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Prospective Memory

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Abstract

Prospective memory (PM) involves remembering to perform an intended action at the appropriate time in the future. After providing an introduction to standard laboratory and naturalistic research paradigms for the study of PM, this chapter includes a critical review of current theories of PM and formal modelling approaches for the study of cognitive processes underlying performance in PM tasks. The authors then provide an overview of the lifespan development of PM from childhood to older adulthood, followed by an overview of applied aspects and a review of the recent literature on PM in clinical populations.

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Prospective Memory

Most chapters in this *Handbook* discuss retrospective memory. In retrospective-memory tasks, such as recognition and recall, we remember what occurred in the past. The suggestion has been made, however, that the purpose of episodic retrospective memory is to prepare and plan for the future (Klein, 2013; see also Chapter 7.3 by Addis & Tanguay, "Prospective Cognition and its Links with Memory"). One type of task that engages retrospective memory to be prepared for future actions are prospective-memory (PM) tasks. PM involves remembering to perform an intended action at the appropriate time in the future. Next to a prospective component (remember *that* we must do something), PM tasks have retrospective-memory components, namely remember *what* we must do and *when*. A further typical characteristic of PM tasks is that there is a delay between the formation of the intention and the point in time when the intention is to be performed without further external prompt (McDaniel & Einstein, 2007).

We must frequently perform PM tasks in daily life. For example, our doctor may tell us to take our medicine before dinner, we may want to congratulate a friend on his birthday when we see him, or we must buy bread on the way home from work. PM tasks are of great importance for proper performance in safety-critical work contexts such as aviation and health care (for a review, see Loft, Dismukes, & Grundgeiger, 2019). Generally, PM is necessary to independently accomplish activities of daily living at appropriate times and is therefore crucial for an independent, autonomous, and productive life (Hering, Kliegel, Rendell, Craik, & Rose, 2018).

Despite the ubiquity of PM tasks in the real world and the challenging theoretical issues related to PM, this topic had only just begun to receive its deserved attention in the scientific community at the time of the publication of the last *Oxford Handbook on Memory* (edited by Tulving & Craik, 2000). Accordingly, no chapter was exclusively devoted to this topic in the former *Handbook*, although PM was mentioned in chapters by Lockhart (2000) and Anderson and Craik (2000), who, by mentioning methods of PM research and pointing to their relevance for cognitive-aging research, respectively, paved the way for an increasing interest in PM. Indeed, since then, research activity on this topic has increased exponentially with more than 100 new journal articles per year (Rummel & McDaniel, 2019b), and great strides have been made both theoretically and empirically. The distinction between retrospective and prospective memory as related but distinct constructs has meanwhile been empirically confirmed via latent-variable approaches (Salthouse, Berish, & Siedlecki, 2004; Schnitzspahn, Stahl, Zeintl, Kaller & Kliegel, 2013; Zeintl, Kliegel, & Hofer, 2007; Zuber, Kliegel, & Ihle, 2016). These developments necessitate the inclusion of a separate chapter on PM in this new *Handbook*. [1]

In this chapter, we first introduce the laboratory and naturalistic task paradigms commonly used to study PM. We will then discuss theories and formal models that have been proposed to explain performance and failure in PM tasks. We will then review the literature on lifespan development of PM from childhood to old age, and the literatures on PM in clinical populations and in applied settings. We will end with suggestions for future research in this dynamic field of study.

Task Paradigms

There are two major categories of PM tasks: *time-based* and *event-based* (Einstein & McDaniel, 1996). In *time-based* PM tasks, we intend to perform an action after a particular time period has passed or at a particular point in time. For example, we may have to remember to take the spaghetti off the stove after 10 minutes. In *event-based* PM tasks, we

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[1] For more detailed reviews of PM research, refer to the books published by Brandimonte, Einstein, and McDaniel (1996), Cohen and Hicks (2017), Kliegel, McDaniel, and Einstein (2008), McDaniel and Einstein (2007), and to the most recent volume dedicated to PM edited by Rummel and McDaniel (2019a).

intend to perform an action contingent on the occurrence of a PM target event. For example, we may want to remember to buy bread when we see a bakery. Both time-based and event-based PM can be measured in laboratory and naturalistic settings.

Laboratory Task Paradigms

In the typical time-based PM laboratory task, participants perform an ongoing task, and at a particular point in time or when a particular period of time has passed they are supposed to perform a PM task. For example, Park, Hertzog, Kidder, Morrell, and Mayhorn (1997) had participants perform an ongoing working-memory task. In addition to this task, participants had to pull a lever every 1 min or every 2 min. As is typical in studies of time-based PM, participants had the opportunity to check a clock to monitor the passage of time. In most studies, the clock is invisible and participants must perform a specific action (such as pressing a specific key) to see it. This allows researchers to directly measure clock-checking behavior. Dependent variables in this paradigm are PM responses within a designated window of time or deviation from the target time, clock-checking behavior, and performance in the ongoing task.

The introduction of a standard laboratory paradigm for event-based PM tasks by Einstein and McDaniel (1990) was a milestone for experimental PM research. In this paradigm, a PM task is also embedded into another (ongoing) attention-demanding task. Upon occurrence of a previously determined target event, the ongoing task must be interrupted so that the PM task can be performed. The task models PM tasks in real life, as these events typically occur during the performance of other activities of daily life. For example, you are riding your bike home from work. When you see a bakery, you must stop to buy bread. In the laboratory, participants perform, for example, an ongoing lexical-decision task (e.g., Horn & Bayen, 2015) in which they must decide whether sequentially presented letter strings are words or non-words. In addition to the ongoing task, they are given a PM task such as responding to the appearance of particular targets, such as particular letters, by pressing a designated PM response key. The standard dependent measure of PM performance in this type of task is the PM hit rate, that is, the proportion of PM target trials that receive correct PM responses. Furthermore, ongoing-task accuracy and ongoing-task response times can be measured.

Variants of this laboratory PM paradigm have been used in countless studies with a large array of participant populations (for a partial list, see Anderson, Strube, & McDaniel, 2019) and have enabled researchers to test for effects of experimental and individual-difference variables on PM performance and to develop theories of PM. To this end, a host of different experimental manipulations have been evaluated. These include instructions regarding the importance of the PM task relative to the ongoing task, varying the number of different PM targets, the frequency of target appearance, PM target characteristics, and characteristics of the ongoing task such as its difficulty.

Naturalistic Tasks to Study PM

Investigating PM in a natural context is crucial to understanding PM functioning in everyday life. It allows researchers to study which strategies and external aids are normally employed to succeed in PM tasks. Using naturally occurring and familiar PM tasks makes the assessment less obtrusive and more ecologically valid (see Phillips, Henry, & Martin, 2008, on ecological validity of different PM tasks). However, of course, the more naturalistic the observation, the less control there is for the experimenter (see also Guynn, Einstein, & McDaniel, 2019).

Instructed naturalistic tasks. Many naturalistic PM studies use experimenter-given tasks that participants are then supposed to carry out in their daily life (e.g., Cauvin, Moulin, Souchay, Schnitzspahn & Kliegel, 2019), for instance, “Please send a text message every day at 11 a.m. and at 3 p.m.” The advantage of these tasks is that the experimenter can control the frequency of their occurrence and can easily measure the accuracy and timeliness of participant responses; however, these tasks may still feel arbitrary to the participants and thus may not be treated as naturally occurring PM tasks.

Self-assigned PM tasks. To further increase the level of ecological validity and thus the personal relevance of PM tasks to participants, PM researchers also seek to investigate PM tasks that naturally occur in the daily life of study participants (e.g., Schnitzspahn, Kvavilashvili, & Altgassen, 2020). Here, the challenge is to assess accuracy as unobtrusively as possible. Different approaches have been taken. One classical approach is the use of *diary* methods. Either whenever participants face a PM task (Crovitz and Daniel, 1984) or at regular times (e.g., in the evening, Schnitzspahn et al., 2016), participants are asked to note down their PM tasks and whether or not they succeeded in them. To increase control, investigators can combine this procedure with a phone call the night before to inquire about planned PM tasks, and with a check about task completion on the subsequent day (e.g., Ihle, Schnitzspahn, Rendell, Luong, & Kliegel, 2012).

Besides asking participants to take notes whenever a PM task occurs, thus relying on the participant's initiative, investigators can also use prompts that come from the outside, as is the case in *experience sampling methods* (e.g., Anderson & McDaniel, 2019). Here, participants receive prompts throughout the day and must report if they had a PM task in mind at the moment (and if so, whether they succeeded in remembering it). Due to further technological progress, other ways of measuring naturally occurring PM tasks are and will be possible, such as the use of electronic medication boxes (e.g., Insel, Einstein, Morrow, Koerner, & Hepworth, 2016).

Theoretical Accounts of Prospective Memory

We now turn to theoretical accounts that have been proposed to explain performance and failure in PM tasks. We will start with a descriptive phase model that distinguishes four different phases relevant to PM from intention formation to intention execution. Most theorizing has centered on the phase of intention retrieval with theoretical debates focusing particularly on the role of attention and control in this phase. Several formal models, both measurement and process models, have contributed to the understanding of cognitive processes underlying PM performance.

