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Failing to forget: Studies on prospective memory deactivation

Universidade do Minho
Escola de Psicologia

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Failing to forget: Studies on prospective memory deactivation

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Licença concedida aos utilizadores deste trabalho

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Statement of Integrity

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Failing to forget: Studies on prospective memory deactivation

ABSTRACT

A great deal of research has emerged opening a new perspective on the nature of long-term memory: Unveiling that it is also future-oriented rather than a simple storage of past memories. While prospective memory (PM) enables us to remember to perform an intention in the future, deactivating irrelevant intentions make it possible to flexibly re-adjust our behavior according to changing contexts and goals. However, PM commission errors may occur if an irrelevant intention is erroneously executed despite no-longer-needed (e.g., accidental overmedication). Recently, one hypothesis suggests that commission errors result from a spontaneous intention retrieval and failed cognitive control.

The studies reported in this dissertation aimed at examining the mechanisms underlying PM commission errors. We attempted to clarify the influence of cognitive control ability as well as the role of the interference mechanisms on PM deactivation.

After discussing some theoretical views and empirical findings of PM functioning, we provide a systematic review exploring PM performance under cognitively demanding conditions. The results indicated that, besides failing to remember to perform a delayed intention, under some circumstances, it also seems to be more frequent to execute an irrelevant PM task if cognitive resources are taxed by the ongoing task demands.

Thus, in Study 1, we aimed to investigate whether PM commission error risk is affected by varying ongoing task demands (Experiment 1). Our results go in line with previous studies, revealing that these memory failures increase whilst participants are engaged in resource-demanding activities. In turn, Study 2 was dedicated to exploring whether PM deactivation benefits from a retroactive interference mechanism by adding a new-PM intention (Experiment 3) or filler tasks with increased difficulty levels (Experiment 2). Taken together, the results pointed to an overwriting or deterioration of the old-PM task representation, reducing PM commission error occurrence.

In sum, the work accomplished in this dissertation clarify the conditions that may lead to or, otherwise, prevent PM commission errors. This work provides a more comprehensive picture of the processes underlying intention deactivation and it will hopefully encourage future studies aiming to provide more indicators of inhibition or spontaneous retrieval processes behind PM deactivation.

Keywords: cognitive control; commission errors; interference; prospective memory

Falhas no esquecimento: Estudos sobre a desativação de memórias prospectivas

RESUMO

Vários estudos têm contribuído para uma nova visão acerca da natureza da memória a longo-prazo: Esta é também orientada para o futuro ao invés de um simples arquivo de memórias passadas. A memória prospectiva permite-nos lembrar de realizar uma intenção no futuro, mas estas memórias devem ser desativadas (ou esquecidas), quando se tornam irrelevantes, de forma a flexivelmente reajustarmos o nosso comportamento de acordo com vários contextos e objetivos. No entanto, podem ocorrer erros de comissão se uma intenção for erradamente realizada apesar de já não ser necessária (e.g., sobre-medicação acidental). Recentemente, uma hipótese sugere que estas falhas resultam de uma recuperação espontânea de uma intenção irrelevante e de uma falha de controlo cognitivo.

Os estudos desenvolvidos nesta dissertação examinaram os mecanismos subjacentes aos erros de comissão da memória prospectiva. Procurou-se clarificar a influência da capacidade de controlo cognitivo assim como o papel dos mecanismos de interferência na desativação de intenções.

Em primeiro lugar, a revisão sistemática efetuada revela que condições cognitivamente mais exigentes conduzem a um maior esquecimento em realizar uma intenção anteriormente planeada, mas também que, nestas situações, esta é mais frequentemente realizada quando já não é necessária.

Assim, no Estudo 1 pretendemos investigar se o risco de cometer um erro de comissão é afetado pela maior dificuldade cognitiva para a realizar a tarefa decorrente (Experiência 1). Os nossos resultados revelam que estas falhas de memória aumentam quando os participantes estão envolvidos em atividades mais exigentes do ponto de vista cognitivo. Por sua vez, o Estudo 2 foi dedicado a explorar se a desativação de intenções beneficia de um mecanismo de interferência retroativo ao adicionar uma nova tarefa de memória prospectiva (Experiência 2) ou tarefas distractivas com diferentes níveis de dificuldade (Experiência 3). Em conjunto, os resultados indicam uma substituição ou deterioração de uma anterior memória prospectiva, reduzindo assim falhas na desativação de intenções irrelevantes.

Em suma, os trabalhos realizados no âmbito desta dissertação clarificam as condições que podem causar ou evitar a ocorrência de erros de comissão no funcionamento da memória prospectiva. Este trabalho fornece também um quadro mais abrangente dos processos subjacentes à desativação de intenções, esperando-se que impulsione estudos futuros com o objetivo de fornecer mais indicadores de inibição e de processos de recuperação espontânea.

Keywords: controlo cognitivo; erros de comissão; interferência; memória prospectiva

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Abbreviations

ANOVA – Analysis of Variance

BDI – Beck Depression Inventory

BF – Bayes Factor

EBPM – Even-Based Prospective Memory Tasks

hr – Hour

LDT – Lexical Decision Task

LTM – Long-Term Memory

M – Mean

Min – Minute(S)

Ms – Milliseconds

NHST – Null Hypothesis Significance Testing

OT – Ongoing Task

PAM – Preparatory Attentional and Memory Processes (Theory)

PI – Proactive Interference

PFC – Prefrontal Cortex

PM – Prospective Memory

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analysis

RI – Retroactive Interference

rIFG – Right Inferior Frontal Gyrus

RM – Retrospective Memory

RT – Response Times

s – Seconds

SD – Standard Deviation

STAI – State-Trait Anxiety Disorder

TBPM – Time-Based Prospective Memory Tasks

tDCS – Transcranial Direct Current Stimulation

WM – Working Memory

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Para o meu Chiquinho ler um dia.

CHAPTER 1

GENERAL INTRODUCTION

1.1. Introduction

Research on human memory has been at the forefront of psychological science for more than a century (Ebbinghaus, 1885; James, 1890; Müller & Pilzecker, 1900). One of the oldest and most widely accepted assumptions is that, after being stored on a short-term system, memory traces are consolidated in long-term memory (LTM; Atkinson & Shiffrin, 1968; Hebb, 1949; Hirsh, 1974; James, 1890). Within this framework, Tulving (1985, 2002) has critically underlined that our LTM supports the ability to *mentally travel through time* by recollecting past events but also by conceiving future-oriented ideas (see also Eustache et al., 2016). Indeed, in daily life, we must deal with information concerning future actions or events that need to be stored in memory and appropriately recalled at a given time or moment. For instance, remember to take medicines at lunch or to buy the David Bowie biography after work to give a friend as a birthday gift. Therefore, LTM has recently been classified in line with the temporal direction of memory traces: While retrospective memory (RM) enables us to remember things from the past (e.g., remembering a concert we went to during childhood), prospective memory (PM) allows us to remember to perform a planned intention at a future time (e.g., returning a book to the library or adhering to a new medicine prescription; Anderson & Einstein, 2017; Einstein & McDaniel, 1990; Loftus, 1971; Rummel & McDaniel, 2019; Sheppard et al., 2020).

For a long time, memory researchers have focused on RM. Still, the picture has changed: Our capacity for prospective thought is theorised as a central and ubiquitous function of our episodic memory. In fact, PM is needed for many different types of behaviors that we plan to complete on a day-to-day basis - thereby, essential for maintaining our independence - and its failures are associated with a variety of health consequences and difficulties in instrumental activities of daily living (Woods et al., 2012). For that reason, a noticeable number of studies have dedicated efforts to understand how we remember to perform intentions that cannot be executed immediately - but need to be delayed and remembered until later - while we pursue different ongoing activities (Anderson & Einstein, 2017; Boag et al., 2019; Rummel

Rummel & McDaniel, 2019; Sheppard et al., 2020). For example, when we intend to buy a birthday gift after work, we need to postpone and maintain that intention until the end of the day and remember shopping. In the last three decades, empirical evidence has been systematically collected revealing crucial differences with our ability to recollect previous experiences and, thus, improving our understanding about human memory organization (e.g., Cona et al., 2015; Uttl et al., 2018; Zeintl et al., 2007).

Importantly, our cognitive system is continuously challenged to keep track of PM intentions to accomplish what we intend to do but also to change plans when some intentions become no-longer-needed. The vital role of deactivating such irrelevant memories is most vividly evident when we experience some lapses such as taking medicines despite being instructed to discontinue its use or paying the same bill twice (e.g., Bugg & Streeper, 2019; Möschl et al., 2020; Schaper & Grundgeiger, 2019; Walser et al., 2017). Still, we hardly consider the challenges that must be overcome to achieve that because forgetting seems so deceitfully effortless. But, remembering and forgetting are rarely a straight-up process as what surrounds us does not remain static while we methodically encode or forget information. The medley of information that surrounds us is complex and overwhelming and the world keeps on turning: Birds migrate, politicians resign, our profession change, and daily goals, too (Hardwicke, 2016). For instance, our work environment´s features are demanding and change daily, such as meeting locations and time or reports to deliver. For the scientist, it would be inconvenient, or even disastrous, if an unfinished version of a manuscript is submitted despite the intended plan to send it only at the end of the week in its revised version. That is to say that some information stored in memory (in this case, PM intentions) can rapidly become irrelevant and, thus, an adaptive organism must retain the ability to update its knowledge by inhibiting information no-longer-needed to adjust our behaviors to environmental demands (e.g., Bjork, 1978).

However, several studies had shown that PM intentions are not necessarily deactivated as soon as they have been completed or when they became no-longer-needed. Instead, they may continue to affect behavior by disturbing the performance of the ongoing activities at hand (e.g., as we keep retrieving the intention to take medicines even though the prescription has ended) or by erroneously executing a PM task despite we must no longer have to do so (i.e., make PM commission errors like taking medicines twice; Bugg & Streeper, 2019; Möschl et al., 2020; Shaper & Grundgeiger, 2019; Walser et al., 2017). Thus, the enthusiasm around PM deactivation has now captured the scientific community as it provides a new approach for what has been occupying the field for decades: Understanding the cognitive mechanisms underlying false memories.

Despite the relevance to forget, inhibit, or deactivate prospective memories that become irrelevant in everyday life, this ability and their sub-processes have only been recently studied. In this scenario, the main subject of this dissertation is to understand the cognitive mechanisms and modulators underlying PM deactivation. The crux of the issue is this: Through which mechanisms our cognitive system mange to deactivate intentions that are no-longer-needed? What leads us to fail to forget those irrelevant memories? Does the availability of cognitive control resources affect prospective remembering? Can PM commission errors be avoided and, if so, how?

To foreshadow, the existing evidence leaves room to wonder if (1), under cognitively demanding conditions, breakdowns on specific inhibitory functions might increase commission error risk due to the impairment on the ability to eliminate or even suppress irrelevant PM representations and activate relevant information to daily ongoing activities. Moreover, (2) although the need for PM updating is clear, the mechanisms that underlie it (and, thus, prevent commission failures) are not. In this regard, we claim that the query of how we deactivate prospective memories may be intrinsically associated with how we forget. It would certainly be tiresome if we had to constantly inhibit or restrict contextual information irrelevant to the task at hand or to perform future goals.

Nevertheless, the impact of cognitive load on PM commission failures remains to be clarified and the literature lacks a systematic investigation on the role of interference on PM deactivation. In this dissertation, we will address these open questions by means of a systematic evaluation of the extant evidence of it and empirical investigations designed to provide strong tests to our predictions.

1.2. Thesis Outline

The main goal of the current dissertation is to explore the cognitive mechanisms and modulators underlying PM commission errors. In the next chapter, we provide an enlightening journey of how this research topic emerged. As so, Section 2.1 is then highly focused on elucidating Tulving´s contribution of a long-term episodic memory system and we also begin with a brief review of the mechanisms of forgetting that we reason that may underlie PM deactivation. In the next section (Section 2.2), we introduce the concept of PM intention and the cognitive processes involved in prospective remembering, the paradigms used to assess them, and two dominant theoretical views of intention retrieval. The previous two sections will allow the reader to understand and place in context the topic upon PM commission errors that follow. The final section of this chapter (Section 2.3) is intended to provide a comprehensive theoretical outlook on PM deactivation, by detailing the well-recognized paradigm designed to assess this issue, the moderators of intentions deactivation, and a recent theory about the nature of PM commission failures. Next, as a critical analysis on the reviewed literature (Section 2.4), we will point out why cognitive control availability and the mechanisms of interference could affect intention deactivation. And, in the last part of this introduction, we will lay out the main goals of the research presented in the chapters to follow.

Next, in Chapter 3, we present a systematic review aiming to provide a clear picture of where research on the effect of ongoing task (OT) load on PM stands and attempt a theoretical advance towards understanding the mechanisms underlying intention deactivation. We intended to offer reliable benchmarks of OT patterns that could help us to characterise PM performance and whether this could be a fruitful avenue to explore failures to deactivate intentions that became no-longer-needed.

Chapter 4 reports two studies, in research article format too, addressing the influence of some environmental conditions that may lead to or, otherwise, prevent the occurrence of PM commission errors. In Study 1 (Experiment 1), we evaluated PM deactivation under varying OT demands. The idea is that the availability of cognitive control resources when an irrelevant PM cue is encountered should impair this process - when, presumably, they are more critical for successfully inhibit a PM task that is no-longer-needed. In turn, Study 2 (Experiment 2 and 3) tested the role of retroactive interference (RI) in the ability to deactivate or forget irrelevant intentions and the conditions in which such an effect may occur.

Chapter 5 will be devoted to concluding remarks, providing a discussion about our studies´ contribution to understanding commission failures on prospective remembering and future research directions.

Finally, since this dissertation is organized in the format of scientific papers, some adjustments were made to ensure that it follows a coherent sequence. Therefore, we included references at the end of each chapter and the indexation of the figures, tables, footnotes, and designation of the experiments (Experiment 1, 2, and 3) were cumulative. The supplementary materials to the papers are presented as an appendix to this dissertation.

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CHAPTER 2

FROM RETROSPECTIVE TO PROSPECTIVE MEMORY RESEARCH

The work presented in Chapter 2 was submitted for publication to international peer-reviewed journals and was publicly presented at scientific meetings:

Matos, P., & Albuquerque, P. B. (2020). *From retrospective to prospective memory research: A framework for investigating the deactivation of intentions* [Manuscript submitted for publication]. School of Psychology, University of Minho.

Matos, P., & Albuquerque, P. B. (2017, May 26). "*Don´t forget the exam": An overview of prospective memory research* [Conference presentation]. VIII Research Seminar in Psychology of the University of Minho, Braga, Portugal.

2.1. Remembering and forgetting:
A framework for investigating prospective memory deactivation

> "(...) there are different types of memory (...) memory areas, each responsible for a different form of information storage. The hippocampus (...) both constructs and stores cognitive maps."
>
> (Nadel and O´Keefe, 1974, p. 373)

Retrospective memory shaped much of memory research until the interest in memory for future intentions enters the spotlight at the end of the XX century. Scientists had begun to recognize the many other adaptive uses to which memory is called: It cannot be secluded to the past since we often must remember to perform delayed intentions at a later point in the future. Therefore, the concept of episodic memory has evolved into a multifaceted construct that is of great interest to researchers in various areas of psychology and neuroscience (e.g., Cona et al., 2020; Szpunar & McDermott, 2008; Tulving & Szpunar, 2009). As mentioned before, there are two branches with which we define the memories we encode: Retrospective memory and prospective memory. While RM refers to memories for previously experienced events, PM enables us to recall at the right moment an intention that we need to perform (Roediger, 1996; Rummel & McDaniel, 2019; Tulving, 2002). In this chapter, we will start by clarifying some basic memory assumptions, emphasizing the idea of a multimemory system as well as the mechanisms thought to underlie forgetting. We will later integrate these ideas into the conceptualization and theoretical basis of our empirical studies on PM commission errors discussed in Chapter 4. (i.e., when a PM task is no-longer active, but the intention is still executed in response to an irrelevant cue).

