salience (e.g. high precision attributed to each and every error would result in all sensory input being 'salient' and deserving of attention). This would load heavily on limited cognitive resources, and would also diffuse the relevance and contextual salience of the PM cue, making it much harder to discern. Thus, the predictive-coding account of Van de Cruys arguably contributes much to the understanding of autism, and to PM. An important potential criticism of the account, however, may be that, so far, much of the literature has been mainly theoretical and conceptual in nature, dealing with autism using the tools and concepts derived from predictive coding and provides therefore nothing more than stories (Bowers & Davis, 2012). Although the unification of a disparate range of impairments under one theory is progress in its own right, we agree that much further work is needed. In particular, the development of quantitative computational models that are able to make predictions about updating, learning, and the adjustment of precision on a trial-by-trial basis (Van de Cruys et al., 2017), would greatly advance the field. For example, the aim of the rapidly emerging field of *computational psychiatry* is to infer the hidden causes (such as the structure of the parameters of an internal model) of measurable quantities (such as actions, reaction times and symptoms; Friston, Stephan, Montague, & Dolan, 2014; Schwartenbeck & Friston, 2016; Stephan & Mathys, 2014). Furthermore, in their recent paper, Van de Cruys et al. (2017) put forward substantial empirical data in support of their account.

So far, we have only focused on the perceptual aspect of prediction-error minimization. However, PM does not simply involve the perception and processing of external sensory signals. Rather, it is a complex process that depends critically on perception *and* action. Specifically, it requires the effective coordination of the mind (perception, desires, intentions), the body (bodily sensations, action) and the environment (PM cues and/or target times; social or occupational expectations; competing sensory and social demands for attention) to ensure successful action at the appropriate moment. Consequently, to fully relate predictive coding to PM and to autism, we need to extend HIPPEA to more embodied predictive-coding models derived from *active inference* (Bruineberg, Kiverstein, & Rietveld, 2016; Pezzulo et al., 2015; Seth, 2013).

According to active inference, action, as well as perception, is integral to the predictive-coding and error minimization process. That is, agents do not only try to predict the current state of the environment, but also cause their environment to be in an optimal state (i.e. a state of physical, social and cultural well-being/safety) *through action*. For example, according to active inference, 'intending to post an important letter in a post box' works like determining the need of posting a letter, expecting oneself (with high precision) to post the letter and then selecting an action (reaching into a bag, grasping the letter, then posting it through the slit in the post box) that fulfils that expectation. Only if an agent has the right predictions (both about what will be an optimal state, and about how it can reach that state), it can cause the environment to confirm to those expectations and consequently lead to an actually optimal state beneficial to the agent (Bruineberg et al., 2016).

Put in more concrete terms, for individuals to flourish in their environment, they must understand their needs in terms of their physical and mental well-being (expected states), and meet them by perceiving and acting upon the environment in an as efficient and beneficial way as possible. This includes among others the congruency of the sensory weighting of prediction-error (precision) with the volatility of the environment and the trade-off between action and perception (Palmer, Lawson, & Hohwy, 2017). Therefore, the role of prediction-error minimization, and the impact of any impairment such as HIPPEA, becomes much more significant, as it mediates all interactions between the brain, the body, and the environment within and between all hierarchical levels (i.e. low-level stimulus to high level concepts/abstractions), facilitating understanding of the self and the world in which it is situated. Active inference and error minimization is therefore deeply interwoven into everyday processes, not least the PM process.

Given then, the essential role of prediction and error precision in mediating the relationships between the brain, the body, and the environment, the adverse consequence of HIPPEA, the precision-weighting deficit put forward as core to autism (Van de Cruys et al., 2014, 2017) already deemed significant to PM, becomes much more problematic. It means that autism is not solely a problem of perceptual evidence accumulation, but involves deficits in the interactions between all levels and modalities (e.g. between simple, sensory signals and higher level conceptual/constructed beliefs), between the brain and body, and the ways they coordinate to respond and act upon the environment. Thus, HIPPEA makes a whole range of other autism phenomena intelligible such as their difficulties with understanding internal states, evidenced by a high prevalence of alexithymia (Milosavljevic et al., 2016), difficulties with interoception (Shah, Hall, Catmur, & Bird, 2016), differences in rhythm and timing (Isenhower et al., 2012; Sheridan & McAuley, 1997), movement and associated social difficulties (Cook, 2016; Cook, Blakemore, & Press, 2013), and diminished sense of agency (Grynszpan et al., 2012; Sperduti, Pieron, Leboyer, & Zalla, 2014; Zalla, Miele, Leboyer, & Metcalfe, 2015), linked to deficits in episodic memory and episodic future thinking (Lind, 2010). We think that extending the unifying account of autism of Van de Cruys et al. (2014) in such an embodied way, brings the account closer to more embodied unifying accounts of autism such as the one offered by De Jaegher (2015) which places differences in movement, rhythm and coordination, between the self, others and environment as responsible for the emergence of autism. Thus, the embodied HIPPEA and enactive accounts of autism both describe systematic differences in movement and perception that ultimately blend with a different conceptual and social understanding of the environment; indeed, a different way of making sense of the world. We feel that together, both accounts offer a more encompassing account of autism. Furthermore, the difficulties caused by such as account would greatly impact upon PM performance.