The Phase Model

Kliegel, Martin, McDaniel, and Einstein (2002) proposed a phase model of PM comprising four distinct phases (see also Ellis, 1996): (i) intention formation – the phase in which the intention is formed, often involving the formation of a plan, (ii) intention retention – the phase during which the intention is maintained in long-term memory and during which the individual usually engages in an ongoing activity (Ellis & Kvavilashvili, 2000) that prevents continuous rehearsal of the intention in working memory, (iii) intention initiation – the phase in which the execution of the intended task is (or should be) initiated, and (iv) intention execution – the phase when the intended action is carried out according to the previously formed plan. These phases are shown in Figure 1.

Insert Figure 1 about here

The Kliegel et al. phase model has stimulated research in two major directions. First, it offers a process perspective on PM and serves as a descriptive heuristic that allows for a more precise localization of the origin of PM failure in general. It also serves to identify the source of possible developmental or clinical deficits in particular (see, e.g., Kliegel, Mackinlay & Jäger, 2008b; Wandschneider et al., 2010). For example, it has been shown that older adults have particular problems with sufficient intention planning and intention initiation, whereas their intention retention seems relatively intact (Kliegel, Martin, McDaniel, Einstein & Moor, 2007). Second, the phase model has been used to specify in which phases the involvement of associated cognitive processes such as episodic-memory components and various executive functions may be localized (see, e.g., Kliegel, Altgassen, Hering & Rose, 2011).

According to the model, the extent to which a specific mechanism is involved in each phase varies depending on characteristics of the individual and the task. The model postulates that functionality of neuro-cognitive networks, which form the basis of cognitive abilities such as retrospective memory (medial temporal networks) and/or executive functioning (frontal networks) may affect each PM phase through interplay of several major cognitive processes (see Figure 1): planning (at intention formation), storage and monitoring (during intention retention), inhibition (at intention initiation), and task switching (at intention execution). The general idea is that impairments in PM are the result of a mismatch between the cognitive demands in a specific phase of a PM task (e.g., a PM task may require more or less planning in the intention formation phase) and individual differences / impairments in those corresponding cognitive abilities. For example, a medical condition such as Multiple Sclerosis may affect planning abilities. The model predicts a PM impairment only if the available cognitive abilities do not suffice for the given PM task at hand. For example, even if particular patients have reduced planning abilities, they may still have sufficient ability to succeed in a PM task that does not require a lot of planning (e.g., a focal single cue event-based PM task). While the task demands depend on the PM phase and other features of the task (such as the salience of the PM targets), the available cognitive abilities of the individual may depend on the specific neuro-cognitive profile of a given neurocognitive disorder and / or of an individual's current developmental stage.

Recently, the phase model has been extended in two dimensions (see Figure 1). First, an individual's metacognition and motivation might additionally influence whether the cognitive demands of a specific PM task phase match their available cognitive abilities: If, for instance, a PM task is judged as particularly challenging or if an individual is highly motivated to succeed in a task, they may decide to mainly invest their abilities in a particular phase and/or may use strategies to change task characteristics (e.g., change a time-based into an event-based task, Kliegel et al., 2011; Kliegel, Schnitzspahn, Souchay & Moulin, 2017). Second, resting on meta-analytic and eye-tracking data, it has been proposed that the initiation phase may have to be further divided into several sub-phases, namely (a) cue-detection, (b) intention retrieval, and (c) post-retrieval task coordination that all precede the onset of intention execution. This is to account for findings showing that detection of a PM target may not necessarily lead to intention execution, and to further understand the micro-structure of processes necessary to coordinate the more or less conflicting ongoing and prospective task sets (Ballhausen, Lauffs, Herzog, & Kliegel, 2019; Ihle, Hering, Mahy, Bisiacchi, & Kliegel, 2013).

PAM Theory and the Role of Context in PM

Theories of PM differ with regard to the role that attention plays when PM targets need to be retrieved from long-term memory at the appropriate moment. In the following paragraphs, we discuss, in turn, the Preparatory Attention and Memory Processes (PAM) Theory (Smith, 2003, 2008, 2010, 2016), variants of the Multi-Process View (e.g., McDaniel, Umanath, Einstein, & Waldum, 2015) and (below under formal models) the PM Decision Control Theory (Strickland, Loft, Remington, & Heathcote, 2018).

The PAM Theory postulates that attention is *always* necessary for the successful completion of a PM task (Smith, Hunt, McVay, & McConnell, 2007). That is, Smith and colleaguesp argue that while performing the ongoing task, the participant must devote some attention to monitoring the environment in preparation of the appearance of a PM target event. Importantly, this attention allocation should take place prior to intention initiation because otherwise the PM target will be missed. For example, if you ride your bike home from work (ongoing task) and want to buy bread (PM task) you must, in addition to paying attention to traffic, devote some attention to prepare for the possible occurrence of a target event in the environment (e.g., a bakery or supermarket). Attention can be devoted to consciously monitoring for target events, or can be more subtle processes taking place in the periphery of attention (Smith, 2017). The amount of attention required is determined by PM task difficulty. For example, salient PM targets (e.g., a big red sign, such as "BREAD SALE," requires less preparatory attention than non-salient targets; Smith et al., 2007).

To measure the attentional demands of PM tasks, Smith (2003) developed the so-called "cost paradigm". The rationale behind this paradigm is that if an attention-demanding PM task is added to an ongoing task, then accuracy and/or reaction time on the ongoing-task trials will suffer. The cost paradigm has since been used in many studies (for a meta-analysis, see Anderson et al., 2019) and has been instrumental in theoretical debates about attentional processes during the retrieval phase (see below).

Smith (2008, 2017; Smith & Skinner, 2019) pointed out the role of context for the initiation of preparatory attentional processes. Assume you are at work and form the intention to buy bread on your way home. Before being able to act on this intention, however, you have a full workday ahead of you. If you were to initiate preparatory attentional processes immediately upon forming the intention, this would be a great distraction throughout the workday. Therefore, according to Smith, preparatory attention is not engaged until we find ourselves in the appropriate context. That is, at points of transition, for example, when you get on your bicycle to ride home, you may initiate attentional processes to prepare for the appearance of a store to buy bread, especially if you are taking an unfamiliar route. Smith, Hunt, and Murray (2017) empirically tested the presumed role of context. In their experiments, participants saw photographs of their college campus. In one experimental condition, these photographs were presented in the order of an actual campus tour; in the other condition, the photographs were presented in random order. The participants had to remember to get money at a particular ATM machine while performing the ongoing task of indicating, for each photograph, whether or not it showed more than five people. The researchers measured the response-time costs of the PM task to the ongoing task and found that these costs were lower in the condition in which the photographs were presented in campus-tour order compared to the condition in which they were presented in random order. However, the costs in the campus-tour-order condition increased at points of transition to a context that was relevant to the PM task (i.e., getting closer to the ATM machine). These results show the sensitivity of attentional processes to context: When the likelihood of target events is low in a particular context, less attention is engaged to prepare for such events (see also Bowden, Smith, & Loft, 2017; Bugg & Ball, 2017).

The Multi-Process View

Around the time of the development of the Preparatory Attention and Memory Processes (PAM) Theory, McDaniel and Einstein advanced the Multi-Process View of PM. This framework broadly distinguishes between two independent pathways to successful PM retrieval (Einstein, McDaniel, & Anderson, 2018; McDaniel & Einstein, 2000; McDaniel et al., 2015). Accordingly, successful PM retrieval can either occur (*i*) via strategic monitoring for the appropriate moment of intention execution or (*ii*) via spontaneous retrieval of the intention at the very moment of intention execution.

The first pathway of this framework is conceptually similar to the preparatory-attention idea of the PAM Theory. The Multi-Process View assumes that PM retrieval is *usually* attention demanding, that is, people will decide to devote some attention to the monitoring of the environment for the appropriate moment of PM task completion in order to meet PM task demands (Einstein & McDaniel, 2008; Rummel & Meiser, 2013; Rummel, Smeekens, & Kane, 2017).

However, the Multi-Process View further postulates that PM retrieval can *sometimes* occur spontaneously, that is, without requiring preparatory attentional processing. Such spontaneous PM retrieval supposedly occurs when PM targets are highly distinct from and/or focal to the ongoing-task (Einstein et al., 2005; McDaniel, Guynn, Einstein, & Breneiser, 2004). A PM target is considered *distinct* when its processing feels noticeably discrepant from the processing of the other ongoing-task items. Proponents of the Multi-Process View assume that such an unexpected discrepancy experience during PM target processing can spontaneously trigger a memory search for the reason of this experience, which then has a high likelihood to bring the PM task back into mind (Lee & McDaniel, 2013; McDaniel et al., 2004). Findings that, while a PM task was pending, a PM-unrelated discrepancy experience led to erroneous executions of the PM task (Rummel & Meiser, 2016) support this idea, but do not rule out involvement of preparatory attention for the occurrence of discrepancy which is then erroneously attributed to PM target status.