2.1.1. Multiple memory systems

Besides an earlier framework, in which memory reflects the presence of an engram (or memory trace) – that is, the physical impression of an experience in the brain (Lashley, 1950; Tulving & Watkins, 1975) -, one of the most popular contemporary ways of looking at memory is the *multiple systems view* (Cohen & Squire, 1980; Milner, 1966). This concept rapidly emerged due to the neuroscientific advances on memory´s biological bases but also to the finding that an amnesic patient, H.M., could show some learning of motor skills. Indeed, this idea that there could be different types of memory was early captured by William James´s (1890) who distinguished between primary and secondary memory and it is prominently reflected in the organization of brain systems by the fact that amnesic patients may have intact short-term memory (STM) despite severely impaired LTM (Baddeley & Warrington, 1970; Cave & Squire, 1992; Milner, 1966). For instance, Milner et al. (1968) reported the study of H.M. who was unable to evoke episodes of his own life, or process new information, but had an average amplitude memory performance. The reverse pattern is also found: The patient K.F., reported by Shallice and Warrington (1970), had a limited digit range of one or two but a normal LTM.

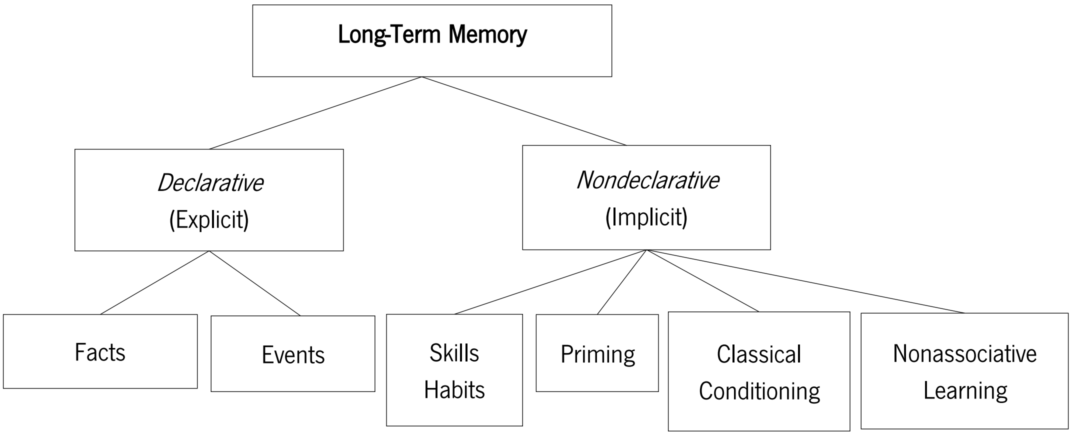
The traditional view of the distinction between STM and LTM has been that the systems operate serially. According to the influential multi-sensory model (Atkinson & Shiffrin, 1968), information initially enters STM and subsequently becomes incorporated in LTM. Simply put, a sensory memory register (i.e., iconic and echoic) enables information to be kept for very brief periods so that it can acquire meaning as it is transferred to the STM system. Then, STM allows a small amount of information to be maintained in an active state for a short period of time. This is usually the information that is used in cognitive tasks and so this system is also called working memory (WM). Baddeley and Hitch (1974) presented the most enduring and influential theoretical framework about WM, which would be responsible for temporarily retain and manipulate the information required to carry out complex cognitive operations. Moreover, based on the work developed by Brown (1958), in England, and Peterson and Peterson (1959), in the USA, it began to be assumed that the duration of STM would be 15-30 s. However, if the subjects repeat the information, it can be kept in the STM much longer and may even be transferred to LTM. Although it is not always possible to retrieve all the information we want, LTM would have unlimited capacity.

Some of the strong evidence for this multi-store model comes from the serial position effect and from studies of brain damage patients. For example, in the first case, if we present participants with lists of unrelated words and ask them to recall this information, they tend to recall more words both from the beginning of the list - *primacy effect* - and from the end of the list - *recency effect* - than words of intermediate positions (Glanzer & Cunitz, 1966). One of the variables that are sometimes manipulated in this regard is the retention interval between the presentation of the last word of the list and the beginning of recall, an interval that is usually filled with a distracting task that avoids word repetition. In this case, the recency effect is found to disappear, but the others remain unchanged. This evidence seems to suggest that this effect may be due to limited, short-lived memory recording that is interfered with when repetition is prevented, a feature found in STM. Similarly, Glanzer (1972) study' showed that the recency effect is not affected by the familiarity of the items, speed of stimuli presentation, subjects' age or performance of any other concurrent task. These variables mainly affect the primacy effect, suggesting that this effect may be attributed to LTM.

An important development that have occurred in the last decades is the recognition that there is more than one type of long-term memories that are mediated by distinct brain systems (see Figure 1). In an earlier writing, entitled *Memory and Brain*, Squire (1987) already referred that there are two well-differentiated memory systems but it only become the subject of wide interest in the early 1980s (e.g., Cohen & Squire, 1980; Tulving et al., 1982). The major distinction is between a conscious (declarative) memory for facts and events and various forms of nonconscious (nondeclarative) memory including skill and habit learning, classical conditioning, and the phenomenon of priming. Non-declarative memory is slow, unconscious, and inflexible as the information is not readily expressed by response systems that were not involved in the original learning whereas declarative memory is fast, accessed through conscious recollection, and it is flexible in the sense that it is accessible to multiple response systems.

FIGURE 1

The fractionation of LTM proposed by Zola-Morgan and Squire (redrawn based on Zola-Morgan and Squire, 1993).



Within this view, Tulving (1983, 2001) has provided an essential input for memory research by proposing that are two subtypes of declarative memory: *Semantic memory,* which refers to the organized knowledge about the world and, most important for the current dissertation, *episodic memory,* which is the system that supports memories for personally experienced events, allowing us to mental time travel as mentioned before. As we will further detail in the next sections, PM is being theorised as a crucial function of our long-term episodic memory.

Interestingly, in the early 1970s, Craik and Lockhart (1972) questioned this idea in a seminal article in which they emphasized encoding and retrieval processes instead of the system or location in which the memory might be stored. The key assumption of the *levels of processing model* was that the type of processing would determine the persistence of the memory trace. Put differently, the deeper information is processed, the better the resulting memory. Despite this prominence on processes, Craik and Lockhart (1972) continued to assume the existence of a separate LTM. From this perspective, STM main function is to ensure two distinct processes, namely, a maintenance repetition, to hold temporary information that is being used on OTs; and, an elaboration repetition, that promote a deeper information processing (i.e., where new associations and meanings are added to the material to be processed) and, consequently, the transfer of information to LTM.

For LTM contents to influence behavior, memory traces are activated through retrieval (Lewis, 1979; Tulving, 1983) which is assumed to be dependent on the presence of internal and/or external cues (Spear, 1973; Tulving, 1974). Some retrieval cues are relevant for the task an individual is performing, others contain the spatial or temporal context, or even the internal state of the organism (e.g., mood, arousal; Capaldi & Neath, 1995; Eich, 1980; Howard & Kahana, 2002). Similarly, the way that our cognitive system promotes the retrieval of a PM intention will be discussed in more detail later in this chapter.

In sum, while the process-oriented view has helped us to understand the essential role of the strategies used in each memory stage (i.e., encoding, storage, and retrieval), the multiple systems view shows us that there are several but interdependent memories. Therefore, our episodic memory primary function seems not to be only about recovering the past, but also to deal with the present or to anticipate the future (Eustache et al., 2016; Tulving, 2002). Before reviewing PM research in more detail, we will also focus on the mechanisms of forgetting to keep track of the key factors that we later propose to account for successful PM deactivation.

2.1.2. **Forgetting**

Human memory seems to be characterized by a unique symbiosis of learning, remembering, and forgetting (Bjork, 2011). Therefore, since the 20th century, a series of experiments (Dewar et al., 2007; Lechner et al., 1999; Müller & Pilzecker, 1900) laid the foundations for a debate about the loci of forgetting effects that continues to this day. Ebbinghaus, in 1885, gave us the earliest report of forgetting as a function of time. He used himself as a subject and memorized lists of nonsense syllables recording the amount of repetitions spent relearning those lists. In one case, he learned eight series of nonsense syllables and then attempted to relearn the same material after one of seven delays raging from 1h to 31 days. The percentage of savings, calculated as the difference repetitions during initial learning and relearning expressed as a percentage of the original learning times, dropped systematically over the delay. When his famous savings function was plotted out, what we know now as the prototypical forgetting function was revealed: There is a negatively accelerating decreasing in retention over time, that is, we forget rapidly at first and then retention slowly levels off.

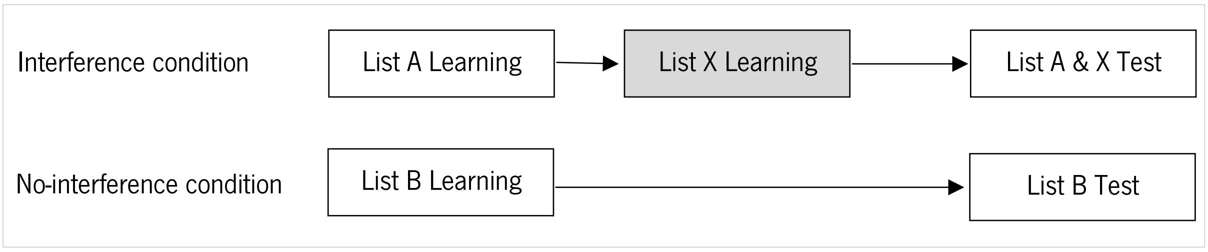
From that on, several theoretical issues have been raised and it is now possible to distinguish between two types of explanations for forgetting: (1) A memory trace *decay* over time or (2) it may be degraded by *interfering* experiences. One of the earliest assumptions was based on passive *decay* supported both by neurological underpinnings, like metabolic processes that overwrites synaptic connections, and behavioral evidence. In this regard, for example, Brown-Peterson (1958, 1959) asked participants to perform a series of recall trials in rapid succession. The stimuli used on each trial are usually similar to each other in terms of some salient dimension; and each trial includes a distracter filled delay interval interposed between presentation and recall (see also Reitman, 1974). The authors found that the longer the retention interval, the greater the participants´ inability to remember the stimuli they had learned. Although this idea is accepted by some neuroscientists (Hardt et al., 2013), the role of decay and disuse in forgetting was only reconsidered in the new *theory of disuse* (Bjork & Bjork, 1992, 2006). Briefly, this theory does not assume that memory traces simply decay over time: It acknowledges the fact that the more time has passed since the information was used, the less accessible it becomes, presumably because it is no-longer-needed.

Memories often remain highly available or even may improve over time, a fact that seems fundamentally incompatible with decay; further, if the passage of time is held constant, the amount of forgetting seems to depend on the specific activities that occur during the delay (McGeoch, 1932). Hence, an alternative class of models holds that memories appeared to decay over a retention interval because they are interfered with by additional memories that the subjects have learned (Nairne, 2002; Wixted, 2010). As Jenkins and Dallenbach (1924) stated, “forgetting is not so much a matter of the decay of old impressions and associations as it is a matter of interference, inhibition, or obliteration of the old by the new” (p. 612). In this sense, interference is thought to operate in two ways: (1) newly learned material can overwrite, erase, or otherwise degrade an existing memory trace or (2) older memories may impair the retrieval of newer memories.

In this regard, early in the last century, Müller and Pilzecker (1900; as detailed by Lechner et al., 1999) contrasted two conditions (Exp. 31). In the interference condition, after the learning of a first pair of syllables (List A), participants learned an interfering list (List X). Then, after 6 min, memory for the List A and List X was examined. In turn, in the no-interference condition, a third list (List B) was learned and tested after an equivalent interval of time (but with no interfering learning). In both cases, the percentage of correctly recalled pairs of List A was collected (see Figure 2). The manipulation of an interfering list brought an important finding: Recall in the interference condition was worse (for items of List A) compared to the no-interference condition. This finding that new memories make it harder to remember old memories led them to put forward that *retroactive interference* is a force that works against the retention of newly formed memories (see also Jenkins & Dallenbach, 1924).

FIGURE 2

Schematic illustration of Müller and Pilzecker´s (1900) procedure.



In another experiment (Exp. 35), the authors further explored whether there is a type of RI that is based only on distraction, and not on the similarity between the memoranda and the interfering stimuli. Here, the procedure was the same, however, images were used as the interfering material. Thus, 6 minutes later after List A learning, a list of images was displayed, and participants had to describe the landscapes they represent. Then, memory for List A was measured. As a control condition, memory for List B was measured with an equivalent retention interval. The pattern of results was the same: The memory performance of List A (24%) was lower than List B (56%). This led to the conclusion that any subsequent mentally effortful interpolated task is expected to impair memory performance (see Dewar et al., 2007 for similar findings in neurologically intact people and in patients with temporal anterograde amnesia). It is worthy to note that, more recently, Wixted (2010) highlights that this nonspecific RI associated with the formation of new memories degrades previously memories and that this interference presumably has its greatest effect on recently formed memories because they have not yet been consolidated.

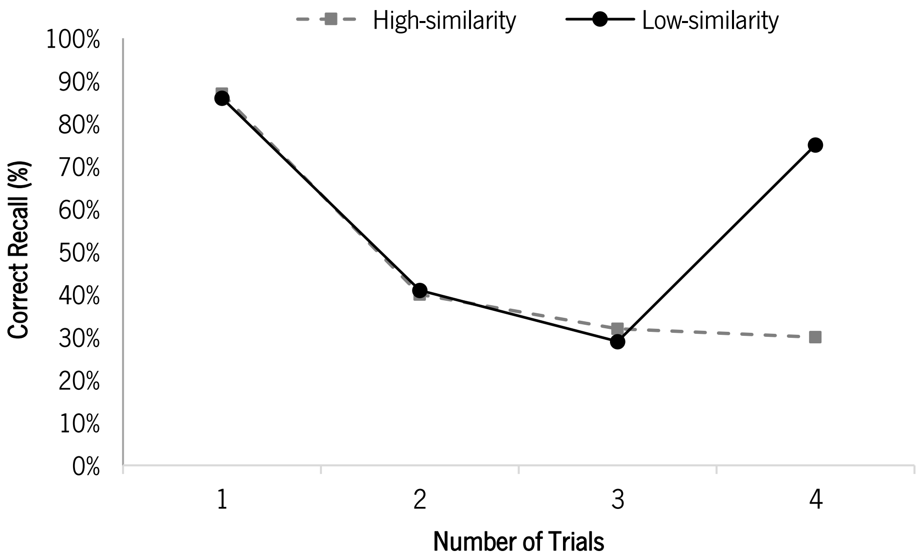
In subsequent years, many researchers have focused on the potential causes of RI. On the one hand, the following activity may lead to *unlearning of the cue-target association* (Melton & Irwin, 1940); or, more commonly accepted, RI may result from response competition (i.e., *cue-overload principle*; Watkins & Watkins, 1975). According to this last idea, using paired-associates paradigms, researchers have shown that the more information (i.e., memory traces) associated with a single retrieval cue, the less effective that cue will be at facilitating access to any specific trace in memory storage. This phenomenon is well supported empirically. For instance, as the number of study items from a specific category increases, the category name becomes less effective for eliciting any one item in particular (Tulving & Thomson, 1973). Other research has documented instances where increasing the number of associate responses to a given target slows down people´s ability to verify any particular cue-target paring (Anderson, 1974). On the other hand, inhibition can be actively used to reduce the activation of interfering memories as seen in part-set-cuing, negative priming, and retrieval practice effects (e.g., Anderson & Spellman, 1995; Radvansky, 1999; Slamecka, 1968).

An alternative explanation was introduced by Underwood (1957) in a classic paper showing that normal subjects exhibited little or no forgetting on the first trial of their paradigm but performed progressively worse across trials. That is to say that older memories may impair retrieval of new memories, termed *proactive interference* (PI). This was an ingenious observation and it was understandably regarded as an important insight into the comprehension of why we forget. Interestingly, PI builds up over time until people are given information that differs from the old knowledge. At that point, memory improves and there is a *release from PI.*

An example of such an effect is the study conducted by Wickens (1972), in which participants were given lists of words to remember. The words in the first three lists were all fruits. If the fourth list was fruit again, then memory continued to decline. Nevertheless, if the fourth list words belonged to a new category, a release from PI occurs (see Figure 3). A possible explanation is that if we need to process a lot of material similar to the cues that we use to retrieve information from memory, these indicators begin to become saturated. By being confronted with, for example, semantically diverse material we will create the possibility that the information will be associated with new indicators and, as a result, it is better retrieved (see also Abel & Bäuml, 2014; Szpunar & McDermott, 2008).

FIGURE 3

A demonstration of PI release: If the class of materials employed as stimuli were switched after a few trials, performance returned to the level of the first trial (adapted from Wickens, 1972).