PM tasks reflect one aspect of the fundamental real-world demand of navigating a complex physical, social and cultural environment, and so require the efficient coordination of the brain, body, and environment to remain in a state of well-being. For example, the environment will create PM demands (work supervisor asks you to pass on important information to a work colleague), generating intentions within the individual (pass message on to colleague). This intention is internalized in terms of relative value (need to please supervisor; consequence for colleague of not receiving message; likely personal emotional state – personal, physical and social consequences of success/failure) which would interact with chances of success (beliefs about own ability to successfully execute task, given likely future

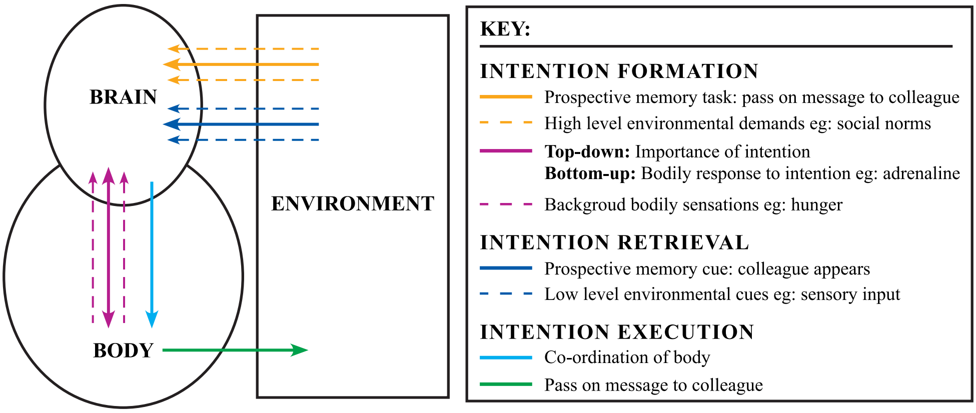

Figure 2. Diagram depicting the role of predictive processing in mediating between the brain, body, and environment throughout the prospective memory process. Illustrates importance of attending to relevant cues (solid arrows), via effective precision-weighting, against a barrage of competing, often task-irrelevant, information (dashed arrows).

context in which task/cue is situated, and predicted ability to employ appropriate action within it; see Figure 2). These states are accompanied by physiological responses (increased heart rate, adrenaline/cortisol) and associated affective responses (arousal, worry, stress) that would need to be understood in the context of their situatedness in a socio-cultural setting. In addition, successfully realizing the PM task requires understanding how attentional resources are employed to perceive relevant cues (recalling my supervisor's request upon seeing my colleague). What is crucial then, is for the agent to be selectively perturbed by aspects of the environment (change your behavior when seeing your colleague, but try to not get distracted by your phone) in a way that is in line with longer term plans and goals and the demands of the situation (such as your supervisor's request). Such selective openness to aspects of the environment (or 'affordances') and coordinating with them in an adequate way represents a process fundamental to life and mind (Bruineberg & Rietveld, 2014).

Seeing PM as reflecting this fundamental life processes means that interventions aimed at addressing issues that may be affecting such life processes (e.g. HIPPEA in embodied predictive coding) would also benefit PM performance.