A PM target is considered *focal* to the ongoing task when the PM target's defining features are processed during the ongoing task (Einstein & McDaniel, 2005). For example, in a study by Scullin, McDaniel, Shelton, and Lee (2010), the word "tortoise" was a PM target that was focal to the ongoing lexical decision task, because the ongoing task required semantic processing of the items (Scullin, McDaniel, Shelton, & Lee, 2010). The letter 't', by contrast, was a non-focal PM target, because the ongoing task did not focus participants' attention on letter identification. According to the Multi-Process View, focal PM processing has the potential to reflexively bring back the PM task into conscious awareness. Reaction time costs were found to be smaller in focal than nonfocal tasks. This focality effect has been replicated several times with a number of different tasks (see for example Kliegel, Jäger, & Phillips, 2008, for a meta-analysis on focality effects in aging). However, statistically significant costs were also observed with single focal targets in some studies (Smith et al., 2007, 2010) but not in others (Harrison & Einstein, 2010; Scullin et al., 2010). Thus, opinions differ regarding the necessity of preparatory attentional processes in all PM tasks.

The initial Multi-Process View postulated that the two proposed pathways are mutually exclusive, that is, that PM retrieval within a given PM task may *either* fully rely on spontaneous *or* on attention-demanding monitoring processes. This strict separation, however, has been somewhat relaxed in a more recent variant of this theory. The general idea of the so-called dynamic Multi-Process View is that attentional monitoring for PM targets is likely to fluctuate. For example, it may decrease over time and/or in the absence of opportunities to execute a pending PM task, whereas encounters of PM targets themselves or PM-related reminders can (re-)initiate attentional monitoring. Empirical support for a dynamic view comes from findings that PM-induced costs to the ongoing task are particularly increased on trials subsequent to a PM target presentation (Scullin, McDaniel, & Shelton, 2013). The dynamic Multi-Process View postulates that the dependency between the two retrieval pathways goes both ways, so that a strong engagement in attentional target monitoring can also strengthen spontaneous retrieval. More detailed descriptions of the dynamic Multi-Process View can be found in the recent work by Shelton and colleagues (Shelton & Scullin, 2017; Shelton, Scullin, & Hacker, 2019).

Multi-Process View and Preparatory Attention and Memory Processes (PAM) Theory were originally formulated as two opposing theories and, in the early years of the 21st century, their advances stimulated a lively scientific debate around the question of whether the addition of a PM tasks will always come at a cost to currently ongoing tasks (see Einstein & McDaniel, 2010; Smith, 2010). In more recent years, these two views have converged. On the one hand, Multi-Process View proponents themselves argued that focal PM target processing is not automatic (Harrison, Mullet, Whiffen, Ousterhout, & Einstein, 2014). On the other hand, within PAM Theory, the attention devoted to the very same PM task can vary considerably depending on the current context (see above). This can account for findings indicating that the size of PM costs fluctuates strongly during the course of a PM task (Kuhlmann & Rummel, 2014).

Despite the increasing convergence of these two views, there is still debate surrounding the cost of PM tasks, but it has shifted into a different direction. The general assumption that PM-induced costs to an ongoing task reflect attentional PM processes, which underlies considerable parts of the empirical grounding of both the Multi-Process View and PAM Theory, has been recently challenged. New theoretical approaches suggest that costs reflect a certain ongoing-task response strategy rather than an attentional PM process (Heathcote, Loft, & Remington, 2015). As these new theoretical ideas are strongly tied to formal modeling approaches, we will review these in the following sections.

Formal Models of Prospective Memory

Evidence accumulation models. Recently, two types of evidence-accumulation models have helped elucidate processes underlying accuracy and reaction times in event-based PM tasks, namely the diffusion decision model (Ratcliff, 1978) and the linear ballistic accumulator (LBA) model (Brown & Heathcote, 2008). For a general description of evidence accumulation models, see Chapter 5.10 (Starns and Heathcote, "Evidence Accumulation and Decision Process"). These models propose that evidence accumulates in favor of particular responses in a cognitive task until a decision threshold is reached, whereupon the participant initiates the respective response.

Ratcliff's (1978) diffusion decision model was designed to model accuracy and reaction times in fast binary choice tasks such as lexical-decision tasks. For a detailed description of this model and an illustration, see Chapter 5.10 (by Starns & Heathcote).

As explained there, the main model parameters are drift rate *v*, which is the speed of evidence accumulation, and the threshold *a*, which determines the amount of evidence needed to reach a decision. Horn and Bayen (2015; also Horn, Bayen, & Smith, 2011; Boywitt & Rummel, 2012) added a PM task to an ongoing lexical-decision task to determine the effects of different types of PM tasks on diffusion-model parameters estimated from ongoing-task trials. In four experiments, Horn and Bayen (2015) found no effects of the PM task on the speed of evidence accumulation in the ongoing task, yet consistent effects on the threshold parameter *a*. They interpreted this as greater cautiousness in the ongoing task due to the greater task complexity when a PM task is added to an ongoing task. Further, nondecision parameter T_{er} was increased by PM importance instructions and was higher with non-focal than focal cues. The authors suggested that in these conditions, participants may have checked the cue for target characteristics before initiating the ongoing-task decision processes.

Modeling data with both a diffusion decision model and a LBA, Heathcote, Loft, and Remington (2015) and Strickland, Heathcote, Remington, and Loft (2017) reported similar results regarding the threshold parameter. That is, the addition of a PM task to an ongoing task affected the setting of the threshold, not processing speed, but within the LBA framework, non-decision time was not associated with PM costs. Most critically, however, results obtained with several evidence-accumulation models in different laboratories indicated no PM-induced costs to the speed of evidence accumulation for ongoing-task options. Heathcote et al. (2015) interpreted this as evidence against capacity-sharing theories such as the Preparatory Attention and Memory Processes (PAM) Theory and the Multi-Process View. They formulated the *Delay Theory* of event-based PM based on their threshold findings. Delay theory postulates that participants strategically delay ongoing-task responses in order to allow time for PM-related evidence to accumulate.

Based on Delay Theory, Strickland et al. (2018) developed the PM Decision Control model that postulates that proactive and retroactive control processes jointly allow for successful PM retrieval. While the previously used evidence accumulation models accounted for accuracy and reaction times in the ongoing-task only, the PM Decision Control model is a LBA model that makes use of *all* the data, namely accuracy and reaction-times in both the ongoing task and the PM task. The PM Decision Control model is illustrated in Figure 2.

Insert Figure 2 about here

In this model, when a test trial is presented, evidence for both ongoing-task options and evidence for the PM option accumulate simultaneously and compete in a race to threshold. The first accumulator that reaches its respective threshold determines the participant's response. In addition to proactive control, the model postulates a form of reactive control: The encoding of a stimulus activates its detector (e.g., the encoding of a PM target activates the PM detector) which in turn excites its respective evidence accumulator. Simultaneously, this detector inhibits the accumulators for the competing response options (e.g., those for the ongoing task). Thus, according to the PM Decision Control model, PM involves both top-down and bottom-up control of attention. Strickland et al. modeled the data from two experiments and reported evidence for both pro- and retroactive control. The idea that proactive control as well as reactive control contribute to performance in PM tasks is not new (Bugg, McDaniel, & Einstein, 2013); however, the PM Decision Control model is the first formal model of PM with both forms of control built in. The authors constantly improve and extend their model, so that the latest version can even account for PM-target learning processes (Strickland et al., 2021).

Delay Theory and its successor, the PM Decision Control model, recently sparked a lively debate in the literature as they challenge longstanding theories that postulate capacity sharing of the PM task and the ongoing task (see PAM Theory and the Multi-Process View above). Anderson, Rummel, and McDaniel (2018) tested Delay Theory against capacity-sharing accounts. They designed an instruction manipulation to increase participants' proactive control according to the PM Decision Control model: Some participants were told to make ongoing-task decisions cautiously, and to not monitor for PM targets. Results showed that, compared with a standard PM instruction, the 'delay' instruction did not improve PM performance. They concluded that strategic delaying of ongoing-task response decisions does not support PM. However, in response, proponents of Delay Theory pointed out that this interpretation is not unequivocal. They argued that participants may have interpreted the instruction not to monitor for PM targets as an "importance manipulation" and may have increased the PM threshold as a result, thus obviating a positive effect on PM performance (Strickland, Loft, & Heathcote, 2019). However, Ball et al. (2020) systematically tested the delay theory assumptions in four experiments and concluded that a delay process alone cannot account for the dynamic attention processes that support PM target noticing. All in all, the debate about which cognitive processes are reflected in PM-induced costs is not yet settled and will certainly trigger further research in the future (see also Anderson et al., 2019).

ExGaussian modeling. Use of the exGaussian function is another way to model PM-induced reaction-time costs to the ongoing task. This approach considers the positively skewed form of reaction-time distributions, which are fit well by the ex-Gaussian function (Luce, 1986) for a wide range of cognitive tasks. An ex-Gaussian distribution is a convolution of a Gaussian and an exponential distribution and as such is characterized by mean and standard deviation of the Gaussian distribution, and skew, which is the exponential component (for details, see Starns & Heathcote, this volume, or Loft, Bowden, Ball, & Brewer, 2015).