In short, as Nadel and O´Keefe (1974) alludes in the opening citation, there are several separate but interdependent memories. Despite the limitations pointed to the abovementioned models, they triggered a new line of approaches on unitary and functional aspects of our memory system which relevance and heuristic value persist today. In line with the multiple systems view, there is a growing acknowledgement that our memory allows us to recall events that happened in the past but also to anticipate and plan future events or intentions. Furthermore, given the complexity of memory, there are many ways that error can enter the system, from encoding to retrieval (Marsh et al., 2008). Hence, the next section is then precisely dedicated to the growing interest in prospective remembering and its failures by providing a brief overview of this emerging field of research. Within this broader historical, as we also will make clear in Chapter 4, we assume an adaptative value of the interference mechanisms along with cognitive control processes, that may have a crucial role helping to inhibit/forget task goal representations that are no-longer relevant.

2.2. Prospective memory: A new research focus

> “A technician is preparing intravenous therapy with several pharmaceutical ingredients. Just as he is about to reach (...) the last ingredient, sodium chloride, he is interrupted by another technician´s call for assistance on another task. Returning to the intravenous therapy a few minutes later, he forgets to add the sodium chloride. The intravenous therapy is administered to the patient, who develops hyponatremia (...).”
>
> (Dismukes, 2010, p. 79)

Remarkably, the ability to imagine and plan for the future has been recently studied across multiple research domains in cognitive psychology, especially in research on episodic future-thinking, mind-wandering and, particularly, prospective remembering (Cole & Kvavilashvili, 2019). In a broader sense, one may mentally imagine and simulate experiences and events that might take place in his personal future (i.e., episodic future thinking) or have freely flowing thoughts unrelated to the task at hand occurring spontaneously while attending to a particular ongoing activity as driving (i.e., mind-wandering; Christoff et al., 2016; Schacter et al., 2017). In turn, as outlined earlier in this chapter, a frequent real-world demand is remembering to perform specific intended actions over some delay, such as taking medicines after breakfast, paying a bill in time, or pick up the kids at day-care after work. This ability that requires memory for delayed intentions is known as PM or the ability of *remembering to remember* (Einstein & McDaniel, 1990). In the past several decades, PM research has explored the question of how to successfully fulfill delayed intentions and tried to understand what causes PM omission errors (i.e., failures to remember to perform an intention).

Historically, the origin of the idea of PM dates back to a paper published by Colegrove (1899) and to Lewin´s essay *Intention, Will, and Need* (1926), in which they already raised the question of how people can remember to keep appointment´s in the future. As Wilkins and Baddeley (1978) wrote: "(...) prompted recall rarely occurs in everyday memory, which usually involves the person remembering to do something at a particular time, or at some particular point in the sequence of everyday events" (p. 2). Later, in 2002, Endel Tulving made an essential contribution by theorizing a forward-looking mind that is capable of recall events that happened in the past but also to anticipate and plan future intentions. As he stated:

> Our observations of N.N. corroborate the idea that the lack of conscious awareness of personal time encompasses both the past and the future. A normal healthy person (...) is capable of mental time travel, roaming at what has happened as readily as over what might happen. (Tulving, 1985, p. 6)

In the current thesis, we follow the definition of PM as a conscious decision to perform a specific task in the future and remember to achieve the intended action while engaged in other ongoing activities, either in response to a particular event (e.g., pay the electricity bill upon encountering the automatic teller machine, ATM) or at a prespecified time (e.g., attend a college meeting at 5:30 p.m.), termed event-based (EBPM) and time-based (TBPM) PM tasks, respectively. For instance, if we plan to pay a bill, we need to suspend and maintain this intention during the workday. Eventually, on the way to lunch, we need to initiate our intended action when seeing the ATM.

Cognitive research has provided evidence that prospective remembering is a central and ubiquitous function of human memory and is vital for successful everyday functioning (Dismukes, 2012; Rummel & McDaniel, 2019). These assumptions are in accordance with the occurrence of PM future-oriented thoughts. Although it is not an easy task, using diary and experience sampling methods, recent studies showed that people think about the future (30%) more frequently than the past (13%); and, that almost 15% of all our daily thoughts are associated with planning and executing PM intentions in the immediate or near future (Anderson & McDaniel; 2019; Cole & Kvavilashvili, 2020; Gardner & Ascoli, 2015). Thus, it is not surprising that PM failures constitute at least half of everyday forgetting (Kliegel & Martin, 2003). More than forgetting information about past events, research suggests that individuals tend to report forgetfulness for previously planned intentions when the appropriate moment arise (Crawford et al., 2003; Smith et al., 2000). Besides, PM plays a remarkable role in daily functioning problems that frequently accompany older age (Sheppard et al., 2020; Woods et al., 2012) and younger adults seem to be overconfident in naturalistic PM tasks. That is, although they remember what they must do precisely, they are inaccurate in predicting in which PM tasks they will remember the appropriate moment to perform the intention (Cauvin et al., 2018).

So, even the best intentions are likely to fail if we forget to execute an intended action at the appropriate time and some PM failures can be devastating. An epidemiological study found that forgetting to take one´s blood pressure medicines at least one time, significantly increased the risk of heart attack and death (Nelson et al., 2006). Also, even though aircraft crew PM failures rarely occur or lead to injury, almost 1/5 of major airline accidents can be attributed to failures in prospective remembering (Dismukes, 2006). Prospective memory is also of enormous clinical relevance. A significant number of patients report PM problems as their main symptoms, and several studies indicate that these failures are also frequent in subjects after brain damage (e.g., Kinsella et al. 2018; Raskin et al. 2018) and in a variety of disorders such as autism, attention deficit and hyperactivity disorder, schizophrenia, Korsakoff's syndrome, multiple sclerosis, stroke, and Parkinson´s disease (e.g., Altgassen et al. 2019; Costa et al. 2018; Lloyd et al., 2020; Rouleau et al. 2018; Hogan et al. 2020; Sheppard et al. 2018).

2.2.1. **What is different about prospective memory?**

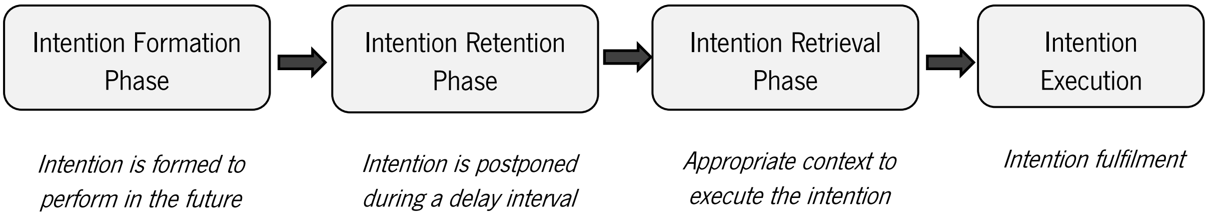
Although Tulving argued for a forward-looking mind, he left many questions open. Are there multiple memories, one of which supports remembering past experiences, the other remembering to perform future intentions? In this case, how do these forms of memory can be distinguished from one another? Do they differ in terms of processes they instantiate? Next, we will begin by highlighting the unique features that endow the conceptual individualisation of PM.

Firstly, remembering intentions for later performance entails several processes and has some unique phases that are not found in RM. As illustrated in Figure 4, according to the multi-phasic model, PM involves (1), forming an intention to perform at a later moment and defining the future context or time in which it must be performed; (2) maintain the intention over a delay (i.e., retention phase) during which one is occupied with a concurrent activity; (3) retrieve the intention at the appropriate moment; (4) execute the intended action; and, (5) deactivate irrelevant intentions in order to avoid, for example, commission errors (Ellis, 1996; Kliegel et al., 2002; McDaniel & Einstein, 2007; Shelton et al., 2019).

An important feature of PM is that delayed intentions usually must be performed when one is engaged in other unrelated tasks, so-called ongoing activities (e.g., writing an email while having to take medicines at 10 a.m.). Then, the appropriate opportunity for performing the intention may occur. That is, upon noticing a relevant cue (e.g., see the medicine box), we need to inhibit the OT at hand and switch directly to intention execution (e.g., take allergy medicines). Here, we are not explicitly advised when it is time to retrieve and execute the stored intention from memory but one may periodically think about our PM tasks or the intention simply pops into mind, as we will discuss later in this section (e.g., see the medicine box should cue the intention to take medicines; Einstein & McDaniel, 1990; Kvavilashvili & Ellis, 1996). Therefore, PM tasks require a large degree of self-initiated retrieval, especially TBPM tasks (Anderson & Craik, 2000). By contrast, in RM tasks, one is externally prompted to recall past information such as recall previous words in a free recall test or our account manager name when meeting him again.

FIGURE 4

The depiction of the four phases of PM adapted from Ellis (1996) and Kliegel et al. (2002).



Much of the research in PM has focused on the mechanisms underlying the *prospective component*, which involves noticing the PM cue and becoming aware that an intended action should be initiated. However, to successfully perform the PM intention it is also necessary to remember the content of the intention and retrieving the action from LTM (termed *retrospective component*; Einstein & McDaniel, 1996; Ellis & Kvavilashvili, 2000; Guajardo & Best, 2000). Put differently, individuals might fail to remember to act on the intention at the intended place, time, or moment (i.e., failure of the prospective component). Less frequently, they may realize that something must be done but cannot retrieve from memory what they intended to do (i.e., retrospective PM component failure). As the next section will begin to make clear, one may also fail to deactivate PM tasks that become no-longer-needed and those intentions may continue to affect behavior or even be erroneously executed.

Secondly, the understanding of the cognitive mechanisms underlying PM had a remarkable growth in the XXI century. As noted, the ability to perform a delayed intention requires a degree of RM functioning (Einstein & McDaniel, 1990; Meacham & Leiman, 1982; Wilkins & Baddeley, 1978). Unsurprisingly, then, some variables or experimental conditions equally affect both types of memory tasks. In an earlier study, Loftus (1971) showed that PM retrieval was found to be facilitated when retrieval cues are present, and it was impaired if the number of activities during the delay interval is increased.

Similarly, PM performance was enhanced if the target cues were generated at encoding in line with the levels-of-processing effect (Craik & Lockhart, 1972; Robinson-Riegler & McDaniel, 1994, Experiment 3). Moreover, according to the transfer-appropriate-processing approach (Morris et al., 1977), the type of processing required by the ongoing activity results in better PM performance when it matches the processing needed to detect the environmental PM cues prompting the intention retrieval (e.g., Abney et al., 2013; McDaniel et al., 1998; West & Craik, 2001; see point 2.2.2, p. 28, for further details about focal and non-focal PM tasks). Finally, reinstating the environmental context at retrieval also aid PM as in recognition and recall tests (e.g., Robinson, 1992, Experiment 2).

As we can see, PM shares some similarities with RM. Undoubtedly, however, it introduces a unique challenge for memory: These tasks are frequently set aside for later, so one must notice the appropriate event (e.g., see the medicine box), retrieve the intended action from memory and coordinate its execution with the ongoing activity (e.g., "Therefore, I need to interrupt breakfast or sending an email to take medicines). Researchers have critically found that patients may show impaired PM with unimpaired RM, but the converse pattern is not observed (i.e., single dissociation). For instance, Shallice and Burgess (1991) described three head injury patients with focal frontal lobe damage with difficulties with scheduling a number of relatively straightforward activities in a restricted period of time. Simply put, when their behavior has to be guided by explicit intentions generated previously or decisions outlined at an earlier time; but with little impairment in RM paired associates. On the contrary, when RM is impaired, what happens to PM? Patients with RM deficits also tend to show low PM. One example came from Burgess and Taylor´s study, with memory-impaired individuals who suffered mainly head injury, showing that plan-following behavior was significantly correlated with RM abilities. A possible, and plausible, explanation for these findings is that RM abilities are a prerequisite for prospective remembering, but not vice-versa.

In addition, several studies examining the effect of the delay interval have shown that longer intervals may kept stable (Einstein et al., 1992) or even increase PM performance compared to shorter intervals (Hicks et al., 2000; Martin et al., 2011). As in many RM studies, PM researchers have varied the length between the PM task encoding and the start of the block of ongoing trials in which the PM task is to be performed. While an unrehearsed memory will grow weaker over time and eventually be forgotten, some studies surprisingly show that PM may not decline during the retention interval. For instance, Hicks et al. (2000) found that PM performance increased with longer delays that involved a large number of intervening tasks compared to shorter delays with fewer tasks. A possible explanation is that more distractor tasks and unfiled breaks between tasks might allow participants to remind themselves of the

PM intention during task-switching, bringing the intention back to participants´ focus of attention (see also Martin et al., 2011).

In fact, most people review their intentions periodically as part of their daily mental life. On the one hand, it is conceivable that a *maintenance repetition* (i.e., the activation of the intention from LTM) allows avoiding forgetting during this period (see Roediger & Karpicke, 2006). For example, Finstad et al. (2006, Experiment 1) introduced short breaks in the OT during which half of the participants received the instruction "Remember what to do when you see the keyword". Results indicated that requesting PM retrieval at scheduled intervals enhanced PM since participants who were instructed to perform the PM task periodically had a better performance (75%) compared to the no-instruction condition (60%). Moreover, cues in the environment can remind us of delayed intentions, such as the sight of one's vehicle serving as a reminder to have the oil changed. These periodic reminders help to strengthen PM representation. Retrospective memory does not enjoy such periodic reminders and then it is arguably more likely to fall into disuse. On the other hand, a *retrieval mode* (see Guynn, 2003) may allow stimuli to be processed as possible cues to achieve the intention while we actively search for environmental cues. In this sense, the stability of PM intentions over the retention interval has been interpreted in the light of an *intention superiority effect* which postulates that PM intentions are stored in a higher level of activation. Thus, the aspects related to a PM task seem more salient, allowing intentions to come to mind quickly in response to relevant environmental cues (Goschke & Kuhl, 1993; Marsh et al., 1998).

Another theoretically important domain that provides evidence of the distinction between RM and PM - but also raises the intriguing possibility that PM may be one of the few cognitive abilities that may be spared from the negative effects of aging in everyday life -, concerns the age-PM paradox (Rendell & Craik, 2000). Aging deficits in both encoding and retrieval in RM are well documented in many studies (see Balota et al., 2000 for a review). Slower processing speed, fewer cognitive resources available for tasks, WM, and inhibitory deficits are cited as possible causes of RM decline in older adults (Anderson & Craik, 2000; Balota et al., 2000). Given that PM tasks require some degree of RM as well as WM and inhibition of the OT processing to retrieve and execute the PM intention, McDaniel and Einstein (2007) initially predicted an age-related decline in PM performance. However, it seems that when more naturalistic PM tasks are studied, older adults may outperform younger adults, possibly due to factors like higher motivation, using their own strategies to be able to compensate for tasks that would otherwise have high monitoring demands, planning their environment to aid in the completion of the task, and as in the case of own self-assigned PM tasks (e.g., Bailey et al., 2010; Haines et al., 2020; Kliegel et al., 2016; Kvavilashvili et al., 2013; Schnitzspahn et al., 2011, 2020; see Henry et al., 2004 for a meta-analysis). Moreover, the typical age differences in PM performance seem to be also eliminated when the importance of the PM task is emphasized (Ball & Aschenbrenner, 2018) or when reducing the OT demands by allowing older adults to devote more attentional resources to the PM task (Rendell et al., 2007).

Third, research has also shown that, besides RM, some other cognitive functions underlie PM ability. More specifically, it seems to be driven by WM and attentional processes (i.e., to temporarily store, process information, and monitor for PM cues) as well as other executive functioning abilities, such as switching (i.e., to shift between different tasks) and inhibition (i.e., to interrupt the ongoing activity at the appropriate time when the PM cue is detected to carry out the intended action, or to inhibit PM intentions when they become no-longer-needed; Bugg et al., 2016; Einstein & McDaniel, 1996; Ellis & Kvavilashvili, 2000; Ihle et al., 2019; Schnitzspahn et al., 2013; Settle et al., 2017; Smith & Bayen, 2014). Several findings support this assumption. For instance, Ball et al. (2019), using structural equation modelling, showed that individual differences in WM are a predictor of the likelihood that an intention will be fulfilled as people may strategically regulate the degree of attentional control to revise the contextual associations formed at encoding. Furthermore, neuroimaging studies show that prefrontal cortex (PFC), especially the anterior PFC (Broadman´s area 10), is essential in different stages of PM namely for planning, maintain, and PM cue orientation (e.g., Cona et al., 2015; Simons et al., 2006). Likewise, studies with event-related potentials revealed different component-dependent modulations in agreement with the expected PM processes, namely, N300 to PM cue detection, and frontal positivity to switch between ongoing and PM trials (Cona et al., 2014). Importantly, however, several studies provided evidence that PM represents a distinct construct with convergent and discriminant validity, with partial independence from WM, speed of processing, and free recall (e.g., Fronda et al., 2020; Monti et al., 2019; Zeintl et al., 2007).