Clinical application

According to HIPPEA (Van de Cruys et al., 2014, 2017), autism emerges primarily from an impaired prediction-error precision weighting process, resulting in and manifesting as sub-optimal learning and attentional mechanisms. When considered in the context of active inference and the brain–body–environment system, HIPPEA would disrupt the critical continuous and reciprocal learning between all three states of the system, resulting in impaired communication and understanding between the brain and the body, and their perception and action in and with the environment. Given these assumptions, autistic individuals would benefit from holistic and embodied interventions that would support them in attending to and engaging with themselves and the world, which would in turn support their PM performance.

As posited by the above assumptions, autistic people experience difficulty in perceiving and acting in the often *irreducibly* uncertain world. One obvious way in which to support such a difficulty is to reduce the irreducible uncertainty as much as possible, and provide predictable clear expectations and a safe physical, social, and cultural environment. This provision of clear, consistent structure, and expectation in the environment is the core principal of the Treatment and Education of Autistic and related Communication-handicapped Children approach (TEACCH; Mesibov, Shea, & Schopler, 2004) which is widely implemented within charities and schools and has good levels of reported effectiveness (Mesibov & Shea, 2010; Panerai, Ferrante, & Zingale, 2002). According to TEACCH, schools/environments should provide autistic individuals with as predictable and 'low arousal' physical environments as possible, for example, low sensory input and similar classroom configuration across all classes (e.g. same furniture, consistently arranged and decorated display boards, neutral colors). Reducing the uncertainty in the environment would not only reduce anxiety but would provide a safe, predictable platform from which to learn. These TEACCH principles could also be directly applied to the PM environment: reducing the physical and social uncertainty in the environment parallels the reduction in cognitive load inferred to be beneficial in empirical PM work (e.g. use of salient cues, simple OT). Providing clear PM instructions that are additionally supported by visual cues, could enhance encoding and increase the physical/perceptual salience of the cue, thus decreasing executive control demands by increasing automaticity of intention retrieval. To increase effectiveness, this approach could easily be incorporated into a person's existing communication strategy. For instance, an autistic child's tailored Picture Exchange Communication System (PECS; Bondy & Frost, 1994) could be employed to provide need-appropriate verbal and visual task instructions when supporting them in bringing their sports kit to school the following day. The relevant symbols could be placed on the appropriate day on the child's daily visual timetable, with copies taken home on the day to act as salient PM cues.

Furthermore, if autism is indeed associated with sub-optimal attentional processes, which may result in difficulties attending to relevant and important cues (internal and external), autistic individuals may benefit from interventions that focus on practicing and training attention. For example, the program Attention Autism (Dawson et al., 2004), originally developed to support the development of joint attention, has been found to improve attention by providing engaging sensory objects. This intervention would thus support the general development of the understanding to engage with relevant cues in the environment, cues which afford personal and social benefits. The benefit to PM of improving attention by way of interventions such as Attention Autism (Dawson et al., 2004) is thus clear: the ability to identify, and allocate attention toward, appropriate event-based cues in a complex environment would be developed, facilitating more frequent automatic retrieval.

A further method of improving self and internal understanding and the relationship with the environment – or the brain–body–environment system – would be to facilitate impaired learning through interventions that involve the use and coordination of all three of these states. Moving, acting and perceiving to achieve internal (fun, pleasure) and external (social interaction, PM tasks) goals, and post-action perception and reflection on the internal (emotions, feelings, bodily responses) and external (effective communication, understanding others' behavior, successfully executing a PM task) physical and social results, would support the understanding of one's own function in one's physical and social environment, and improve PM performance at every phase. One would slowly become more attuned to one's own body and its responses and actions within its environment. Examples for such embodied/enactive approaches are movement (for a review, see Lee, Lambert, Wittich, Kehayia, & Park, 2016), drama (Corbett et al., 2011), music (Whipple, 2004), and art therapies (Koch, Mehl, Sobanski, Sieber, & Fuchs, 2014) that are currently already employed to support autistic people.

The approaches described above can be incorporated to generate more concrete, PM-specific support and learning strategies. One approach would be to augment the largely non-conscious, impaired embodied predictive coding and error weighting processes that are involved at every PM phase, with explicit, metacognitive processes. Metacognition has been shown to be important in PM, suggesting, for example, that attention-allocation strategies depend somewhat on metacognitive expectations of the PM task demands (Rummel & Meiser, 2013), and an awareness of one's cognitive difficulties may encourage the use of reminders to make sure one does not forget the implementation of the delayed intention (Gilbert, 2015; Phillips, Henry, & Martin, 2008). Although, interestingly, a recent study by Cherkaoui and Gilbert (2017) found that autistic participants gave good metacognitive judgments of their (poorer) PM abilities and predictions of performance, but did not compensate with an increased use of reminders. It may be that the autistic participants differed only in their metacognitive control, but not awareness, in line with the, albeit scarce, literature pointing to difficulties autism in metacognitive control, and to deficits in using monitoring processes to influence cognitive control (for similar results see Grainger, Williams, & Lind, 2016; Wilkinson, Best, Minshew, & Strauss, 2010; but see Wojcik, Allen, Brown, & Souchay, 2011 for contrasting findings).