The exGaussian function has been used to disentangle components underlying reaction times on non-target trials of event-based PM tasks (Ball & Brewer, 2018; Ball, Brewer, Loft, & Bowden, 2015; Brewer, 2011; Loft et al., 2014). The idea is that continuous monitoring for PM targets during the ongoing task should result in an overall shift of the distribution of reaction times on non-target trials to the right in comparison to an ongoing-task-only condition. Transient or intermittent monitoring, however, should result in increased skew as reaction times increase on some ongoing-task trials only.

Several studies have used ex-Gaussian modeling, and results hint that both continuous and transient monitoring may occur in event-based PM tasks, possibly to different extent depending on task demands and participants' attention allocation strategies (for a review, see

Cohen & Hicks, 2017, Chapter 3). Ball and Brewer (2018) found that only the parameter presumably measuring continuous monitoring predicted PM performance, whereas the variability parameter did not, suggesting that intermittent monitoring may not lead to successful PM. Thus far, however, the interpretation of the distributional parameters have not been systematically validated. Experimental validation would be important as Matzke and Wagenmakers (2009) generally cautioned against the interpretation of differences in ex-Gaussian parameters as reflecting differences in specific underlying cognitive processes. If in the event-based PM paradigm, the distributional parameters could be unequivocally interpreted as reflecting different types of monitoring, this approach would have great potential to advance theories of attentional processes in event-based PM tasks, and could help elucidate such processes especially in populations that may be prone to lapses of attention.

The Multinomial Processing Tree (MPT) Model of event-based prospective memory. Often, researchers want to separate the prospective component of a PM task from its retrospective component, be it that variables are presumed to have different effects on the two components, or be it that a pure measure of the prospective component is needed that is not confounded with retrospective memory. In traditional approaches, a PM task is administered followed by a purely retrospective-memory task such as recall of the PM target(s). A disadvantage of this approach is that the prior retrieval of PM targets during the PM task likely confounds performance in the retrospective-memory task (Smith & Bayen, 2006). Further, as mentioned, the traditional measure of performance in PM tasks is the proportion of PM target trials that received a correct PM response (i.e., the hit rate). This measure not only confounds the prospective and retrospective components of the task (which are both necessary for a PM hit); it also neglects error responses and responses on ongoing-task trials. To solve these issues, Smith and Bayen (2004) developed a formal model of event-based PM to separately measure prospective and retrospective components of PM in standard event-based PM laboratory tasks.

The model is of the class of multinomial processing tree (MPT) models, which are formal stochastic models that generally allow researchers to estimate probabilities of certain cognitive processes from category response frequencies in particular cognitive tasks. Each MPT model is tailored to a specific experimental task paradigm. MPT models have been developed and validated in many areas of memory research including clustering in free recall (Batchelder & Riefer, 1980; Michalkiewicz, Horn, & Bayen, 2020), conjoint recognition memory (Stahl & Klauer, 2008), source monitoring (Bayen, Murnane, & Erdfelder, 1996; Schaper & Bayen, 2021), and directed forgetting (Rummel, Marevic, & Kuhlmann, 2016; Sahakyan & Delaney, 2005) to name just a few. New developments in MPT modeling were recently presented in a special issue of the *Journal of Mathematical Psychology* (Erdfelder, Hu, Rouder, & Wagenmakers, 2020). For accessible general reviews of MPT modeling, see Batchelder and Riefer, 1999, or Erdfelder et al. (2009).

The PM model for event-based PM by Smith and Bayen (2004) uses the empirical frequencies of all responses in an event-based PM task (i.e., correct and incorrect responses to both ongoing-task trials and PM trials). From these observed frequencies, the model estimates separate parameters for the ongoing task, the prospective component (remembering that something must be done in addition to the ongoing task), and a retrospective component (discriminating PM target items from distractor items).

Insert Figure 3 about here

The model is shown in Figure 3. The processing tree to the left refers to a trial with a PM target. With probability *C*, the participant knows the correct answer to the ongoing-task. With probability *P* (for prospective component), the participant remembers that there is a PM task in addition to the ongoing task. If the prospective component is successful, the participant recognizes the PM target with conditional probability *M* (for the retrospective-memory component) leading to a PM target hit. If the prospective component is unsuccessful, a PM target hit cannot be achieved and the participant responds to the ongoing task. If the prospective component is successful, but the participant does not recognize the PM target (with probability *M*), then they must guess. With probability *g*, they guess that a PM target is present; with the complementary probability 1-*g*, they guess that there is no target, and respond correctly to the ongoing task. It is also possible that the participant does not know the correct answer to the ongoing task, with probability 1-*C*. In this case, they may still remember that there is a PM task (prospective component *P*), and may recognize the PM target (with probability *M*) or not. If they do not and guess that it is a distractor, they must guess their response on the ongoing task, with probabilities *c* and *1-c*. The processing tree to the right represents trials that do not include a PM target, but instead include a nontarget. The structure of this tree follows the same logic as that of the first tree.

The probability parameters are estimated from the observed frequencies of PM-target responses, correct ongoing-task responses, and incorrect ongoing-task responses in trials with PM targets and those with nontargets. See Smith and Bayen (2004) for a more detailed explanation of the model including parameter estimation and restrictions, proof of identifiability, and goodness-of-fit testing.

When the model was first introduced (Smith & Bayen, 2004), parameter *P* (prospective component) was presented as measuring an attention-demanding prospective component in the sense of the Preparatory Attention and Memory Processes (PAM) Theory. This was justified, because in the experiments presented in that article, the PM task was non-focal to the ongoing task, and therefore, as explained above, required preparatory attention according to several theories. The MPT model is not tied to the PAM Theory. *P* measures the prospective component generally, regardless of how much attention is devoted to this component (see also Rummel, Boywitt, & Meiser, 2011). It must be considered, though, that tasks that require little attention are very easy (i.e., tasks with single salient focal PM targets) and thus yield low frequencies in some error categories. This makes it very difficult to obtain stable model estimates. We, therefore, recommend that the MPT model shall be used with sufficiently difficult tasks.

The core model parameters have been successfully subjected to experimental validation as measuring the prospective component, a retrospective recognition-memory component, and ongoing-task proficiency, respectively (Smith & Bayen, 2004; Horn, Bayen, Smith, & Boywitt, 2011; Rummel et al., 2011). The model has been used for a number of substantive research questions that required the separation of the prospective from the retrospective component ranging from stimulus and task characteristics (Schnitzspahn, Horn, Bayen, & Kliegel, 2012; Zhang, Tang, & Liu, 2017) to effects of strategy use (Smith, Rogers, McVay, Lopez, & Loft, 2014), from cognitive development (Smith, Bayen, & Martin, 2010) to cognitive aging (Smith & Bayen, 2006), and from personality (Smith, Persyn, & Butler, 2011) to clinical disorders (Pavawalla, Schmitter-Edgecombe, & Smith, 2012) and effects of substance use (Walter & Bayen, 2016). Advances in hierarchical MPT modeling (e.g., Heck, Arnold, & Arnold, 2018; Klauer, 2010) have recently enabled researchers to use correlational approaches to relate components of PM to individual-difference variables (e.g., Arnold, Bayen, & Smith, 2015; Arnold, Bayen, & Böhm, 2015; Böhm, Bayen, & Schaper, 2020).

Because the MPT models the response frequencies in all 12 response categories (3 response options × 4 types of task trials, see Smith & Bayen, 2004) it makes much better use of the data than PM hit rate. However, at this point, the MPT model of event-based PM cannot make use of reaction-time data. Note that it is a measurement model designed to measure the probabilities that participants succeed in the prospective and the retrospective components of PM. That is, although the model does include some (testable) theoretical assumptions, it is not a process model, which would provide a detailed account of cognitive processes involved in the prospective and retrospective components. The parameter that measures the prospective component, for example, does not distinguish between different theoretical mechanisms, that is, the model does not reveal which cognitive processes are involved in remembering that we have to do something.

Although the development and use of formal models in PM research is a considerable advance over the use of simple behavioral measures such as accuracy and mean reaction times, the mapping of model parameters onto theoretical processes underlying performance in PM tasks is often not straightforward. For example, while Heathcote et al. (2015) interpreted an increase in the threshold parameters of the diffusion and LBA models as a delay in the ongoing-task response, Horn and Bayen (2015) assigned a similar meaning to the non-decision parameter T_{er} of the diffusion model. As another example, according to Ball and Brewer (2018), the μ parameter of the ex-Gaussian distribution may reflect delay (among other possible underlying processes), whereas Anderson et al. (2018) reject such interpretation. As formal models are currently being suggested and evaluated, we expect to see more validation studies and hope that formal models in combination with compelling experimental designs will lead to theoretical advances in the near future.