To conclude, an important aspect merit consideration: The interest on PM did not appear due to experimental effects found in other studies about human memory, but rather due to the idea that retrieving and forgetting intentions have somehow different properties compared to remembering and forgetting past events. Indeed, what started with some scepticism - “Is the study of PM any more than the study of the list to do in the future? Is PM another form of episodic memory?” (Roediger, 1996, p. 151) - was later established as a new field of research. In contrast to RM, PM tasks are future-focused and we must use (external or internal) cues to recall the intention that we need to perform (Roediger, 1996; Rummel & McDaniel, 2019; Tulving, 1985, 2002). More, although conceptualized as a multiphase process reliant on an interaction of RM and executive processes, earlier empirical evidence clearly showed a dissociation between PM and other cognitive functions. The question that we will now turn on is the experimental procedure to investigate prospective remembering in order to make clear the methodological option that we have considered to study PM commission errors.

2.2.2. **The dual-task paradigm**

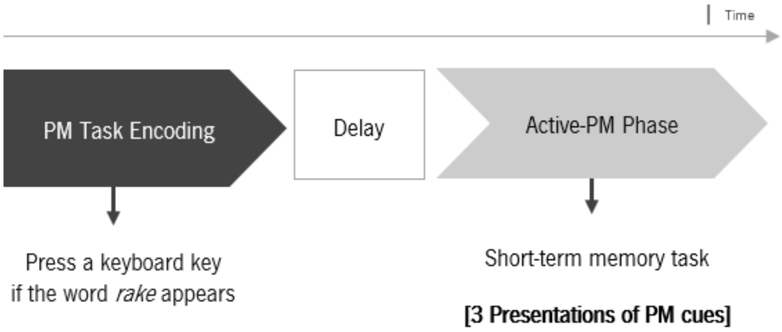
Human memory assessment has changed in the last decades, especially with the growing interest in topics such as implicit memory or prospective remembering. To foreshadow, in PM experiments, participants are asked to remember to perform a specific task when an associated cue arises, instead of being requested to recall previously learned information. The pioneering studies were semi-naturalistic, in which participants must tell the place of birth after concluding a survey (Loftus, 1971) or send postcards (Meacham & Singer, 1977; see also Kvavilashvili, 1987; West, 1988). These tasks stimulated the interest in factors thought to influence PM. Still, the lack of experimental control (McDaniel & Einstein, 2007), the susceptibility of ceiling effects (Kvavilashvili, 1992), and the narrow range of scores that might not be sensible to accommodate heterogeneous and diverse PM performances (Rendell & Henry, 2009) were some of the pointed critical disadvantages.

Therefore, the systematic research on PM did not begin before the topic was brought into the laboratory. A milestone was the publication of a seminal study by Einstein and McDaniel, in 1990. The authors developed a paradigm to study PM in laboratory. The standard procedure was as follows (see Figure 5). First, participants are asked to perform an intended action (e.g., press the *Q* key) upon encountering specific, rarely occurring events that serve as retrieval cues (e.g., the word *rake*). In laboratory settings, the PM task is embedded within an OT (e.g., lexical decision task, LDT, or image rating task) to mimic real-life situations of being busy engaged in ongoing activities (e.g., driving home from work) when also needing to remember to perform an intention (e.g., return a book to the library). In this scenario, the stimuli contain features relevant to perform the OT on every trial. But, on some trials, it also includes features indicating that it is the appropriate moment to fulfil a planned intention. The retention interval that follows is often filled with some delay task to prevent participants to holding the intention in WM. Next, they perform an OT (during an active-PM phase) and must remember to execute the intention in response to the PM cues without being explicitly reminded of that additional task.

This dual-task paradigm has been adapted in multiple ways, yet its prototypical structure is quite preserved across experiments. Namely, (a) there is a delay between the initial PM task instruction and the chance for retrieval, (b) there is an absence of external prompts to retrieve the PM task, and (c) participants are involved in activities that must be interrupted to perform the intention (Ellis & Kvavilashvili, 2000; McDaniel & Einstein, 2000). Using this paradigm, researchers can make inferences about the mechanisms underlying PM by examining both PM task and OT performance.

FIGURE 5

Schematic representation of Einstein and McDaniel´S (1990) dual-task paradigm.



Thus, Einstein and McDaniel´s (1990) study received a lot of attention mainly for two reasons: It was an easy-to-use laboratory paradigm allowing well-controlled manipulations and due to the surprising finding of no-age decrements. More specifically, one type of error/mistake was considered the first evidence that memories for future intentions might fail: There was a percentage of PM cue trials on which participants forgot to perform the separate PM action (i.e., omission errors). This straightforward measure is considered the *PM hit rate* (i.e., number of correct responses to PM cues relative to the total number of PM cue occurrences). Unexpectedly, their study showed that older adults did not have a worse PM performance than younger adults, initially suggesting that PM could differ from RM. Yet, further studies showed that PM follows an inverted U-shape function across development like other cognitive domains like RM or some executive functions (e.g., Bailey et al., 2010; Haines et al., 2020; Kliegel et al., 2016; Kvavilashvili et al., 2013; Zimmermann & Meier, 2006, 2010; Schnitzspahn et al., 2011, 2016 for different findings).

Thereafter, as further discussed, a consistent body of research has assumed that successful prospective remembering always implies an OT performance cost due to the laboratory PM´s dual-task nature. However, we would hardly be able to accomplish daily´s life complex requirements if every intention would constantly require cognitive resources. Hence, another theory states that different strategies must be available: A spontaneous retrieval would allow retrieve and execute the PM task at the appropriate context without an effortful monitoring. The next section is precisely devoted to these theoretical approaches that seek to explain what cognitive processes enable retrieving a PM intention from memory and why its retrieval so often fails.

2.2.3. **Competing theoretical accounts of PM retrieval**

In the first decade of laboratory-based PM research, a key question was whether aging impaired PM, but the field comprises now a large body of literature that has used controlled procedures to understand the cognitive mechanisms that support PM retrieval and intention fulfilment. Since early 2000, the study of how our cognitive system promotes the retrieval of an intention in the expected moment has been fuelling distinct theoretical predictions. A reasonable starting point to understand this issue is to describe the strategic (top-down) versus spontaneous (bottom-up) views and whether, depending on the situation, these processes are drawn upon to support PM retrieval. This conceptualization has been theoretically useful and doing this may foster our understanding about which conditions are more prone to PM omission errors and, as discussed later, to PM commission errors.

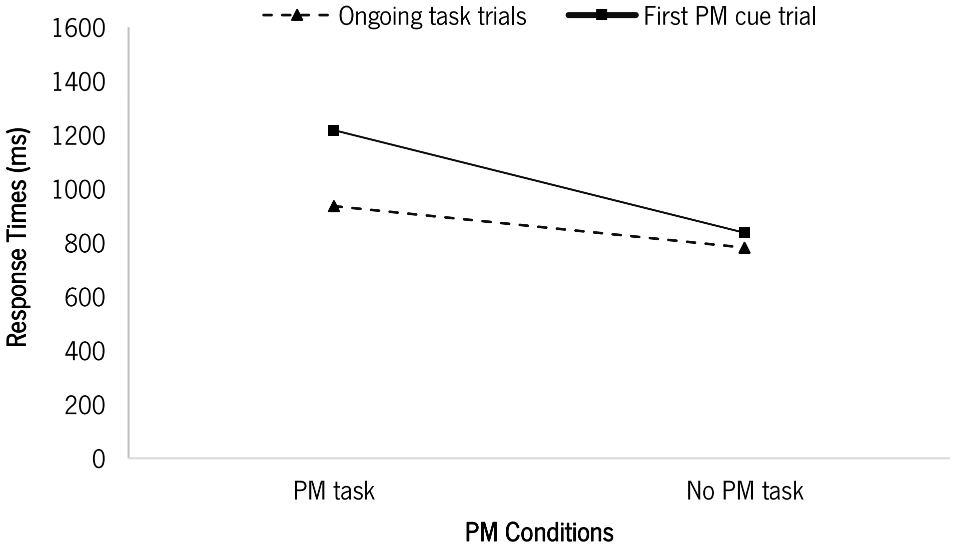
*2.2.3.1. **Preparatory attentional and memory processes (PAM) theory***

Although PM tasks may not necessarily change our immediate actions, we may experience costs to ongoing activities while maintaining and actively pursuing an intention. Smith (2003) considered PM´s possible impact of OT performance instead of considering PM performance alone. Accordingly, the assessment of OT costs became a fundamental part of laboratory PM research. In an influential adaptation of the dual-task paradigm, participants were asked to remember to press the *F1* key when six target words appeared (i.e., PM task). Critically, two conditions were contrasted. In the PM condition, participants perform a PM task and an OT simultaneously. Then, in the no-PM condition, participants were asked to perform the OT in the absence of any PM demands. In both conditions, OT response times (RTs) were collected. Results revealed that the ongoing activity was impaired when a future intention must be executed: Participants were significantly slower when performing the ongoing activity with an additional PM task than to respond to the OT alone (Figure 6). In other words, monitoring is inferred by showing that OT responding is slower when processing a PM task compared to when the same task is performed without an intention. This result indicates that being prepared to execute a delayed intention seems to entail cognitive resources in competition with performing the ongoing activity.

Based on this finding, the PAM theory (Smith, 2003; Smith & Bayen, 2004) sates that there is a diversion of resources away from the OT toward rehearsing one´s intention in WM (perhaps via a retrieval mode responsible for constantly sustain an increased activation of the PM goal) and/or detecting or evaluating potential environmental cues that indicate opportunities to perform the delayed intention. In this view, intentions cannot be retrieved unless WM and preparatory attentional processes are devoted to monitor for PM cues because the stimulus will only be considered an OT item and the PM cue will be missed.

FIGURE 6

Mean OT items and first PM cue RTs as a function of the presence of a non-focal PM task. Strategic monitoring is indexed by a slower OT performance with a concurrent PM task (adapted from Smith, 2003).



Additional support for the claim that PM retrieval is resource-demanding was then gathered. First, studies on individual differences were used to test this theoretical assertion about the structure of prospective remembering. They found that participants with higher WM capacity generally performed better on non-focal tasks (i.e., when there is a low overlap between the OT processing and those processes needed to detect the PM cue and, thereby, some increased level of attentional control is necessary for detecting these cues[1]) but had a similar level of costs as those with lower WM (Brewer et al., 2010; Smith et al., 2011). More, adding the extra demand of maintaining intentions should result in a performance cost to the ongoing activities but it also should increase the probability of perform a delayed intention. In

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[1] The interplay between the processes relevant to successfully perform the intention and those relevant for performing the OT also determines PM task performance. That is, PM performance is affected by how OTs direct attention - either toward or away from PM cues. This has led to an important distinction between focal and non-focal tasks. A PM task is considered focal when the OT processing highly overlaps with PM task processing, while it is non-focal if the processing overlap is low. For instance, in a LDT, which requires the assessment of the semantic features of a string of letters, a focal PM task is to press a key to a particular word (i.e., *rake*) because determining whether or not a string of letters is a word encourages processing of what that word is, which aligns with the information relevant to the PM task. A non-focal task is to press a key if the string of letters contains the syllable *tor* because determining if the OT stimulus is a word does not require the syllabic processing needed to detect the PM cue (Einstein & McDaniel, 2005). In line with the transfer-appropriate-processing effect (Morris et al., 1977), a typical pattern is often cited in the literature: There is better PM performance in situations with high-processing compared to low-processing overlaps (Meier & Graf, 2000).

fact, participants are more successful (in non-focal PM tasks) when they exhibit higher OT costs, suggesting that diverting more resources away from the OT improves PM (Smith, 2003; Smith & Bayen, 2004). Another interesting finding showed that this engagement seems to occur at points of transition between activities or locations (Smith & Loft, 2014), in line with the idea that a monitoring process must be engaged at the appropriate time. For example, when leaving the office, one might think about whether something needs to be done on the way home, leading to engagement of a preparatory attentional processing. Taken together, these findings support the idea that controlled attention must be allocated to maintain goal information in WM and to strategically monitor the environment for the right time and place to act.

2.2.3.2. ***Multiprocess theory***

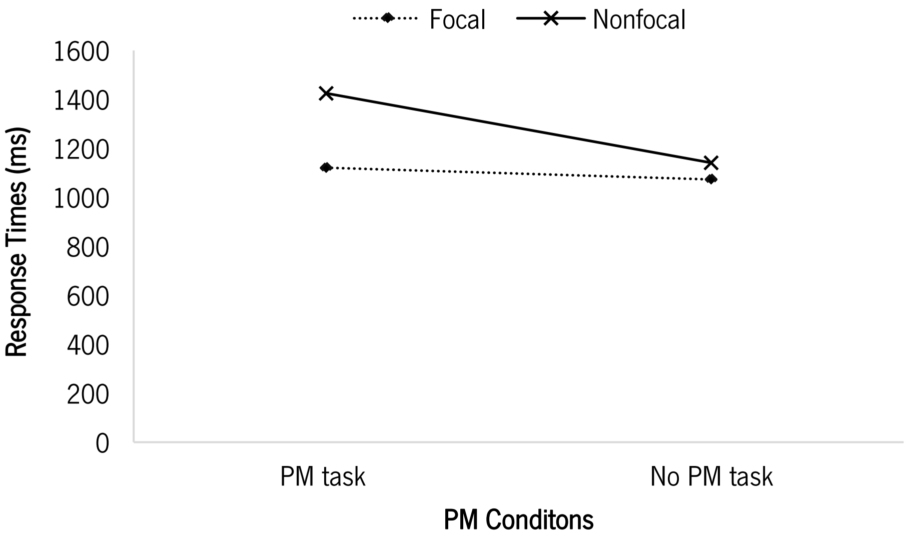
As noted by Anderson et al. (2017), the idea that PM always implies attention-demanding processes appeared counterintuitive to daily life (e.g., catching sight of an ATM, seems to trigger retrieval of the intention to pay bills) and maladaptive (i.e., engaging strategic mechanisms often over long delays would be heavily taxing). In this sense, Einstein and McDaniel (2005) challenged the PAM theory by claiming that people are more likely to rely on spontaneous retrieval, which is often conceptualised as an intention popping into mind even though sustained monitoring may be beneficial in some cases. For example, after seeing a child's red balloon we might spontaneously remember that we must buy a gift for our mother's birthday. In a series of studies, as the ongoing activity, Einstein et al. (2005) presented a word and a category heading and asked participants to decide as quickly as possible whether the word was a member of the presented category. In Experiment 1, the manipulation was PM cue focality. Hence, in the focal condition, a key must be pressed whenever a target word appeared (e.g., *tortoise*), while in the non-focal condition participants must press a key whenever a target syllable (e.g., *tor*) occurred.

The results showed high PM performance in the absence of costs (both on the accuracy and speed of performing the OT) suggesting that participants can rely on a (bottom-up) spontaneous PM retrieval without monitoring (Figure 7). Conversely, if the cue is non-focal, PM performance is lower and, in such cases, participants are slower in response to the OT, which is considered as monitoring costs (see also McDaniel & Einstein, 2000; Smith, 2003; Smith & Bayen, 2004). One of the most reliable findings in PM research is that the engagement of attentionally demanding processes are needed during non-focal processing conditions in which the OT processing (e.g., making lexical decisions) does not orient attention to the relevant features of the PM cue (e.g., the syllable *tor*; Abney et al., 2013; McDaniel et al., 1998). In other words, more self-initiated operations seem to be required as environmental support decreases. In this regard, there is recent evidence that OT costs and PM accuracy trade-off with increasing focal target list length (Anderson et al., 2019). Moreover, in Experiment 3, the authors also found greater costs with six focal PM cues (six different words) than with only one. Finally, their last experiment showed a similar PM performance in focal PM conditions between those participants who demonstrate no evidence of monitoring compared to those who had monitored for PM cues. The authors conclude:

> Our assumption that there is a bias to accomplish PM retrieval with spontaneous retrieval processes emanates from both empirical and logical concerns (...) From a rational perspective, when the delays between forming the intention and the opportunity to respond are substantial, it would seem adaptive to have a system that allows spontaneous retrieval so as not to compromise the performance of ongoing activities. This analysis is consistent with that of Bargh and Chartrand (1999) who have argued that most of our behaviors are not initiated by conscious will over a broad range of situations but rather are automatically triggered in response to the presence of environmental stimuli (...). (Einstein et al., 2005, p. 341).