Given the benefit of metacognitive strategies to the learning of those who experience learning difficulties (Chevalier, Parrila, Ritchie, & Deacon, 2017) it may be that autistic individuals, indeed any individuals that experience PM difficulties, would benefit from training and support in the use of direct PM metacognitive strategies. Such training could be designed by drawing on the principles of TEACCH (Mesibov et al., 2004) to provide a highly structured, cyclical PM predict-perform-evaluate processes, scaffolded appropriately according to individual cognitive and communication needs (e.g. the use of PECS symbols as mentioned above). Figure 3 provides an example of how this could be implemented in, for example, schools, to be completed by children with an appropriate level of adult support. Through this sheet, children would be encouraged to consciously consider a particular PM task, such as remembering their swimming kit, and why it is important to them. Children would also predict the likely environment in which the intention will be executed, how difficult it will be, what reminders or cues they will use and, ultimately, their likely chances of success. The children could then evaluate their predictions and performance, once the task was over, comparing them with what was experienced, informing future strategy and predictions for the same or similar tasks in the future. This cyclical process would augment the predictive processing problems we posit to adversely affect PM in autism, while also developing PM-specific, and more general, metacognitive ability. It would also have the added benefit of directly supporting the factors posited by the multiprocess framework (McDaniel & Einstein, 2000) to influence attention allocation and intention retrieval during the PM process (such as deeper intention encoding, stronger cue-action association, as well as highlighting cue salience and task importance).

To summarize, the findings of the PM and autism literature shows that making small changes to the PM environment, such as clearly demonstrating the value of completing the

Table 2. Description of assessment techniques.

Task name	Task description	Time to complete	PM cue type	Cue delay length	Psychometric properties	Appropriate age range	Appropriate severity range	References
Dresden Breakfast task	Preparation of breakfast following certain rules and time restrictions	15 min (including planning; excluding delay)	2 EBPM tasks (each 1×) and 2 TBPM tasks (each 1×)	5 min	Inter-rater reliability was high in the Altgassen et al. (2012) study (plan performance $r = .95$; plan adherence $r = .93$); validity shown by detrimental effects of various disorders and aging	Starting from about 12 years	Mild to moderate	Real-life version; used in autism and older adults: Altgassen et al. (2012); Hering, Cortez, Kliegel, and Altgassen (2014) virtual version; used in ADHD and older adults: Altgassen, Kretschmer, and Kliegel (2014); Altgassen et al. (2015)
Driving game	Computer-based driving game	8 min per condition	2 conditions: (a)1 EBPM task (6×) (b)1 TBPM task (6×)	No delay	–	7–14 years	Mild to moderate	Williams et al. (2013)
Virtual Week	Computer-based board game that imitates daily PM task demands	About 45 min	EBPM & TBPM each day 4 tasks (2 regular, 2 irregular); total of 3 days, thus 24 PM tasks	No delay	Good reliability (Cronbach's Alpha) ranging between .57 and .84 for Henry et al. (2014) and .62 and .86 for Kretschmer et al. (2014); validity indicated by detrimental effects of various forms of pathology and aging (see review Rendell & Henry, 2009)	Children version: 8–12 years adult version: starting from around 13 years	Mild to moderate	Children's version: Henry et al. (2014) adult version: used, e.g. in autism, older adults, multiple sclerosis, Parkinson's disease, traumatic brain injury: Kretschmer et al. (2014); Altgassen et al., 2015; Rendell, Henry, Phillips, de la Piedad Garcia, Booth, Phillips, and Kliegel (2012); Foster, Rose, McDaniel, and Rendell (2013); Mioni, Rendell, Henry, Cantagallo, and Stablum (2013)

Note: EBPM = Event-Based Prospective Memory; PM = Prospective Memory; TBPM = Time-Based Prospective Memory.