Prospective Memory Across the Lifespan

Since the early years of PM research, there has been a particular interest in investigating PM from a developmental perspective. “Remembering to remember” was suggested as the memory task in which the least environmental support would be provided and thus the most self-initiation would be required (Craik, 1986). As a consequence, PM would be the memory task with most age-related decline. However, this was not confirmed by the first aging studies, in which older adults performed as well as younger adults (e.g., Einstein & McDaniel, 1990). This discrepancy motivated research over the past thirty years to not only investigate developmental patterns of PM but to also understand mechanisms that would determine the presence or absence of age effects. Importantly, this research explored PM development across the entire lifespan, from early childhood to very old adulthood (for a more detailed review, see Ballhausen, Hering, Rendell, & Kliegel, 2019).

Until today, most studies of PM development have focused on comparisons between younger and older adults. Despite the intriguing first finding by Einstein and McDaniel (1990), more recent meta-analytical evidence suggests older adults to show lower PM performance than younger adults (Henry, MacLeod, Phillips, & Crawford, 2004). However, this seems to be only true for the laboratory; in naturalistic tasks, older adults show similar performance or even outperform younger adults (*age-PM paradox*, Rendell & Thomson, 1999; for a more fine-grained investigation of different task types, see Schnitzspahn, Kvavilashvili, & Altgassen, 2020, and Haines et al., 2020). Nevertheless, the results of laboratory studies on aging vary, ranging from the presence of age differences (e.g., Ballhausen, Schnitzspahn, Horn, & Kliegel, 2017; Smith & Bayen, 2006) to no age differences (e.g., Einstein & McDaniel, 1990) to even age benefits (e.g., Patton & Meit, 1993). Very generally speaking, older adults present lower PM performance in situations where the requirements of the PM task do not match the respective resources of a person. This argument has also been put forward by both the Preparatory Attention and Memory Processes (PAM) Theory and the Multi-Process View, stating that the shortage in attentional resources in older adults and thus the lack of resources available to monitor for PM targets underlies age differences (see Smith, 2008; McDaniel, Einstein, & Rendell, 2008). In line with this, age differences have been shown for nonfocal tasks in particular, which require a high amount of attentional resources for target monitoring (see the meta-analysis by Kliegel, Jäger, & Phillips, 2008). Moreover, using the MPT model (Figure 3), Smith and Bayen (2006) found that age differences in PM performance in a nonfocal task were due to age differences in the resource-demanding prospective component (not in the retrospective-recognition component, which demanded few resources).

Why do older adults have difficulties with resource-demanding PM tasks in particular? There are age-related losses in a number of cognitive abilities including abilities that are important for performance in resource-demanding PM tasks. Along these lines, age differences in laboratory PM tasks have been shown to relate to task switching and inhibition, but not to updating (e.g., Schnitzspahn et al., 2013). This however was not true for naturalistic time-based PM (Azzopardi, Auffray, & Kermarrec, 2017). PM age differences seem to be further linked to spontaneous engagement in planning (for laboratory tasks, see Shum, Cahill, Hohaus, O'Gorman, & Chan, 2013; for naturalistic tasks, see Niedzwienska et al., 2013), the importance of the PM versus ongoing task (e.g., Hering, Phillips, & Kliegel, 2014), social feedback (Niedzwienska, Rendell, Barzykowski, & Leszczynska, 2014), incentives (Aberle et al., 2010), and metacognition (e.g., Schnitzspahn, Ihle, Henry, Rendell, & Kliegel, 2011). The role of retrospective memory abilities is still under debate: While some studies demonstrated greater PM age effects when retrospective load was high (e.g., Kelly, Hertzog, Hayes, & Smith, 2013), others found age effects to be unaffected by high maintenance load (e.g., Ballhausen, Schnitzspahn, Horn, & Kliegel, 2017) and only little forgetting over a four week delay (McBride, Coane, Drwal, & LaRose, 2013). For a discussion of effects of aging on retrospective episodic memory see Chapter 8.4 by Light “Memory and Aging.”

Formal models are generally valuable tools to address theoretical and methodological issues in research on memory and aging (cf., Spaniol & Bayen, 2004); yet thus far, formal models have rarely been used in studies of PM and aging. One reason is that the formal-modeling approaches that have been used in research on event-based PM, namely MPT modeling (Figure 3) and diffusion modeling, pose specific demands on the design of the PM task. In particular, they require a large number of items and responses of different types. This poses a challenge to research with PM tasks, where by definition, PM targets rarely occur within the ongoing task (cf., McDaniel & Einstein, 2007), and an even greater challenge to research on PM and aging as older adults tire more quickly than young adults when a task is lengthy. Nevertheless, in two studies, diffusion modeling was used to shed light on cognitive processes underlying event-based PM performance in older adults. Using this approach, Horn, Smith, and Bayen (2013) found similar reasons in younger and older adults for the interference of an event-based PM task with an ongoing task. Ball and Aschenbrenner (2017) added an importance manipulation and found a selective benefit for older adults on nondecision parameter T_{er} that may have been due to checking the cue for target characteristics.

Most PM aging studies investigated young-old adults only. Studies that go beyond this age are vital, however. Focusing on *old-old adults* has revealed that PM performance is further reduced compared to young-old adults (e.g., Henry et al., 2015). This seems to be particularly true for tasks requiring a great amount of attentional resources (e.g., time-based tasks, Kvavilashvili, Kornbrot, Mash, Cockburn, & Milne, 2009) and when stereotype threat is accentuated (Zuber, Ihle, Blum, Desrichard, & Kliegel, 2019). This, however, may not be the case in naturalistic tasks, in which young-old and old-old adults seem to perform comparably well (Kvavilashvili, Cockburn, & Kornbrot, 2013).

What about PM development at earlier stages of the lifespan? By the age of three years, children are able to perform PM tasks (e.g., Kelly, Perdue, Love, Parrish, & Beran, 2018; Causey & Bjorklund, 2014). This ability then further develops during the *preschool* years, independent of whether assessed with laboratory tasks (e.g., Zhang, Ballhausen, Liu, Kliegel, & Wang, 2019) or naturalistic tasks (e.g., Slusarczyk & Niedzwienska, 2013). PM performance of preschoolers is strongly influenced by person-related factors such as their motivation (e.g., Kliegel, Brandenberger, & Aberle, 2010) and their theory of mind (e.g., Ford, Driscoll, Shum, & Macaulay, 2012), but also by task-related factors such as salience of the PM targets (Mahy, Moses, & Kliegel, 2014b) and cue-action reminders (Kliegel & Jäger, 2007). Across studies, inhibition was shown to be the main capacity underlying developmental differences in this age group (e.g., Mahy et al., 2014b, but see Mahy & Moses, 2011).

Around the time of transition to school (Hajdas, Grzegorzewska, & Niedźwieńska, 2021), cross-sectional studies suggest that PM shows further developmental increase between five and six years (Kretschmer-Tendowicz, Ellis, & Altgassen, 2016) that continues throughout *school age* (Smith, Bayen, & Martin, 2010). This pattern of results has been mainly attributed to the parallel maturation of attentional control processes and formalized by the executive framework of PM development (Mahy, Moses, & Kliegel, 2014a). Indeed, executive functions and in particular updating abilities of eight-year-old children predicted their PM performance eight months later (Spiess, Meier, & Roebers, 2016). More specifically, investigating the impact of shifting, inhibition, and updating on focal, nonfocal, and time-based PM tasks in 212 school-aged children revealed that updating predicted PM performance on all tasks; performance in focal and nonfocal, but not time-based tasks were predicted by inhibition, and nonfocal task performance was the only one being predicted by shifting (Zuber, Mahy, & Kliegel, 2019). Generally, resource-demanding processes like target monitoring are particularly challenging for school-aged children. In time-based PM tasks, clock checks to monitor the passage of time increased in the interval prior to the target time. This strategic clock-checking behavior was shown to improve with advancing age (Kerns, 2000), but older children's time monitoring was more disturbed by high executive demands of the ongoing task (e.g., Mahy et al., 2015). In event-based tasks, task-related factors that vary the attentional control required for the monitoring of the PM targets, were also shown to be linked to developmental differences in PM (e.g., Kliegel et al., 2013): Under conditions of high requirements for attentional control, differences between younger and older children were especially high (but see Smith et al., 2010).

Surprisingly few studies investigated factors unrelated to attentional control. Smith et al. (2010) showed that the retrospective recognition component of an event-based task (as measured with the MPT model explained above) was superior in 10-year-old compared to 7-year old children. However, asking children to plan how to execute a complex PM task and then comparing how many details of their plan they remembered, 7- and 10-year old children recalled a comparable number of details (Kliegel, Mackinlay, & Jäger, 2008a). Further research is needed to elucidate the role of retrospective memory processes in the development of PM in children (see also Chapter 8.3. by Ghetti "Memory Development in Middle-Childhood and Adolescence"). Similar to the impact of motivation on preschool children's PM, promising a reward enhances PM performance (Sheppard, Kretschmer, Knispel, Vollert, & Altgassen, 2015) in school-aged children. Besides, metamemory seems to be linked to PM performance, particularly the allocation of resources to monitor for categorical targets (Cottini, Basso, & Palladino, 2018), which seems to be much less the case in preschool children (Lavis & Mahy, 2021). Moreover, children who used active strategies such as rehearsal also showed higher PM performance and more monitoring costs than those using passive (e.g., reacting to target once it appears on the screen) or no strategies (Cottini, Basso, Saracini, & Palladino, 2018).