FIGURE 7

Findings of Einstein et al. (2005). A demonstration of spontaneous PM retrieval, mean OT RTs as a function of the presence of a PM task and of the type of PM cue (adapted from Einstein et al., 2005, Experiment 1).



Such a flexible system would be highly efficient for being able to achieve daily functioning without much mental effort or time spent. Therefore, Einstein et al.´s work motivated many researchers to examine the mechanism supporting spontaneous PM retrieval. Two paths have been proposed: (1) The reflexive-associative hypothesis and (2) the discrepancy-plus-search hypothesis. On the one hand, in line with a *reflexive-associative hypothesis*, a strong link between the cue and the intention may reflexively recall the intention after the full processing of the related cue. Then, top-down control is needed to maintain the intention in WM and organize the motor responses. For example, if we form a good encoding to give a friend a message, later seeing that friend will make the message pop into awareness. Accordingly, research has shown that PM increases with stronger cue-intention associations. For example, McDaniel et al. (2004) observed that high semantic associations bolster that link and, thus, PM cue-intention pairs higher associated were more susceptible to be executed. Further, implementation intentions allow strong background associations (i.e., when *X* occurs, then I do *Y*; e.g., "When I leave the office, I will buy the medicines") and tying the intention to environmental stimuli also increases the possibility of an automatic retrieval. Thus, leaving the office can serve as a strong retrieval cue for the intention to buy medicines or pay a bill (e.g., Gollwitzer & Sheeran, 2006; McDaniel et al., 2008; Rummel et al., 2012).

On the other hand, based on Whittlesea and Williams's (2001) proposal that we continuously assess the processing quality of the cue information, spontaneous retrieval might also occur due to a *discrepancy-plus-search* process. As PM cues were previously associated with an intention at encoding, we might spontaneously notice that a stimulus has intention significance and then engage in controlled memory search to retrieve the full intention (McDaniel & Einstein, 2007). Consider the previous example of giving a message to a friend. Later encountering that friend cause us to process him more fluently than other friends in the group. This could prompt a search for the significance of the discrepancy, which is likely to cause the PM intention to give him a message to be retrieved. Some factors are hypothesized to increase spontaneous noticing like familiarity, distinctiveness, and discrepancy in processing (e.g., Lee & McDaniel, 2013).

Second, another major area of enquiry in PM research has also been to explore which factors bias an individual either to monitor or rely on spontaneous processes to ensure that intentions do not go unfulfilled considering the environmental demands (see Anderson et al., 2019 for a recent review). As abovementioned, the need for monitoring resources decrease when the PM task processing highly overlaps (i.e., it is focal) with the cognitive processing needed to perform the OT rather than when there is a low overlap between them (i.e., non-focal tasks; e.g., Anderson et al., 2019; Harrison & Einstein, 2010; Harrison et al., 2014; Scullin et al., 2010a, 2010b; Walter & Meier, 2016). Interestingly, while focal PM tasks seems to elicit sustained activation in the cerebellum and ventral parietal regions, in non-focal tasks the left anterior PFC showed a greater activation (Cona et al., 2016; see also McDaniel et al., 2015). Such a finding advocates that an automatic bottom-up process mostly mediates focal PM tasks, whereas strategic, top-down processing, mediates non-focal PM tasks. Additionally, spontaneous processes can trigger timely intention retrieval when PM cues are salient or distinctive (e.g., PM cues printed in all capitalised letters or printed in a colored background occurring in a series of uncapitalized words; McDaniel & Einstein, 2000), when there is a long delay between the formation of an intention and the opportunity to complete the intended action (Scullin et al., 2010a), or when the PM task is well-specified rather than ill-specified (i.e., a specific word or belonging to a category, respectively; Hicks et al., 2005; Meier et al., 2006). Similarly, as detailed in the next chapter, the cognitive resources required to complete the ongoing activity and those still available for performing a delayed intention were also found to influence PM performance (Matos et al., 2020).

Noteworthy, based on findings from literature on prospective thoughts in everyday life, PM intentions seem to more frequently pop into mind while people are mind-wandering during the retention and retrieval PM phases (Kvavilashvili & Rummel, 2020). That is, in line with this multiprocess theory (Einstein & McDaniel, 2005), intentions will keep coming to people's minds periodically while they are engaged in other tasks. Importantly, such thoughts often occur in response to incidental cues allowing people to plan their lives and carry out multiple tasks (Baumeister et al., 2018; Kvavilashvili & Rummel, 2020).

In relation to this point, Scullin et al. (2013; see also Shelton et al., 2019) recently proposed the *dynamic multiprocess theory* - a friendly amendment to the multiprocess theory – suggesting that one may dynamically adjust their PM strategy[2]. According to the core assumptions of this theoretical view, top-down and bottom-up processes support each of the PM phases (encoding, storage, retrieval, and its deactivation) but there is a bias toward reliance on strategic monitoring when PM cues are not expected and, conversely, on spontaneous processes when the PM cue is excepted. Moreover, one can flexibly adjust these strategic or spontaneous processes at a given moment primarily relying on whether the PM cue is expected, but also with the effectiveness of that processes depending on a variety of dimensions such as the PM task, OT, context, and individual differences.

In this context, Scullin et al. (2013), for example, observed that when participants must perform several OTs and the PM cues could occur at any point in the experimental session, they only monitor after they had spontaneously retrieved the PM intention. Put differently, environmental contexts might

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[2] There are often some costs in focal tasks (in terms of RTs data) and, even though age-differences in focal cue detection are reduced, they are not eliminated at a meta-analytic level (Kliegel et al., 2008). Therefore, it is reasonable to argue that it might be a continuum between monitoring to spontaneous processes or even that they can operate simultaneously. For instance, one might reflexively be reminded to buy a gift and monitor for the ATM for withdrawing cash.

serve as bottom-up retrieval cues that prompt monitoring processes for the appropriate moment to perform the PM task (e.g., we may automatically retrieve the intention to go to the ATM upon getting to a shopping and monitor until its execution). In a similar vein, there is evidence that participants increased their monitoring strategy in the context in which they knew that PM cues would occur (Ball et al., 2015; Marsh et al., 2006) or when a salient screen appeared after being advised that this would signalled that the PM cue will soon appear (Scullin et al., 2010a).

In turn, people may adjust their reliance on spontaneous processes if there is a great environmental support to notice the PM cue (Ball & Bugg, 2018), once an individual realizes the context in which the PM cue appear (Kuhlman & Rummel, 2014), and if the PM task is less demanding than anticipated (Lourenço et al., 2015). It is also worthy to note that participants can use contextual information (i.e., if the type of OT processing automatically oriented attention to the relevant features of the contextual cue) to strategically increase and decrease monitoring in focal conditions to conserve processing resources when possible (Ball & Bugg, 2018; Lourenço & Maylor, 2014)[3]. Interestingly, in a recent study, Koslov et al´s (2019) not only found that people fluidly shift their control strategies in response to changes in environmental demands (i.e., shifting from spontaneous to a strategic process when task difficulty decrease) but also that this cognitive flexibility improved the ability to remember to perform future intentions.

2.2.3.3. ***Delay theory***

Today, the textbook account for PM retrieval states that the monitoring costs reflects people´s decision to respond with a delay to the OT to allow more time for PM-related information to be processed (Heathcote et al., 2015; Loft & Remington, 2013; Strickland et al., 2018). In line with the delay theory, the idea is that this additional time is not being used for capacity-consuming processes but rather increase the likelihood of noticing the PM cue. As an empirical test, Heathcote et al. (2015) asked participants to perform a LDT and to press the *F1* key whenever they saw a word or a nonword containing the syllable *tor*. According to this theoretical view, participants must accumulate both semantic (e.g., “Is this item a word?”) and syllabic information (e.g., “Does this item contain *tor*?”) at the same time. Thus, in this study, they will not successfully perform the intention if syllabic information has not accrued sufficiently before the accumulated semantic information exceeds a decision boundary (for the LDT). Through accumulation

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[3] Interestingly, Möschl et al. (2019) observed reduced OT costs but similar PM performance between stress and non-stress participants. The authors speculate that, according to the dynamic multiprocess theory, stress could have increased the use of spontaneous processes in the sense of an increased preparedness to retrieve the intention or promoted an increased cue–target activation, which reduces the need for top-down monitoring. Alternatively, non-stressed participants were always monitoring for PM cues while stressed subjects were quicker to up- and down- regulate this strategy.

computational models, the authors observed that participants set higher decision thresholds for OTs suggesting that they used a delay strategy. That is, individuals are slower in response to the OT to allow more time for PM response selection to occur. Another piece of evidence provides support for this view: Participants showed a similar PM accuracy to focal and non-focal PM tasks when forced to withhold responding over varying delays (600-1600 ms; Loft & Remington, 2013). The idea is that simply slowing down responding allows for more opportunity for bottom-up processes to respond to environmental non-focal cues, because if the delay is sufficient information will be accumulated and thus the PM cue should be noticed.

Still, there is some evidence against the predictions derived from the delay theory. In a focal PM task, participants showed higher PM accuracy despite those in a non-focal PM group in a condition in which the requisite information to perform an OT accumulated more slowly in order for PM information to reach threshold (Anderson et al., 2018, p. 1). Also, Anderson et al.´s (2018) combined behavioral and modelling techniques with embedded parameter validation to clarify the underlying processes involved in PM. Here, the authors stimulated participants to use either a monitoring strategy or a delayed response. Critically, a third group served as a control PM group, with no strategy instructions. First, results showed a beneficial effect of the monitoring strategy on PM performance compared to the delayed responding strategy. Second, and notably, these monitoring processes were reflected in the behaviors and modelling parameters observed in the standard PM instructions group.

In sum, as Roediger (1996) stated, PM field is "on balance, (...) impressive, with researchers developing new paradigms" and now there is an agreement that the ability to remember to perform delayed intentions might occur due to top-down self-reminders or to a bottom-up reactivation in response to cues. It is also known that people seem to adjust their approach in response to different sorts of manipulations and these strategies have distinct behavioral and neural profiles: Strategic monitoring is cognitively demanding and interferes with OT processing, whereas spontaneous retrieval has the advantage of supporting PM without effortful processes. Apart from this, since PM is cue-dependent, as we will begin to make clear, processing a strong retrieval cue might spontaneously retrieve an old and irrelevant PM intention to consciousness, which may lead, in some situations, to PM commission errors. This issue has recently gained interest in PM research: How does our cognitive system deactivate PM intentions after they become no-longer-needed? The next section marks a comprehensive discussion of the theory behind these memory failures and its empirical support.

2.3. Intentions deactivation: An emerging field

> “Memory is impressive. People can recognize hundreds of pictures seen only once (Shepard, 1967) (...). And yet memory´s failures can be equally impressive.”
>
> (Marsh et al., 2008, p. 221)

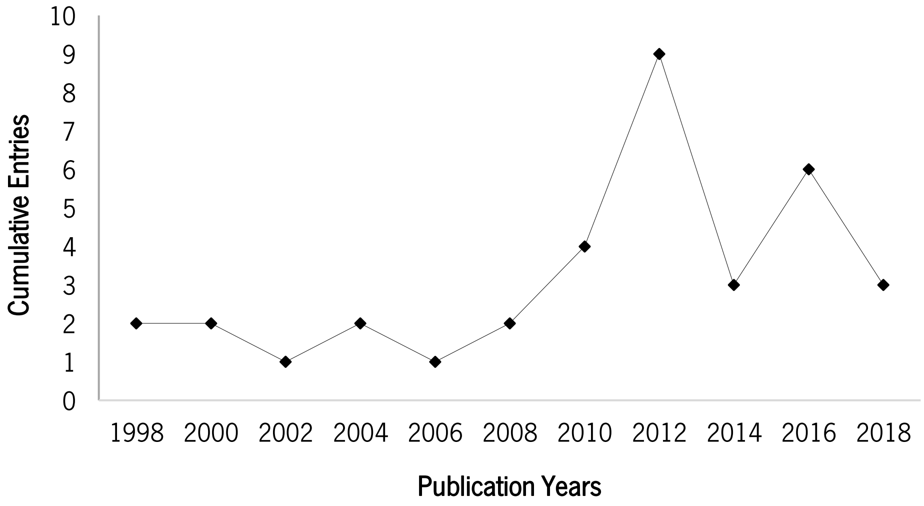
Until recently, PM field has nearly exclusively focused on omission errors such as forgetting to take one´s medicine. An important and unanswered question concerns how we deactivate, or otherwise forget, PM intentions when there is no need to do so. Curiously, in his book *The Seven Sins of Memory*, Schacter (2001) already stressed that persistence is a memory problem in which memory is compromised by incorrect knowledge that should be forgotten but it is not. The incorrect information may continue to infiltrate our stream of thought and distort memory, decision making, and thinking in general. In this context, in recent years, PM researchers have become increasingly interested in a different type of error: PM commission errors. This memory failure occurs if we erroneously perform a PM intention when it is no-longer relevant and it has been clearly illustrated by examples of medication double-dosing (Kimmel et al., 2007).

In this section, we aim to give an updated overview of the experimental procedures and main results of PM deactivation research and, then, introduce two dominant accounts for the occurrence of PM commission errors.

Although PM deactivation enables us to flexibly adapt to changing contexts and goals, there is compelling evidence that, in some occasions, intentions remain active. Both younger and older adults might be slower in response to PM cue trials that previously signalled the opportunity to retrieve an intention (termed *intention interference*) or even made commission errors. That is, participants might fail to forget (i.e., "turn-off") an irrelevant intention and erroneously execute the PM action (Anderson & Einstein, 2017; Boywitt et al., 2015; Bugg & Scullin, 2013; Bugg et al., 2013, 2016; Scullin & Bugg, 2013; Scullin et al., 2013, 2020; Schaper & Grundgeiger, 2019; Walser et al., 2014, 2017; see Möschl et al., 2020 for a systematic review). Interestingly, the continued retrieval of an irrelevant intention is also supported by evidence of repeated thoughts about a finished PM task after encountering associated (but no-longer relevant) PM cues (Anderson & Einstein, 2017) as well as brain activation during these specific trials in areas that are also activated by PM cues when PM tasks are still active. For example, a neuroimaging study demonstrated a pattern of activation thought to mobilize reactive control due to the conflict between the OT and the PM cue response (namely, in the anterior cingulate cortex and transient activation of rostrolateral PFC; Beck et al., 2014).

FIGURE 8

The number of publications on PM aftereffects per 2-year interval since 1998. Data were derived from Web of Science, Pubmed, Psycarticles, and Psycinfo database search for journal articles with the keywords "PM commission errors" or "PM aftereffects" occurring in the title or abstract.



These observations have fueled a growing body of literature, aiming to understand the mechanisms underlying this kind of PM failures and identify factors that modulate intention deactivation. As can be seen in Figure 8, the number of publications on this issue has shown a noticeable growth since 2012.

To foreshadow, since 2000, two seminal articles emerged, fostering the investigation on PM commission errors. Scullin et al. (2009) made the first contribution by providing evidence that PM intentions may not be easily deactivated (or otherwise efficiently forgotten). The authors asked participants to execute a PM task alongside an ongoing image-rating task and then told them that the PM intention was either suspended (i.e., they must perform the task again at a later time) or finished (i.e., the PM task was completed) before completing a LDT (with irrelevant PM cues). Although it was not the case for completed PM tasks, PM cues spontaneously trigger remembering of the suspended intention. A second and well-recognized investigation, in 2013, was conducted by Bugg and Scullin in which they showed that, under some circumstances, both younger and older adults effectively make commission errors. Next, we will detail the commission error paradigm proposed by these authors, which have been recognized and acknowledged, offering interesting and new insights about prospective remembering.

2.3.1. **Commission errors paradigm**

Under laboratory conditions, researchers have attempted to study PM commission errors using two forms of *event-based PM paradigms* (i.e., with semantic associates of PM cues or with no-longer relevant PM cues)*.* They all follow a common logic in which a PM intention is encoded, maintained, and actively pursued during an active-PM phase, and a subsequent finished-PM phase in which PM aftereffects are measured. Most of these studies used paradigms with no-longer relevant PM cues which can be divided into three main subtypes: (1) *repetition-error paradigm*, (2) *repeated-cycles paradigm*, and (3) *PM commission error paradigm*. The procedure of each paradigm is detailed in Table 1.