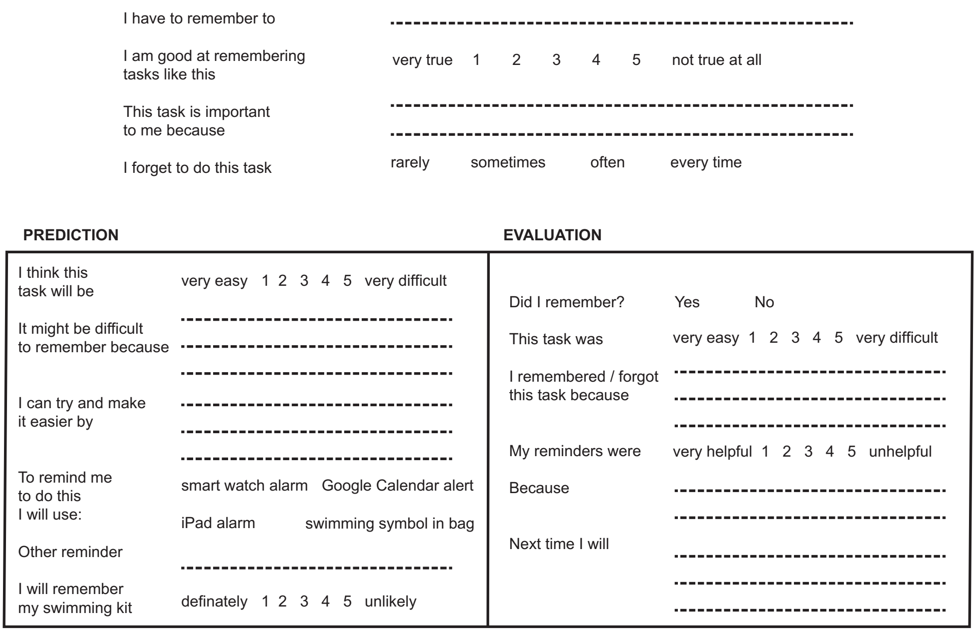

Figure 3. PM metacognition worksheet to support individuals with specific PM tasks. Metacognitive awareness and control would be developed by encouraging individuals to regularly predict and evaluate their PM performance, based on their understanding of self-PM ability, task importance, past performance, self-chosen reminders/cues, and the likely environment in which it will occur. Levels of support, formatting, could be adapted to an individual need-appropriate level, e.g. full adult support, the use of symbols in place of words.

task may improve PM performance. Such a demonstration might increase motivation, offset an impaired understanding of self and may improve PM performance by supporting intention encoding, shielding of the intention from PM-irrelevant stimuli, encouraging monitoring for the PM cue and enabling switching to the intended action. Furthermore, the salience of the cue, both in terms of the sensory distinctiveness as historically described by the PM literature, and in terms of its relevance to the task, may influence the extent to which retrieval of the intention relies on automatic vs. strategic, executive control processes.

Conclusion

The evidence from studies conducted to date strongly suggests that autistic individuals experience difficulty with PM. However, the few studies in which autistic PM performance was spared, even for severely autistic children, demonstrated that PM success is possible under very structured conditions, with simple OTs, highly salient, focal PM cues and motivating rewards. According to the multiprocess framework, these conditions more automatically encourage the allocation of attention toward PM cues, supporting intention retrieval and execution, and rely less on cognitive functions that are impaired in autism (e.g. executive functions, retrospective memory, episodic future thinking).

According to our proposed account of autism, the commonly found cognitive, social and motor deficits in autism are deeply underpinned by an impaired prediction-error weighting ability. This impairment disrupts the development and understanding of the brain–body–environment relationships and interactions, culminating in differences in the way that autistic people perceive, move, and make sense of the world. Thus, these differences fundamental to autism may lead to their problems with functioning successfully in the world, a critical aspect of which is successfully performing the frequent and challenging PM tasks. Therefore, while treating the 'symptoms' of poor PM performance by increasing, for example, cue salience and focality, is easily implemented and almost certain to result in better performance, we propose to directly address problems of prediction and action through embodied autism and PM research paradigms and interventions.

Notes

1. We have used identity-first, rather than person-first, language throughout the paper in line with the preferences of the autism community (Kenny et al., 2015; Sinclair, 2013).
2. The current paper will focus on the multiprocess framework as it is the theory most used by the reviewed studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

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