Very little research has investigated PM of *adolescents*. While many studies show lower PM performance in adolescents than in young adults (e.g., Wang, Kliegel, Yang, & Liu, 2006), others suggest similar performance (e.g., Kretschmer-Trendowicz, & Altgassen, 2016). These discrepant findings may be related to tasks differing in the amount of attentional control required to monitor for the targets. Due to ongoing brain development throughout adolescence (see also Bowman, Cutmore, & Shum, 2015), these task characteristics can affect the occurrence of age effects (e.g., Wang et al., 2011). In line with this, task switching, but also theory of mind, predicted adolescents' PM performance (Altgassen, Vetter, Phillips, Akgün, & Kliegel, 2014). The role of retrospective-memory processes is unclear in this age group as well. Only Zöllig et al. (2007) showed that adolescents more often pressed the wrong key after PM target detection than young adults did, which indicates a problem in a retrospective component of PM in that age group. Further, Zhao, Fu, and Maes (2019) recently conducted a PM process training in 13- to 15-year-old children. Improvements in the trained event-based task were found that persisted even over an extended period of time. However, transfer was limited to an untrained time-based PM task and a working memory task and did not persist over an extended period. Still, this attempt raises some hope that PM can be improved in adolescence and it may be worth investigating whether PM process training may be equally beneficial for school-aged children.

Younger adults are considered as presenting the optimal level of PM (e.g., Maylor & Logie, 2010). Therefore, studies on both children and older adults use younger adults as a comparison group that most of the time shows better or at least similar PM performance compared to the other age groups (but see below for an exceptional pattern).

Few studies have examined whether PM remains at a stable high level during *middle adulthood.* Whereas some studies suggested that PM decline already starts in middle adulthood (e.g., Maylor & Logie, 2010), others find no reliable differences between younger and middle-aged adults (e.g., Blondelle et al., 2016). Further, task types (e.g., Mioni, Stablum, Biernacki, & Rendell, 2017, demonstrating lower PM performance for middle-aged compared to younger adults in time-based, but not event-based tasks), but also task environment (e.g., Niedzwienska, Janik, & Jarczynska, 2013, showed middle-aged adults' naturalistic PM performance to be better than younger adults', but comparable to older adults') seem to affect these patterns. A more systematic investigation of factors that influence potential age differences is still missing for this age group.

In line with the research presented above, over the *lifespan*, PM development follows an inverted U-shaped function (e.g., Zuber & Kliegel, 2019). Yet, not many studies of PM were performed with several age groups over the lifespan using a similar PM task. Existing studies agree on the inverted U-shaped trajectory (e.g., Hering et al., 2016; Mattli, Schnitzspahn, Studerus-Germann, Brehmer, & Zöllig, 2014), but more data are required to understand the transitions from childhood via adolescence to young adulthood and equally from young adulthood over middle-age to older adulthood. Furthermore, lifespan studies can provide more information on mechanisms underlying the rise and the fall of PM over the lifespan. Zöllig and colleagues (2007) suggested the rise in childhood to be related to the retrospective component of PM, while Mattli and colleagues (2014) highlighted the importance of the prospective component. Thus, this relationship is still under debate, but more lifespan studies could help to shed light on these mechanisms.

Most developmental PM research is based on cross-sectional data. Even though developmental scientists have repeatedly highlighted the importance of longitudinal designs to investigate true change, there is currently very little longitudinal evidence regarding PM changes across the lifespan. Employing a longitudinal design to investigate change in PM in childhood, Spiess et al. (2016) showed that PM performance of eight-year-olds significantly increased over eight months with a medium effect size. Longitudinal studies of PM in older adults demonstrated decline when comparing performance five to six years apart (Sullivan et al., 2020; Kamberis, Cavuoto, and Pike (2021). Interestingly, Sullivan and colleagues showed a decline in event-based PM, but not time-based PM. Moreover, comparing performance in a one-time PM task with that in a naturalistic habitual PM task (i.e., a task that was to be performed twice daily for two weeks) in older adults with high and low subjective cognitive decline showed that performance on the non-habitual PM task declined independently of participants' subjective cognitive decline. Habitual PM, however, showed an objective decline for the group of high but not low subjective cognitive decline (Kamberis et al., 2021). Overall, the effect sizes of the few available longitudinal studies are rather small, and time intervals of that length seem to be required to be able to observe change (see Sullivan et al., 2020).

Clearly, many more longitudinal studies are needed to better understand the rise and fall of PM across the lifespan.

Applied Aspects of Prospective Memory

In real life, PM failures occur quite frequently in the course of a regular day (Dismukes, 2012). Some everyday PM failures may manifest themselves as tedious but harmless hassles, such as a mobile phone forgotten at home (Rose, Csik, & O'Rear, 2018). Others, however, may be more serious or even fatal, such as a baby forgotten in the car (Lee-Kelland & Finley, 2019). In fact, many missed appointments, emails with missing attachments, or messages not passed to the relevant authorities may be manifestations of daily-life PM failures. Recently, the interesting case has been made that even the exceedance of speed limits may – under some circumstances – be the consequence of a PM failure rather than an intentional act (Bowden, Visser, & Loft, 2017). In a simulated driving environment, these authors showed that almost all drivers (99%) adhered to the temporarily reduced speed limit in a low-speed zone under normal circumstances. However, the adherence rate dropped to 67% when the drivers were interrupted after encountering the reduced-speed sign but before reducing their speed. Bowden and colleagues made the point that such interruptions, which are not uncommon during driving (Gregory, Irwin, Faulks, & Chekaluk, 2014), turn the adherence to road signs into a PM task. For a discussion of prospective memory and safety concerns in the legal context see Chapter 11.6 by Spellman and Weaver “Memory and the Law.”

Another important daily-life aspect is the role PM plays for the adherence to healthcare measures. A considerable number of people today need to regularly control their physical status (e.g., blood pressure) or to take, at least periodically, some kind of medication on a regular basis. In North America, for instance, more than 50% of the adult population takes at least one prescription medication per month (Che et al., 2014). For these people, it is important to not forget to take their medication as prescribed. Of course, this problem is not limited to people with some kind of temporary or chronic disease, but also applies to women taking contraceptive pills for safe and reliable birth control. Despite best intentions, people seem to forget to adhere to their medication schedule from time to time. For instance, in one study of patients with a variety of chronic diseases, 62% of all patients reported at least one instance of unintentional non-adherence within a four-week period (Gadkari & McHorney, 2012). A considerable 21% of women using contraceptive pills reported to have forgotten to take them at least once per month according to a recent survey (National Survey of Family Growth, 2013-2015). As only approximately one third of medication intake failures seem to be noticed afterwards (Hou, Hurwitz, Kavanagh, Fortin, & Goldberg, 2010), the true PM failure rate in this area may be even higher than these survey data suggest. Interestingly, failures in medical adherence seem to occur despite the fact that these PM failures can have serious personal consequences for the individual. In a laboratory study, the risk of losing 50 cents due to a PM failure considerably improved PM performance (Cook, Rummel, & Dummel, 2015). Therefore, it seems surprising that even the risk of an unwanted pregnancy or serious health consequences is not enough to prevent PM failures in medical adherence.

Notably, PM omission errors (i.e., errors of not executing a PM task at the correct time) are only one type of PM-related error that can intervene with adherence to medical regimens. Another, similarly important problem can result from errors of commission, for example in terms of accidental medication over-dosing (Gummin et al., 2018). Laboratory research has shown that especially older adults are generally prone to PM commission errors (Boywitt, Rummel, & Meiser, 2015; Scullin, Bugg, & McDaniel, 2012). Given that older adults are more likely to maintain quite extensive medication schedules, finding ways to prevent PM commission errors in older populations is of critical importance.

Omission and commission errors in medical adherence have been discussed as everyday PM problems for quite some time (McDaniel & Einstein, 2007). Only recently, however, have researchers begun to develop interventions to prevent such failures. One promising route is to make use of cognitive strategies known to reduce the attentional demands from a PM task, such as forming *when-then plans*, so-called implementation intentions (Gollwitzer, 1999; Rummel, Einstein, & Rampey, 2012). Insel and colleagues (2016), for example, asked patients to associate their medication intake with a certain event (e.g., breakfast) or time point (e.g., 8:00 am) and to imagine themselves taking their medication at this point. This rather simple intervention increased medical adherence from 57% prior to the intervention to 78% after the intervention. Follow-up investigations showed, however, that the adherence benefits disappeared 5 months after the intervention. In a randomized controlled trial comparing implementation intentions with a processed based training of cognitive control, Brom and Kliegel (2014) showed that older adults' blood pressure monitoring was improved in the implementation-intention strategy condition only. As an interesting secondary effect, the authors showed that this effect interacted with cognitive control ability levels indicating that these strategy effects particularly benefitted older adults with lower ability to exert cognitive control.