Specifically, in the repetition-error paradigm, participants are asked to remember to press a key once and only once during an OT. In the repeated-cycles paradigm, at the end of the first block, the PM task is declared completed but this procedure is repeated for several blocks. Hence, in both cases, participants must constantly use their output monitoring and memory updating of the status of the to-be-performed intention (Einstein et al., 1998; Marsh et al., 2002, 2007). Results reveal that younger adults more frequently claimed that they had responded to a previous PM cue (i.e., make an omission error) while older adults were more likely to forget they had already responded to those cues (i.e., make commission errors). Theoretically, older adults had more difficulty monitoring their output (e.g., maintaining that they had pressed *F1*) than younger adults, a skill that likely requires cognitive resources (Koriat et al., 1988). Thus, although some evidence for PM commission errors occurrence, in these studies participants must flexibly control attention to detect PM cues as well as engage controlled retrieval of previous actions every time a particular cue appears (Ball et al., 2018).

Table 1

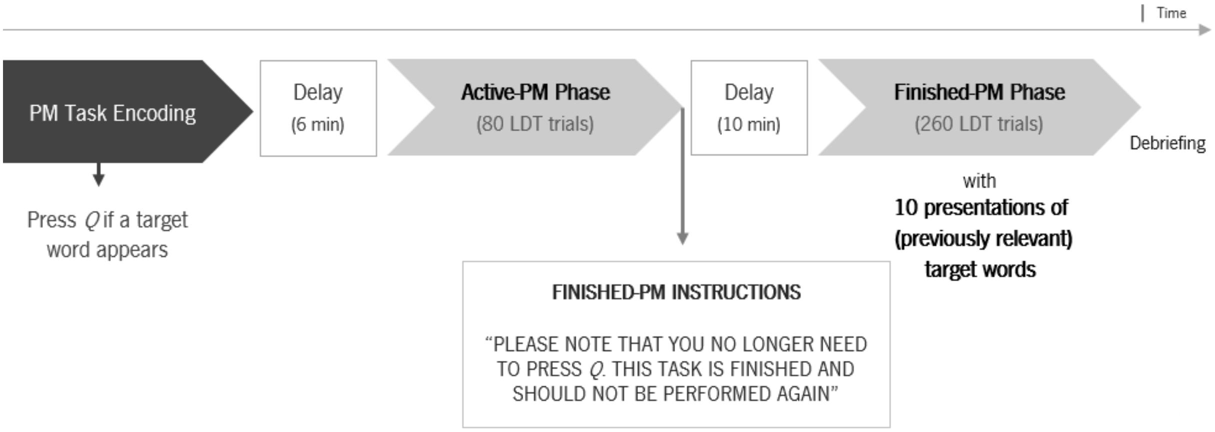
Summary of PM aftereffects paradigms and related procedures (adapted from Möschl et al., 2020).

Paradigm	**Procedure**
Event-based PM paradigms	
With semantic associates to PM cues	Participants perform an EBPM task that requires detecting a combination of pictures during an image-rating task, followed by a LDT. PM aftereffects are assessed by comparing lexical decision RTs between words semantically related to the PM cue (e.g *glasses* - professor, read) and unrelated words (e.g., food, plastic).
With no-longer relevant PM cues	
Repetition-error paradigm	Participants are asked to remember to press a key once and only once during an OT. Or to make a standard PM response upon the first presentation of PM cues (e.g., animal names) and to press a different response key when a PM cue reappeared. If they make a correct response to the first presentation of a given word, a subsequent "repeat" response reflects a correct memory for having completed the intention the first time the word was encountered. By contrast, a "first" PM response reflected a commission error.
Repeated-cycles paradigm	In the active phase, a PM intention is firstly encoded (e.g., press the spacebar whenever they encounter a specific symbol around a digit) and, at the end of the first block, the PM task is declared completed. This procedure repeats in the subsequent blocks with a new, active PM intention being encoded at the beginning of each block. Aftereffects are assessed by comparing OT performance between no-longer relevant PM trials and control trials.
PM commission error paradigm	Participants perform a single active phase, followed by a single finished phase. In the active phase, they are additionally instructed to press the *Q* key whenever they see a specific word (PM cue) presented on a salient background. Then, they are instructed that the PM task has been completed and should not be performed again in the finished phase. Commission errors occur if they continue to press *Q* there is no need to do so.

Bugg and Scullin (2013) explored whether this phenomenon could be observed after all intentions are completed. They followed the canonical structure of previous PM studies (see Figure 9): In Phase 1, participants are asked to press a particular key (e.g., the key *Q*) when an infrequent PM cue (e.g., the word *dancer*) is presented during an OT (e.g., a LDT). Upon this active-PM phase, participants are told that the PM task is finished and no-longer needs to be performed. Critically, during the finished-PM phase that follows, they perform another OT in which unexpected former cues occur as OT stimuli (Phase 2). Researchers initially evaluated whether participants responded slower to (re)presented PM cue trials relative to control trials (i.e., trials matching PM cues characteristics but never serves as retrieval cues), inferring that slower RTs to target trials indicated a spontaneous (but erroneous) PM retrieval of the intention (e.g., Cohen et al., 2005; Scullin et al., 2009). In subsequent work, they also observed that, under some circumstances, participants made commission errors (i.e., pressed *Q* in response to *danc*er). The critical difference between this procedure and the previous output-monitoring procedures – in which participants must actively monitor their output to update memories of cues – is that it allows examining whether a commission error could occur after all PM intentions were fulfilled. Until then, PM commission errors have never been examined in this manner.

FIGURE 9

Schematic illustration of Bugg and Scullin´s (2013) PM commission error paradigm.

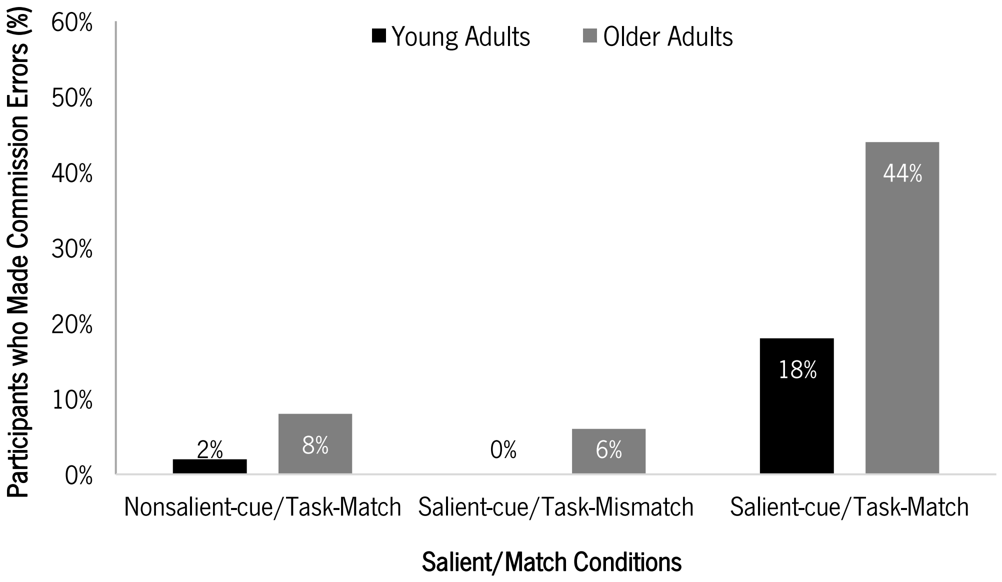


In their study, Scullin et al. (2013) explored the components that may trigger intention retrieval and a PM deactivation failure by examining three experimental conditions that differed in cue salience and whether the OT employed during the initial active-PM phase overlapped with that which was used during the finished-PM phase (non-salient cue/task-match; salient-cue/task-match; salient-cue/task-mismatch). In particular, in the salient conditions, a colored background screen (e.g., red) accompanied PM cues in the active-phase and again in the finished-phase in which PM cues were no-longer relevant. In the OT-match conditions, the OT in both Phase 1 and Phase 2 was a LDT, whereas in the mismatch-task condition, Phase 1 was an image-rating task and Phase 2 remained a LDT. They reasoned that commission error incidence should be greater with salient PM cues and matching the OTs between Phases 1 and 2. Another critical prediction was that if spontaneous retrieval is relatively preserved in older adults, then they should perform the initial PM task as well as young adults. Yet, as they are less likely to effectively exert executive control to override a previously associated PM response, they should demonstrate an increased tendency to make PM commission errors. The results are displayed in Figure 10.

As predicted, the analysis of the proportion of commission errors (i.e., *Q* presses to PM cues divided by the total number of these trials during Phase 2) showed that these failures were most likely with a salient cue and when the OT was the same in Phase 1 and Phase 2. Importantly, this paper provided an important contribution by showing the influence of environmental features, such as a combination of a salient cue and an OT match, in stimulating spontaneous retrieval and, consequently, increasing commission error risk. Outside the lab, the implication is that cues that are likely to capture attention (e.g., a new medicine box) and which are present in contexts where the PM intention has previously been performed (e.g., kitchen table) may be especially likely to stimulate retrieval of a previous intention (e.g., take medicines) regardless of whether retrieval is no-longer-needed (e.g., because they are no-longer prescribed). Notably, these factors can explain why some studies did not observe PM aftereffects even though their PM task features are thought to encourage spontaneous retrieval. For instance, this happens when PM cues were non-salient and require additional processing than ongoing-task trials (Cohen et al., 2017; Möschl et al., 2017; Walser et al., 2012) and aftereffects were measured during a subsequent mismatching condition (Anderson & Einstein, 2017; Beck et al., 2014; Bugg et al., 2016; Möschl et al., 2017; Pink & Dodson, 2013; Scullin et al., 2009, 2011; Walser et al., 2014).

FIGURE 10

Percentage of younger and older adults who made commission errors in the finished-PM phase across cue salience and OT conditions (adapted from Scullin et al., 2012).



In another study, Scullin et al. (2012) showed that older adults had a higher risk of responding to PM cues when it is no-longer appropriate to execute the intention than younger adults (not only in terms of the mean proportion of commission errors but also in the percentage of participants who made at least one commission error). Given age-related preservation of spontaneous retrieval (Jennings & Jacoby, 1997; McDaniel & Einstein, 2011), but impairment in deleting (inhibiting) irrelevant information (Lustig et al., 2007), their study also emphasizes the point that individual differences in executive control integrity could influence commission errors occurrence. First, they found that older adults, who have compromised cognitive inhibition, have more difficulty deactivating finished intentions (see also Scullin et al., 2011). Besides that, they observed that individuals with low scores on executive function tests (i.e., Stoop interference, Trail Making Test, and Wisconsin Card Sorting Task) were more susceptible of making commission errors than individuals with higher executive function scores. Recent findings provided additional support for this idea. For example, there is a higher commission error risk for patients with Alzheimer´s disease (El Haj et al., 2018) and if PM tasks are needed to be briefly suspended (Boywitt et al., 2015).

Together with the results outlined above, Scullin and collaborators suggested that "commission errors occur when a completed intention is spontaneously retrieved and individuals fail to suppress executing the intention" (Scullin et al., 2012, p. 52). Thus, the authors offered a preliminary theoretical explanation for commission errors that was carried out in the following studies.

2.3.2. **Moderators of intentions deactivation**

The investigation on PM commission errors is still emerging. This section will review the extant literature exploring the cognitive mechanisms thought to influence PM deactivation (see Table 2). We discuss some of the main research findings mostly obtained with the commission error paradigm and how they inform this complex mechanism. At the end of this section, we briefly introduce open questions regarding theoretical views about this memory failure as well as the role of interference in PM deactivation, underscoring that both are fruitful research directions.

2.3.2.1. ***Increasing commission error risk***

Having provided initial evidence that an intention could be spontaneously retrieved (i.e., especially when salient contextual cues and task processing demands served as reminders of the PM intention) and erroneously performed due to executive control failures, Scullin and colleagues suggested a dual-mechanisms account and lift the veil for their next steps. Critically, these authors are assuming that a spontaneous retrieval underlies PM commission errors. An alternative view is that PM retrieval of irrelevant intentions is not spontaneous but rather due to continuous monitoring for PM cues associated with previously formed intentions (Smith, 2003); or, in line with the delay theory described earlier, because individuals strategically slow down their OT responses for increasing the chance of detecting the cue (Heathcote et al., 2015; Strickland et al., 2018). In other words, from these alternative perspectives, commission errors would result from a top-down controlled monitoring process or due to a strategic response slowing even after intention completion, respectively. Yet, in light of the cue-dependent nature of episodic memory (Tulving & Pearlstone, 1966), although spontaneous retrieval may be beneficial as it offers another mechanism for PM retrieval besides monitoring, it may continue to trigger PM intentions after processing an (irrelevant) retrieval cue (Cohen et al., 2005; Scullin et al., 2011).

It seems to be the case. In 2013, Scullin and Bugg run a new experiment that evaluated if the increase in the susceptibility of accidentally executing a no-longer relevant intention is especially prominent in conditions that have been shown to stimulate spontaneous PM retrieval. Here, the procedure was the same as the standard paradigm (Figure 9), however, a no-PM control group was added, in which participants never held a PM task. Until then, no study has used a between-subjects, no-PM control group to determine whether participants were monitoring for their PM intentions. The theoretical relevance here is that the spontaneous retrieval view recognizes that commission errors can occur in the absence of monitoring. One outcome was then hypothesised: Participants in the experimental condition should respond (RTs) to PM cues similar to those in the no-PM control condition – and in that case, results would suggest a more automatic PM retrieval and the monitoring hypothesis will be weakened.

The data analysis was conducted with a more refined approach by examining RTs to the 20 trials preceding PM cues (rather than averaging across all trials; Smith, 2003; Smith & Bayen, 2014). There were two key findings: (1) Participants who held a PM task and the control no-PM condition did not differ on their OT performance and (2) participants who did versus did not make commission errors also have a similar OT performance – that is, there was no behavioral monitoring. This finding supports the idea that individuals seem not unnecessarily engage monitoring in a context in which a PM task needs not to be performed (e.g., Knight et al., 2011; Marsh et al., 2006). Additionally, this study provided an important contribution as it showed that the length of the delay interval between the active-phase and the occurrence of PM cues in the finished-phase does not affect PM commission error risk. In other words, participants in the long delay condition were equally likely to make a commission error than those in the short delay condition.

Along with the previous studies, there was further evidence favouring of the dual-mechanisms predictions by eliciting spontaneous PM retrieval. Specifically, Bugg et al. (2013) strengthened PM encoding by using an implementation intention strategy, which is known to foster a stronger association between the PM cue and the associated action, compared to a standard encoding. Applying Deese´s (1959) work on backward associative strength (Roediger et al., 2001, as cited by Bugg et al., 2013) to the PM commission errors paradigm, the authors reasoned that the encoding manipulation should affect the vulnerability for intentions spontaneously pop into mind when PM cues (no-longer relevant) are encountered. To this end, only in the experimental condition, participants repeated "When I see *corn* or *dancer* on a blue background, I will press the *A* key" three times and then spent 30 s mentally imagining completing the intention. Results showed that commission error risk was significantly higher in the implementation intention condition than in the standard condition. This finding suggests that using an implementation intention strategy pose difficulties in the deactivation of intentions no-longer-needed (Bugg et al., 2013).