Another way to prevent everyday PM failures is the implementation of external memory aids. Some authors suggest that cloud calendars can be effectively used to improve PM in people who particularly struggle with PM, like participants with brain injuries (McDonald et al., 2011; Petrie, Goudie, Cruz, & Kersel, 2012). New technologies such as applications for smartphones and smartwatches offer exciting new opportunities for PM support (Jamieson et al., 2019). Bayen et al. (2013) showed that a custom-tailored memory aid system installed in the bathroom can help older people adhere to their daily care routines. The current rise of highly sophisticated smart-home technologies that even verbally interact with their users will certainly provide new opportunities for preventing PM failures in everyday life. The investigation of the optimal setup for such PM-aid technologies as well as their effectiveness but also their potential risks and downsides will be an important future endeavor.

PM failures can also become a problem in many work contexts. Especially in safety-critical work environments, PM failures can have serious consequences. This point has been particularly made for pilots and air-traffic controllers, for whom 38% of errors are assumed to involve PM failures (Shorrock, 2005), as well as for professionals working in intensive healthcare units, for whom even 50% of all failures seem to involve PM (Rothschild et al., 2005). Dismukes (2012) identified four critical features of PM tasks that render them particularly error prone in these work domains. First, at the point of intention initiation (see Figure 1), these tasks are typically likely *to be interrupted* before execution. Second, specialists in these work areas seem to strongly rely on cues that signal the appropriate moment of PM-task execution (Dismukes, 2012). Whereas this is generally a good mental strategy, problems arise when the *cues do not occur* but the intention still needs to be carried out. Third, specialists in these areas are usually well trained in certain tasks that are routinely performed. However, some situations require the specialists to deviate from their routines and a common error is that they still *stick to the routine* even when it is not appropriate. Fourth, Dismukes points out that the cognitive demands in safety-critical work environments are usually very high because the ongoing tasks already *require coordinating several tasks with each other* in addition to the pending PM task. Indeed, laboratory research has shown that the demands from ongoing tasks negatively affect PM (Marsh, Hancock, & Hicks, 2002). For a more extensive review of the PM literature on PM failures in safety-critical environments, we recommend the recent book chapter by Loft, Dismukes, & Grundgeiger, 2019. Dismukes (2012) pointed out that PM tasks with these four features regularly occur in certain work environments but also in the context of other everyday PM situations; however, a systematic investigation of these features in daily life is still pending.

Prospective Memory in Clinical Populations

Recent years have seen a rapid increase in PM research with different clinical populations. Even mentally and physically healthy individuals experience challenges in everyday PM tasks, and these challenges are exacerbated for people with mental health issues, brain injury, or neurodegenerative disease. For these individuals, frequent PM failures in daily life may imply losses in independent functioning and community living skills (Au et al., 2014). Lack of medication adherence due to PM failure poses serious health threats for people with medical conditions that also affect cognitive functioning such as chronic heart failure (Habota, Cameron, Thompson, & Ski, 2021), multiple sclerosis (Rouleau et al., 2018), and schizophrenia (Wang, Chan, & Shum, 2018).

In addition to applied concerns, theoretical and empirical advances in PM research have been an impetus for increased research on PM in clinical populations. Some mental disorders affect basic cognitive processes that are now known to be related to PM, such as attention, executive functions, and retrospective memory (for reviews of disorders of retrospective memory, see Volume II, Chapter 9 of this Handbook). This offers the opportunity for theory-based research on PM in clinical populations.

PM deficits have been found in a large array of clinical populations. In 2008, Kliegel, Jäger, Altgassen, and Shum provided a general review. By now, the literature has exploded for many clinical populations, such that it would be difficult to fit it into one single review article. In fact, a special issue of *The Clinical Neuropsychologist* included reviews of PM in specific clinical populations such as people with autism (Sheppard, Bruineberg, Kretschmer-Trendowicz, & Altgassen, 2018), schizophrenia (Wang et al., 2018), HIV (Avci et al., 2018), and brain injury (Raskin, Williams, & Aiken, 2018; see also Chapter 9.5 by Vakil "The Mnemonic Consequences of Moderate-to-Severe Traumatic Brain Injury") to mention only those with the largest body of research. For all these disorders, the reviews reported PM impairments. Impairments were also found in meta-analyses of PM in mild cognitive impairment and dementia (van den Berg, Kant, & Postma, 2012), Parkinson's disease (Coundouris et al., 2020), depression (Zhou et al., 2017), bipolar disorder (Zhou et al., 2018), and regular use of alcohol or illicit drugs (Platt, O'Driscoll, Curran, Rendell, & Kamboj, 2019). People with obsessive-compulsive symptoms are also on the long list of populations at risk for PM impairments (for a review, see Bhat, Sharma, & Kumar, 2018).

Many studies included in these reviews have compared performance on time-based versus event-based PM tasks. Where impairments in time-based PM were found to be larger than those in event-based PM, some authors concluded that deficits are larger with greater attentional requirements of the PM task (Raskin, 2018). However, as explained above, dependent on task and stimulus characteristics, attentional demands of event-based tasks can vary greatly. Only few studies with clinical populations have systematically varied the attentional demands of event-based PM tasks (e.g., Altgassen, Kliegel, & Martin, 2009, McDaniel, Shelton, Breneiser, Moynan, & Balota, 2011). Kliegel, Mackinlay, and Jäger (2008) called for a theory-guided approach toward determining the loci of and reasons for PM failures in specific clinical populations. The process model outlined above (Kliegel et al., 2002) can serve as a framework for such endeavors. For an application of this model to PM impairment in Parkinson's disease, see Kliegel et al. (2011).

Generally, there is great interest in the assessment of PM in clinical populations (Raskin, 2018). Many researchers and clinicians seek to assess PM by administering the PRMQ (Prospective and Retrospective Memory Questionnaire, G. Smith, Della Sala, Logie, & Maylor, 2000) or other self-report measures of errors in everyday prospective memory tasks; however, self-report has low validity for the assessment of actual PM performance (Arnold & Bayen, 2019). Raskin, Shum, Ellis, Pereira, and Mills (2018) suggested that laboratory, clinical, and self-report measures may assess different aspects of PM. Performance tests with known psychometric properties for at least some populations are the Cambridge Prospective Memory Test (CAMPROMPT by Wilson et al., 2005; Man, Chan, & Yip, 2015) and the Memory for Intentions Test (MIST by Raskin, Buckheit, & Sherrod, 2010; Kamat et al., 2014). Blondelle, Hainselin, Gounden, and Quaglino (2020) offer a systematic review of

PM assessment tools. An interesting new approach is the use of virtual reality to assess PM (Canty, Fleming, Patterson, & Shum, 2014; Kourtesis, Collina, Doumas, & MacPherson, 2021).

Several different management strategies have been proposed to help clinical populations with PM task. Some of these aim at offloading PM tasks to external reminders such as calendars and electronic devices (see above). Other management strategies that have been used with clinical populations are cognitive in nature, such as visual imagery (Raskin, Smith, Mills, Pedro, & Zamroziewicz, 2019), implementation intentions (e.g., Goedeken, Potempa, Prager, & Foster, 2018), future event simulation (Mioni, Bertucci et al., 2017), rehearsal training (Ihle, Albiński, Gurynowicz, & Kliegel, 2018), and meta-cognitive training (for a review, see Mahan, Rous, & Adlam, 2017).

Most training studies have used isolated intervention approaches to test effects on PM performance (e.g., Ihle et al., 2018). Comprehensive PM training programs for specific clinical populations are still missing. Waldum, Dufault, and McDaniel (2016) presented and evaluated a comprehensive PM training program for normal older adults and suggested its use for clinical populations as well. Raskin (2018) stressed the necessity to tailor interventions to the individual because difficulties with everyday PM tasks may differ depending on diagnosis, individual cognitive functioning, and life situation.

In conclusion, it is important for clinicians to be aware that their patients may have PM problems that may affect their everyday functioning (Raskin, 2018). We hope that theoretical advances in PM research can be made fruitful to understand PM in clinical disorders, to develop valid instruments for the assessment of PM failures in different population, to develop and evaluate comprehensive PM training programs tailored to specific clinical populations, and to help patients manage their PM tasks in daily life.

Conclusion and Outlook

Engaging theoretical debates in the PM literature have greatly advanced theoretical progress in the field (e.g., Einstein & McDaniel, 2010, vs. Smith, 2010; Anderson et al., 2018, vs. Strickland et al., 2018) and inspired the development of a diversity of theoretical and methodological approaches. For example, the stimulating debate whether and, if so, to what extent PM retrieval can occur in the absence of preparatory attention resulted in more integrative theorizing that conceptualizes PM retrieval as a dynamic rather than a static process (Shelton & Scullin, 2017) and emphasizes the moderating role that context plays for PM retrieval processes (Smith, 2017). These theories allow researchers to make specific predictions as to when PM will likely succeed, and to also account for a broad range of extant empirical findings. Yet, many theoretical issues remain unresolved. For example, while all current theories emphasize the role of attentional and control processes involved in (at least some) PM tasks, the exact nature of the processes is currently under lively debate and spurs the development of new methodologies. Notably, over the past 30 years, not only did PM theories evolve, but the research field also matured. Whereas early PM researchers tended to stress the aspects that make PM unique (e.g., Ellis, 1996), researchers are currently more eager to relate PM to other areas of cognition and to identify domain-general rather than domain-specific attention control and memory retrieval processes that contribute to PM as well as to other cognitive functions (e.g., Schaper, Horn, Bayen, Buchner, & Bell, 2021; Strickland et al., 2018).