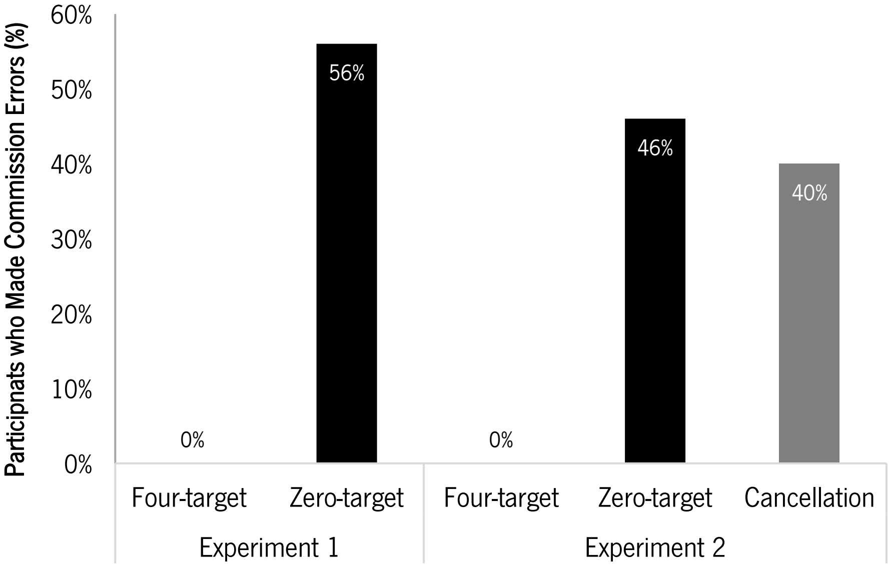
Moreover, a few studies have examined if participants are inclined to perform a previously relevant PM task that they never had the opportunity to fulfill. For this purpose, Bugg and Scullin (2013) made a crucial manipulation: Participants encode the PM intention to press the *Q* key in response to target words, but these PM cues appeared four times during the active-PM phase in the *four-target condition* while they are never presented in the *zero-target condition*. As in the standard paradigm, PM commission errors were compared between groups. The results are presented in Figure 11. Surprisingly, the analysis reveals that approximately 50% of younger adults make PM commission errors when they never responded to a PM cue (zero-target condition). In contrast, even though it may seem intuitive that a PM task executed multiple times would be harder to deactivate, no commission error was committed when the intention had been fulfilled (four-target condition). The same pattern of results was found with older adults (Bugg et al., 2016, Experiment 1). This means that it appears just as easy to remember intentions we intend to do but never did even when we are told we can forget them.

However, the authors questioned if the reported effect could be a consequence of anticipatory monitoring in the zero-target condition. To tackle this question, a cancellation control group was added, in which participants did not have the opportunity to perform the PM task during the active-PM phase as the intention was cancelled immediately before that phase began. The rationale behind this experiment was that, in the cancellation condition, participants should exhibit less anticipatory monitoring (i.e., as there is no need to maintain the intention in WM while expecting searching for PM cues; Smith, 2003) compared to the zero-target condition. Thus, if anticipatory monitoring is responsible for the high vulnerability of making commission errors in Experiment 1, then they should be significantly lower in the cancellation condition compared to the zero-target condition. On the contrary, they reasoned that this memory failure should not differ across conditions supporting the idea that this error occur due to the absence of intention fulfilment.

Results were in line with this later assumption: There was evidence of less strategic monitoring in the cancellation than in the zero-target condition, but commission errors were similar across groups. Although it was not the case for completed intentions, it may be difficult for younger adults to deactivate a suspended intention after never performing it. Recently, Streeper and Bugg (2020) provided support for an *episodic retrieval account* suggesting that performing an intention aids its deactivation because of the episodic traces (of prior responding) an individual has when encountered the PM cue. Put differently, this would allow participants to associate a stop-tag with that concrete episodic experience or it may help to dissociate the cue-action link. This interpretation is based on the finding that responding to the target words multiple times (as in the four-target condition) strengthened the stimulus-response link for that target than responding just once (as in the one-target condition). The other possibility is the Zeigarnik account according to which commission errors occur due to the perseveration of PM intentions that have never been fulfilled. However, results reveal that the number of commission errors were not lower in the four-target condition compared to the one-target condition as expected since both involved partial completion of the PM task.

FIGURE 11

Percentage of participants who made commission errors in the finished-PM phase as a function of condition in Experiment 1 and 2 (adapted from Bugg and Scullin, 2013).



Taken together, the abovementioned findings summarise two important aspects of the dual-mechanisms account: Prospective memory commission errors can result from a combination of spontaneous retrieval of the intention in an inappropriate context and failed cognitive control (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2012). The second idea is that whether an erroneous spontaneous retrieval result in a commission error would be partially predicted by executive control, such as response inhibition processes that may override the prepotent tendency to press *Q* when the associated PM cue is shown. Alternatively, according to the output-monitoring view, participants do not sufficiently encode that the PM task has already been performed and is finished, therefore leading them to repeat the PM action when they later process the target cue (Koriat et al., 1988; Marsh et al., 2002, 2007). However, in a recent neuroimaging study, a higher number of PM commission errors was associated with larger medial temporal lobe volume/hippocampal grey matter volume supporting the dual-mechanisms hypothesis than the prediction of highest failures in individuals with smaller medial temporal lobe volume of the output monitoring theory.

However, the occurrence of PM commission errors was only correlated with inhibition abilities in older adults. Moreover, those adults who made commission errors did not have reduced inhibition scores relative to those who did not make a commission error (Scullin et al., 2012). In addition, Schaper and Grundgeiger (2017) found that younger adults make commission errors in a delay-execute paradigm. This procedure mimics real-life situations in which people commonly retrieve a PM intention, but its execution needs to be delayed because of the demands of the OT at hand. Therefore, the authors introduced a delay of 45 s after the PM cue appear and the opportunity for the associated response, during which participants continued performing the ongoing activity. They observed that commission errors still occur despite the retrieval and execution of the intention has been separated by a delay, suggesting that PM retrieval seems to result in a deliberate decision to execute the PM response.

A few years later, Schaper and Grundgeiger (2019) suggested that failed suppression of the PM intention is not essential for commission errors to occur which was nicely illustrated in their next study. The authors gave participants additional time to think and suppress the erroneous PM response by introducing a response lag condition in which they had to delay their response to OT trials for 1 s (Experiment 1) or 2 s (Experiment 2 and 3); and, a pause condition during which the delay occurred between OT trials (i.e., participants immediately respond to the OT and a black screen appeared for 1 s after they made an input). Their reasoning was the following: Participants should exhibit less commission errors when more time has been given to suppress the PM response compared with a condition where they could make their response immediately. Yet, results showed that providing time for response suppression after encountering a no-longer relevant PM cue did not reduce commission error risk. Thus, the authors emphasised the need for some theoretical adjustment to account for their findings. In that sense, they suggested a modified version of the dual-mechanisms theory claiming that the erroneous execution of an irrelevant intention may be formed after spontaneously retrieving the PM intention when encountering associated (but no-longer-needed) cues but rather persist over delays between intention formation and its execution (i.e., since commission errors were only made after the response lag had occurred). In other words, according to this assumption, if the person fails to evaluate the PM cue as no-longer relevant correctly, the retrieved intention is directly implemented to be executed. Conversely, it will be tagged for suppression if the previously relevant cue is correctly processed, which means with the knolewdge that the intention should not be executed.

Table 2

Moderators of intentions deactivation.

Conditions under which pm deactivation becomes difficult:

1. Salient PM retrieval cues
2. Remaining in the context in which the PM task was completed
3. Strong link between the PM retrieval cue and the intended action (e.g., trough implementation intention encoding or repeatedly performing an intended action)
4. High overlap between OT processing and PM task processing (i.e., with focal PM intentions)
5. PM task is not performed after becomes irrelevant and no-longer-needed
6. Failure of cognitive control over intention execution

In general, under some circumstances, our cognitive system may not deactivate or inhibit intentions representations after completion. Tackling this issue may further our theoretical understating of PM deactivation and our knowledge about the conditions under which these commission failures are particularly likely and individuals who are at most risk to experience that. Together with the fact that PM may not decline during the retention interval and that an irrelevant intention might remain active and accessible for a minimum of 48 hours (Dasse & Scullin, 2016), it stands to reason that a fruitful avenue for PM research is to explore which variables may prevent this memory failure.

2.3.2.2. ***Decreasing commission error risk***

Individuals complete many intentions every day, so an inability to forget these finished (or cancelled) tasks might interfere with daily functioning. To date, however, only a few studies examined which factors decrease the likelihood of making PM commission errors.

First, Anderson and Einstein (2017) evaluated the impact of three strategies (one-off, clarity, and new-PM task). After performing the active-PM phase, participants in the *one-off condition* were informed that they would see one PM cue and the PM task would be finished once they have responded to that cue. The objective was to highlight PM intention fulfilment and remove any confusion about whether the PM task was finished in the experiment´s remaining. The finished instructions were strengthened in the *clarity condition* by asking participants to write down and repeat the experimenter´s instructions. In turn, those participants assigned to the *new-PM task condition* encoded a new PM intention to perform during the finished-PM phase. Nevertheless, none of the abovementioned strategies significantly reduced commission error risk (14% in the one-off, 14% in the clarity, and 10% in the new-PM task condition).

In this respect, in 2017, Walser et al. investigated whether the similarity between a previous intention and a new-PM intention to perform during the subsequent finished-PM phase affects PM deactivation. The main finding (Experiments 1 and 2) was that there was more intention interference (i.e., the finding that participants are slower in response to PM cue trials that previously signalled the opportunity to retrieve a relevant intention as compared to control trials) when the PM cue category matched across PM tasks. In contrast, the similarity of the PM response did affect PM commission error risk. In another experiment, the authors examined the role of a monitoring account (i.e., "attentional dependency") and an overwriting account of intention interference by including a new, OT only (control) condition that did not receive a new-PM task. The authors reasoned that, if the monitoring account has merit, intention interference would be reduced in the OT only condition because there is no new-PM task to increase monitoring for any cue in the finished-PM phase. In turn, if the overwriting was valid, then intention interference should be found in the OT only condition because there is no new-PM intention to overwrite the previous intention. Supporting the monitoring account, the results showed no intention interference for the OT only condition, but there was an intention interference in the conditions in which the PM cue category matched across phases (i.e., facilitates deactivation).

Walser et al. (2014) also manipulated the frequency of PM cues presentation (4 vs.12 times), and the finished-PM phase length (14 trials vs. 48 trials). Their results indicated that repeatedly encountering a previously relevant PM cue serves to facilitate deactivation, while delay itself does not reduce intention interference (see also Walser et al., 2012). The idea is that with each encounter, the PM cue becomes more associated with the OT, reducing the strength of the association between the original intention/response. In 2016, Bugg et al. exhaustively explored two more strategies that could be working for that purpose (i.e., preparatory instructional and forgetting-practice strategies). As in the standard paradigm, a PM task was given and was declared completed after the active-PM phase. In Experiment 2, both young and older adults (under zero- or four-target cue presentations) were instructed that they would see irrelevant PM cues in the finished-PM phase and were encouraged to prepare themselves not to respond. Conversely, they did not use this strategy in the control condition. Even though fewer older adults made a commission error relative to the control condition, this strategy did not lead to a low level of commission error rates. Then, to test an alternative idea, in Experiment 3, the authors used a forgetting practice strategy in which participants practiced physically withholding their response when they saw irrelevant PM cues before beginning the finished-PM phase. The idea was that if this PM cue-withholding response link was practiced instead of just instructed, it would strengthen the link between the PM cue with the response of stopping. Their findings indicated that the forgetting-practice strategy brought commission errors to the floor for older adults, suggesting a translational value of this strategy.

Overall, PM commission errors do not occur due to poorly understanding of the task instructions or continued monitoring but rather by a continued spontaneous retrieval triggered by irrelevant PM cues. Previous work consistently shows that these failures are modulated by the same variables that modulate retrieval of intentions when they are still active (Möschl et al., 2020). As noted, commission errors tend to occur under conditions that foster spontaneous retrieval such as when there is a strong association between PM cues and intended actions, a high overlap between the processing needed for detecting a cue and execute the OT, and a context match between the tasks during which an intention is actively pursued and the tasks during which it is no-longer necessary to execute the PM task. As stated, some key factors seem to affect PM retrieval suggesting that "intention deactivation moves along a continuum between a full re-activation and a full deactivation or inhibition" (Möschl et al., 2020, p. 27)

Until now, it seems that several of strategic and automatic mechanisms may be engaged upon an intention is completed or became no-longer-needed (see Bugg & Streeper, 2019). First, one may cease monitoring processes (Scullin & Bugg, 2013). Second, a stop-tag may be associated to the PM cue, such that participants encode not to perform the action when they saw irrelevant PM cues again (Bugg & Scullin, 2013). Third, once an individual realizes that an intention is completed, they may engage inhibitory processes to attempt to supress activation of that intention or mentally prepare themselves for not performing it again (Bugg et al., 2016). Finally, there may be a relatively automatic decrease of the level of PM cues activation or on the association between the cue and the PM response, thereby reducing discrepancy or reflexive processes, respectively (Scullin et al., 2009).

In brief, in daily experiences, individuals must focus on the tasks at hand and in tasks to perform in the future without being distracted by recollecting intentions that became no-longer-needed. Yet, the reviewed studies were especially compelling showing that PM intentions remain active under some circumstances. Intentions deactivation may fail or take time and, consequently, they may continue residually active or even be retrieved and erroneously executed. In the next point, we will discuss how cognitive control availability could affect the occurrence of PM commission errors and the potential relevance of interference on PM deactivation, summarize what we now about these issues so far, and which open questions we will address in this dissertation.

2.4. A critical analysis on the reviewed literature

As reviewed in the present chapter, a great body of PM research has fleshed out researchers' knowledge about important issues that have emerged. A fundamental issue that, so far, has yielded little information and motivated the current studies concerns the ability to successfully deactivate a previously PM intention which became no-longer-needed. Yet, understanding PM commission failures is of great importance considering both the scientific interest in false memories and its societal implications. At this point, after discussing behavioral data and theoretical views on this topic, we present some considerations that emerged from the existing evidence, aiming to provide a theoretical framework for the experimental studies reported in this dissertation.

2.4.1. **Is cognitive control a key feature to understand PM commission failures?**

As stated, prospective remembering involves cognitive control resources for monitoring time or recognizing a cue in the environment for acting upon the intention at the appropriate time (Einstein & McDaniel, 1996; Ellis & Kvavilashvili, 2000; Ihle et al., 2019; Schnitzspahn et al., 2013; Settle et al., 2017; Smith & Bayen, 2014). Likewise, according to the dual-mechanisms theory, PM commission errors might occur, in conditions that promote spontaneous retrieval, due to a failure to deactivate or inhibit a an irrelevant intention via a cognitive control mechanism (Bugg et al., 2016; see also Schaper & Grundgeiger, 2019). Notably, our cognitive control ability is a key element to understand adaptive goal-directed behavior and is broadly corroborated by prefrontal brain networks which selectively attend and maintain information, inhibit irrelevant stimuli and impulses, and evaluate and select the appropriate responses (Miller & Cohen, 2001; see also Miyake et al., 2000). More specifically, inhibitory control is one important component of this control system and is crucial to suppress prepotent or inappropriate actions and thoughts (Aron et al., 2014). Hence, the availability of cognitive control resources (namely, inhibitory mechanisms) may be a potentially relevant factor underlying PM deactivation.

Some findings support this idea. More broadly, past work has shown that cognitive control over memory can affect retention and as well as suppression of memories (Benoit & Anderson, 2012; Wierzba et al., 2018). An essential claim is that inhibitory control processes modulate the state of traces in memory by being flexibly targeted at different stages of the mnemonic processing. For example, at the retrieval stage, once a memory trace has been formed, one can try shifting the mental context or avoid cues that remind one of this trace; or, when exposed to a cue, try to suppress reflexive retrieval, making the remembered item less accessible (Baddeley et al., 2015; Benoit et al., 2015). Regarding PM commission errors, they are more frequently observed under cognitively demanding conditions. For instance, some studies showed that participants are more prone to make a commission error when the deactivation demands are increased due to a implementation-intention strategy used at encoding (Bugg et al., 2013), or when there is a lack of retrieval opportunities for executing the intention when it is still active (Bugg & Scullin, 2013; Bugg et al., 2016). Moreover, the frequency and magnitude of PM commission errors is more pronounced in older adults compared to younger adults possibly due impaired cognitive control functioning in older adults (Bugg et al., 2016; Hasher et al., 2007; Lustig et al., 2007; Scullin & Bugg, 2013; Scullin et al., 2012).

However, from our perspective, a systematic examination of the role of the OT demands on prospective remembering is lacking. Furthermore, a potential role of cognitive control resources on PM deactivation was not directly tested, and little is known whether PM commission errors are susceptible to the availability of these resources when (irrelevant) PM cues are encountered. To the best of our knowledge, only two studies explored this issue (Boywitt et al., 2015; Pink & Dodson, 2013), but using a paradigm in which there is no-longer any PM task to perform in the future is essential to avoid the potential confounds raised by source monitoring failures.