We would like to point out two research directions that we expect to receive increased attention in the future. One is the role of metacognition in PM (for a general discussion of metacognition, see Chapter 7.5 by Metcalfe “Metacognition: Puzzles, Biases, and Remedies.”) McDaniel and Einstein (2007) already called for greater consideration of metacognition in PM, and the dispersed work on this topic was organized in chapters by Smith (2016) and Kuhlmann (2019). The seminal work by Gilbert and collaborators (e.g., Gilbert et al., 2020) investigates the relationship of metacognition with strategic offloading of intentions (i.e., reminder setting). This research program is leading the way to further programmatic study of people’s metacognitive monitoring of their own PM performance in different types of PM tasks and settings and of possibly resulting efforts of individuals to control PM in various ways, with implications for different populations and applications.

Another aspect of PM that is not yet receiving its deserved attention is its possible role in evolutionary adaptation. As mentioned in the introduction to this chapter, according to the adaptive-memory framework, the purpose of memory is to prepare us for future events (e.g., Klein, 2013; Schacter & Addis, 2007; Underwood, Guynn, & Cohen, 2015). Merging expertise in PM and adaptive memory, Schaper et al. (2021) recently tested this assumption in a standard laboratory event-based PM task with faces of cheaters, cooperators, and neutral controls as PM targets. The prospective component of the PM task (as measured by the MPT model described above) was superior for cooperator and cheater faces possibly indicating an adaptive function of PM for social relations.

Due to space limitations, we cannot discuss all areas of PM research in this chapter. For a summary of the current state of knowledge regarding neuroscientific approaches and neuropsychological and physiological correlates of PM, we refer to the recent chapter by Cona and Rothen (2019) and to the recommendations by McDaniel and Einstein (2019) in the same book. They call for increased efforts to reveal which brain structures or neurological processes underlie specific cognitive processes involved in PM. For the future, we look forward to further theoretical, methodological, empirical, and applicable advances in the diverse and rapidly expanding field of PM research.

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Figure 1. Revised Phase Model of Prospective Memory. Adapted from “A process-model based approach to prospective memory impairment in Parkinson’s disease” by M. Kliegel, M. Altgassen, A. Hering, & N. Rose, 2011, *Neuropsychologia, 49,* p. 2169. Copyright 2011 by Elsevier. For a detailed description of this figure, please refer to the text.

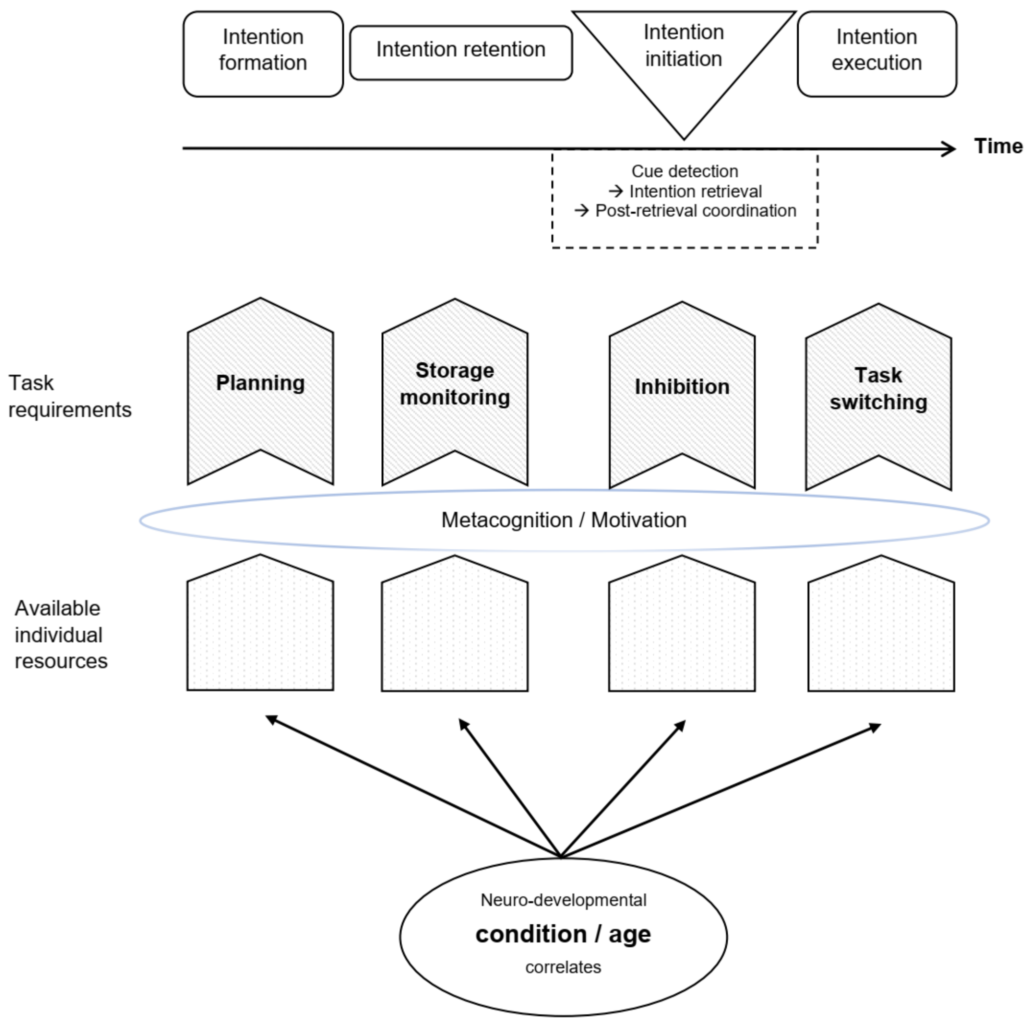

Figure 2. Illustration of the architecture of the Prospective Memory Decision Control model. Solid lines indicate that input to each detector excites accumulation toward the corresponding response. Dashed lines indicate that input to each detector inhibits accumulation toward the alternative responses. Adapted from “Racing to remember: A theory of decision control in event-based prospective memory” by L. Strickland, S. Loft, R. W. Remington, & A. Heathcote, 2018, *Psychological Review*, *125,* p. 856. Copyright 2018 by the American Psychological Association. Adapted with permission.

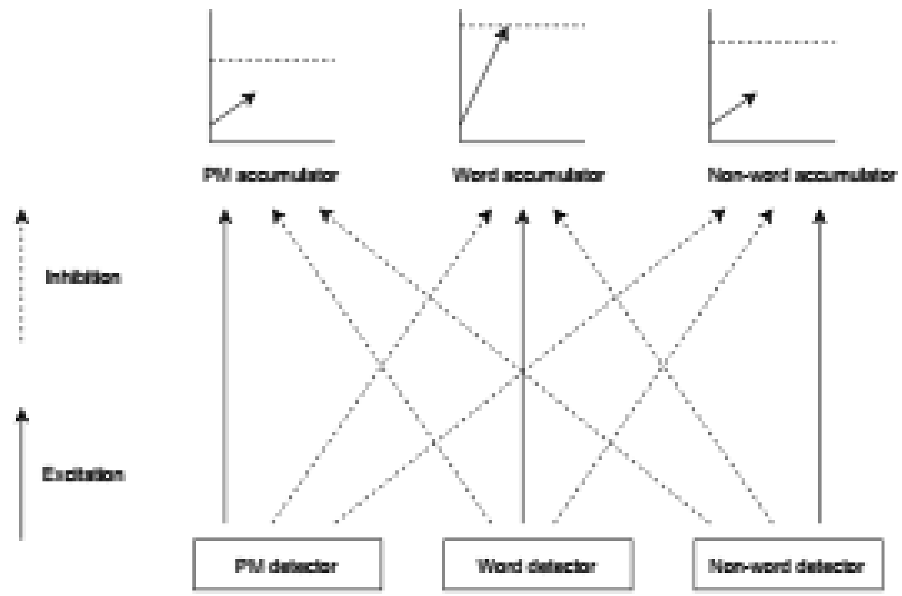

Figure 3. Multinomial Processing Tree (MPT) Model of event-based prospective memory (Smith & Bayen, 2004). PM = Prospective Memory. *C* = probability of knowing the correct answer to the ongoing task; *P* = prospective component; *M* = retrospective component; *c* = probability of guessing the correct answer to the ongoing task; *g* = probability of guessing that the item is a prospective-memory target. Adapted from “A multinomial model of event-based prospective memory” by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, p. 758. Copyright 2004 by the American Psychological Association.