The general idea that we advance here is the following: Considering the role of cognitive control in generating and maintaining appropriate task goals and suppressing task goals that are no-longer relevant (Cowan, 2005, 2017; Engle et al., 1995; Engle & Kane, 2004; Miller & Cohen, 2001; Posner & Snyder, 2004), a critical test to this view would be to directly examine PM deactivation under variations in the cognitive control demands of the OT (i.e., whatever activity is being performed when an irrelevant PM cue appears). Having this in mind, we will suggest that PM deactivation would more frequently fail if our cognitive control resources are taxed by demanding ongoing activities when a (no-longer relevant) PM cue reappears. The idea is that if fewer inhibitory mechanisms are available to inhibit an irrelevant PM representation when the cognitive system is subjected to incremental and concurrent loading of demanding activities, PM deactivation will suffer.

Additionally, in line with the dual-mechanisms theory (Bugg et al. 2016), even after an intention is completed, processing a retrieval cue may cause spontaneous retrieval of it. Thus, a similar investigation that sheds light on the type of PM retrieval (spontaneous vs. strategic) underlying commission errors is warranted. Thereby, in Chapter 3 we initially provide an up-to-date review of the main results of the influence of OT load on prospective remembering and, in Study 1 (Chapter 4), we will provide a direct test of the involvement of cognitive control resources in PM deactivation.

2.4.2. **The need for studying interference on PM deactivation**

Life is busy and keeping track of what we are doing and what we do not have to do anymore can be challenging. Even though the executive control processes signal current task goals that are no-longer necessary and guide the system to implement newly relevant goals, it is arguable that forgetting might help to inhibit/suppress irrelevant prospective memories (Dewar et al., 2007; Walser et al., 2016; Wixted, 2004). Moreover, it is also worthy to note that the deactivation of irrelevant intentions does not simply rely on the availability of time (Scullin & Bugg, 2013; Walser et al., 2014). Surprisingly, the role of forgetting in PM deactivation has not been thoroughly studied so far regarding the specific role of the interference mechanisms. To foreshadow, in this dissertation, we suggest replacing the emphasis on the question of how to reduce forgetting with the question: Could PM intention deactivation benefit from an interference effect as forming new memories may interfere with the retrieval of older memories?

Several studies have been dedicated to exploring the robustness of stored information to decay and interference. As reviewed earlier, forgetting is in part assumed to result due to interference from distracting elements, either being presented before learning (i.e., proactive interference) or after learning (i.e., retroactive interference; Underwood, 1957; Müller & Pilzecker; 1900; Jenkins & Dallenbach, 1924). Interestingly, newer perspectives belie the common assumption that forgetting is a negative outcome. A bulk of behavioral and neuroimaging studies (Anderson & Hanslmayr, 2014; Benoit & Anderson, 2012; Dewar et al., 2007; Wixted, 2004, 2010) brought some important new insights showing that inhibitoy mechanisms may be engaged either during memory encoding or retrieval to limit retention of unwanted memories, for example (e.g., Anderson & Hanslmayr, 2014; Benoit & Anderson, 2012).

Based on these assumptions, our brain needs mechanisms to reduce everyday distractions so that appropriate information is retrieved, and appropriate tasks are performed. Thus, we will further suggest that this could be how we update our PM demands, such that moving to address a new intention help to deactivate/inhibit an old-PM memory trace, thereby reducing commission error risk. Indeed, there are only a few studies addressing whether a new-PM task representation might help to deactivate older prospective memories (Anderson & Einstein, 2017; Walser et al., 2012, 2017), which claim for further investigation. We will explore this possibility in Study 2 (Chapter 4).

In sum, we hope that combining information regarding the variables that might modulate intention deactivation will offer a more comprehensive understanding of the cognitive mechanisms involved in prospective remembering. The presented considerations will steer the reader in the main goals of this dissertation presented below.

2.5. Research aims of the current dissertation

To understand human memory, we must understand memory´s successes as well as its failures. In this sense, the literature reviewed in this chapter led to some considerations regarding gaps in PM deactivation research motivating the studies presented in this dissertation. As so, three main questions guided the studies conducted in this work:

1. What are the cognitive mechanisms behind PM deactivation? Does the availability of cognitive control resources influence the occurrence of PM commission errors?
2. What is the role of RI - that has long been held to cause forgetting – in deactivating intentions that become no-longer-needed?
3. Are irrelevant PM tasks spontaneously retrieved after encountering associated PM cues?

To evaluate the issues outlined above, we first provide a systematic overview of the role of OT load on prospective remembering (Chapter 3). Then, Study 1 (Section 4.1) aimed to extend previous findings suggesting that cognitive load plays an important role in deleting no-longer relevant intentions, by varying OT demands. Critically, we reasoned that PM commission errors should increase with an additional burden on cognitive control demands for OT processing in line with the dual-mechanisms account.

A second, largely neglected topic, refers to which factors might prevent PM commission errors. Study 2 (Section 4.2) was then conducted to reach our second goal. In Experiment 2, we tested if having to perform new intentions subsequently reduces the vulnerability of commission errors to deepening the role of interference mechanisms on intentions deactivation. Finally, in Experiment 3, we further examined the beneficial effect of RI by manipulating the amount of cognitive resources available by varying the cognitive load required by the filler task (right after an intention becomes irrelevant). To the best of our knowledge, this was not systematically explored in previous studies.

To test the evidence of a spontaneous PM retrieval, we also added a no-PM control group in Study 1 and 2. This allowed us to accomplish our third goal of examining the type of PM retrieval of irrelevant intentions. Noteworthy, the use of Bayesian data analyses methods along with the traditional null hypothesis significance testing allowed us to draw more appropriate conclusions from the collected data.

In conclusion, the present dissertation raises several questions. Tackling these may not only further our theoretical understanding of the deactivation of PM intentions but might also help improve predictions about the conditions under which PM aftereffects are particularly likely or may be prevented.

2.6. References

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CHAPTER 3

PROSPECTIVE MEMORY AND ONGOING TASK LOAD

The work presented in Chapter 3 was submitted for publication to an international peer-reviewed journal:

Matos, P., Pereira, D., Albuquerque, P. B., & Santos., F. H. (2020). How does performing demanding ongoing activities influence prospective memory? A Systematic review. *Advances in Cognitive Psychology, 16*(3), 268-290. https://doi.org/10.5709/acp-0302-0

CHAPTER 3. How does performing demanding activities influence prospective memory? A systematic review

3.1. Abstract

This paper is the first systematic review on the role of OT load in prospective remembering, which was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). Forty articles published between 1995 and 2020 were included. They evaluated PM performance (i.e., the ability to remember to execute a delayed intention) in adult samples aged between 19 and 50 years old when the PM cue appeared under cognitively demanding conditions. The results revealed that people are more likely to fail to remember to perform a delayed intention at the appropriate circumstances or time in the future when their cognitive resources are taxed by demanding ongoing activities. We conclude the review by highlighting that the degree of WM and executive resources seems to account for some of the discrepant findings and by proposing directions for future research.

Keywords: prospective memory; ongoing task load; omission errors; commission errors

3.2. Introduction

A common real-life demand is remembering to perform a specific task after some delay, termed PM (Einstein & McDaniel, 1990; Loftus, 1971). Prospective memories are often formed and executed during other ongoing activities. Therefore, one must frequently be able to manage PM requirements alongside the demands of those background tasks - which can be difficult if the OT processing is cognitively demanding. For instance, taking intermittent medicines while preparing a challenging meeting presentation while also attending a dental appointment in the middle of the afternoon. In such cases, the vital role of PM is most vividly evident when we experience some lapses, such as forgetting to take those medicines at the appropriate times.

Prospective remembering is effortful by recruiting cognitive resources that enable a complex balance between executing an intention and maintaining simultaneous OTs (Einstein & McDaniel, 1996; Ellis, 1996; Kliegel et al., 2002). More specifically, apart from episodic memory, WM and attentional processes may be required to recognize the appropriate contextual signals (e.g., seeing the medication box) without an explicit prompt to recall or act upon the intention. Moreover, executive functions such as inhibitory and task-switching abilities are essential to disengage from the OT and to interrupt it when the PM cue is detected or at the proper time (e.g., McDaniel et al., 1998; Schnitzspahn et al., 2013; Scullin et al., 2010). These processes are also required to manage PM processes within the context of concurrent activities that may offer distractions (Einstein & McDaniel, 1996; Ellis, 1996; Kliegel et al., 2002). In this sense, PM intentions may be recalled by the association to a specific event that acts as a cue (i.e., EBPM tasks; e.g., "I have to take the first shot with the breakfast"); or actively retrieved from memory at a specific time (i.e., TBPM tasks; e.g., "I have to take my allergy medicines at 4:30 p.m."). An extensive body of literature has investigated how do people successfully initiate EBPM and TBPM retrieval at the appropriate moment (e.g., Anderson & McDaniel, 2019; Einstein et al., 1998; McDaniel & Einstein, 2000; Shelton & Scullin, 2017; Smith, 2003; Smith & Bayen, 2005). Time-based PM tasks place greater demands on self-initiated processes compared to EBPM tasks as they require active monitoring for the passage of time.

Theoretically, the PAM theory holds that PM is dependent upon the engagement of strategic monitoring of the environment that supports the detection of associated cues (Smith, 2003; Smith & Bayen, 2005). In this view, the realization of delayed intentions seems to always require the allocation of controlled executive resources. In turn, the multiprocess theory suggests that an intention is spontaneously retrieved (Einstein & McDaniel, 2005) when the PM cue is salient (e.g., stands out perceptually from the OT stimuli) or focal (i.e., the PM cue information may be easily decoded from the OT when there is a processing overlap between the PM and the OT). For example, while doing an account report at work we may need to actively search for some cues or review our intentions periodically in order to remember to take medicines. At other times, catching sight of the medicine box acts as an environmental cue that triggers retrieval to take them. Still, it should be noted that even if the context may support an automatic noticing of the PM cue, resources are likely to be mobilized to select and interpret the contextually cued retrieved intention (Anderson et al., 2019; Einstein & McDaniel, 2010; McDaniel & Einstein, 2000).

Overall, WM and attentional executive resources are devoted to maintaining concurrent activities in an activated state, while evaluating whether the responses are appropriate for other intended tasks to properly retrieve and execute previous planned intentions (e.g., Basso et al., 2010; Cowan, 2017; Einstein et al., 1997; Engle, 2002; Kidder et al., 1997; Marsh & Hicks, 1998). Within a limited capacity system in which different goals may compete for resources, a good deal of research has considered that PM retrieval might be influenced by differences in OT demands. Simply put, the idea is that PM may be sensitive to the number of resources that are available when a cue is encountered. That is, when engrossed in a task, environmental cues that are related to previously established intentions are less likely to be noticed. For instance, we may not be able to monitor for the PM task to take medicines or spontaneously retrieve that intention to interrupt our ongoing activity to do so, because our cognitive resources are taxed by a challenging annual account report that we are required to complete at work.

When studying PM in laboratory settings, participants are commonly required to press a designated key whenever they see a target cue or after a specific period of time had elapsed while they are engaged in other ongoing activity (Einstein & McDaniel, 1990). To simulate highly demanding settings, the primary OT is made more challenging by increasing its difficulty (e.g., a *n*-back task with two levels of difficulty) or by introducing a secondary OT (e.g., signal the occurrence of two odd digits while performing a LDT; e.g., Kidder et al., 1997; Marsh & Hicks, 1998; McDaniel & Scullin, 2010). In this review, we assume that OT difficulty can be determined by the amount of cognitive resources required to perform it. The more the ongoing activities recruit cognitive resources, the fewer resources may be available to perform the PM task (Kidder et al., 1997; Marsh & Hicks, 1998).

Although it has been shown that individuals might be less likely to successfully remember to perform a PM task if they are busily engaged in demanding situations (e.g., Einstein et al., 1997, Experiment 1; Harrison et al., 2014, Experiments 2 and 3), some contradictory results have been reported (e.g., Harrison et al., 2014; Marsh & Hicks, 1998; Smith & Hunt, 2014). Importantly, examining the available literature hints at the idea that the mixed findings can be framed as differences in the amount of WM and executive resources that people must allocate to the OT and PM processing (Baddeley, 1996; Cowan, 2017; Engle, 2002). In other words, changing the difficulty of the OT via manipulation of short-term memory load without changing the executive control demands might be insufficient for affecting young adults' PM performance (Marsh & Hicks, 1998). In line with this, studies that manipulated the retrieval context by asking participants to decide whether the color of the words matches any of the colors shown on previous trials, or by asking them to monitor a string of background digits for the consecutive presentation of odd numbers showed that PM performance was not particularly disturbed in these conditions (e.g., Horn et al., 2011; Smith & Hunt, 2014; Smith et al., 2012).

Contrary to this, switching between task sets limits processing resources that are available for strategic monitoring, thereby reducing the likelihood of realizing a delayed intention (Marsh et al., 2002; McNerney & West, 2007). Likewise, in random generation tasks, people are required to monitor their output for stereotypic sequences and plan changes in their strategy (Baddeley, 1986; Harrison et al., 2014, Experiment 2 and 3; McDaniel et al., 2008, Experiment 2). These findings indicate that higher levels of OT task-switching, monitoring, or planning requirements may impose more cognitive control demands and, thus, PM may suffer due to overload. However, it should be noted that depending on other factors, such as PM cue salience or focality, PM performance may be enhanced despite OT difficulty (Trawley et al., 2014). In line with the multiprocess theory, salient cues are likely to capture attention and prompt further processing, and, as a consequence, PM-related responses may be executed without much effort.

Thus far, it is not yet clear which load conditions are more prone to influence PM performance. Therefore, the present systematic review aimed to (a) examine the prevalence of PM failures under demanding OT contexts; and to (b) synthesize the extent to which EBPM and TBPM tasks are affected by highly demanding ongoing activities. By having these two goals in mind, we intended to identify possible factors that could account for the discrepant findings already described in the literature (e.g., characteristics of the OT or the type of cognitive load manipulation, type of PM task, focality and salience of the PM cue) and, ultimately, to characterize which cognitive load conditions are more susceptible to the occurrence of these memory failures. In line with this proposal, we were particularly interested in OT load manipulations which are known to influence the availability of cognitive resources at the time of PM retrieval (see Meier & Zimmermann, 2015, for supporting evidence of different types of load). Given the methodological heterogeneity across studies, we opted to systematically organize the selected articles as a function of the PM tasks (i.e., EBPM and TBPM) and OT manipulation (i.e., increasing OT difficulty, adding a secondary OT, and task-switching procedures).

3.3. Method

3.3.1. Search strategy

This systematic review follows the guidelines of PRISMA (Moher et al., 2015). First, Scopus, PubMed, and Web of Science databases were searched, from the earliest available date to the end of April 2018, for the following descriptive verbal expressions: "prospective memory", "prospective remembering", "delayed intentions", combined with "OT demand*", "divided attention", "cognitive load", "working memory load", "background activit*", "load manipulation", and "secondary demand*". The search was then updated to include articles published from 2018 until January 2020. Additionally, we hand-searched reference lists on the articles identified through the prior database search and relevant articles. This strategy was also used to include articles with task-switching paradigms since it has been demonstrated that switching between tasks involves more costs, and thus more cognitive load, than repeating the same task across time (Monsell, 2003). The first two authors worked independently, selected the articles at each stage of the review (identification, screening, and inclusion) by using Cochrane´s online software for systematic reviews, Covidence® (2015). The authors resolved disagreements through discussion until a consensus was reached.

3.3.2. Eligibility criteria

Included studies were required to meet the following criteria: (a) Had experiments involving young and middle-age adults, (b) used EBPM or TBPM tasks, (c) tested PM performance as a dependent variable, (d) manipulated the cognitive load during the OT (i.e., by increasing OT difficulty, adding a secondary task or using a task-switching procedure), (e) embedded the PM cues in the OT to ensure that resources were shared between those tasks, and (f) were published in a peer-reviewed, English language journal. Hence, records in other languages, commentaries, narrative/qualitative reviews, editorials, book chapters, and abstracts were not considered for further analysis. The following exclusion criteria were also applied: (a) Studies that manipulated the cognitive load of the PM cue (e.g., Ballhausen et al., 2017; Cohen, 2013) as these conditions have been shown to affect OT performance (Meier & Zimmermann, 2015), (b) studies that included delay-execute conditions or activity-based PM tasks (i.e., the PM response had to be performed after a particular task has finished; Brewer et al., 2011) since PM cues did not appear during the OT, (c) studies that included clinical samples as PM might be particularly affected in this context (e.g., Albinski et al., 2012), (d) studies that involved drug interventions and/or ingestion of substances (e.g., Rusted & Trawley, 2006), that manipulated other factors including sleep (e.g., Barner et al., 2016), or that used neuromodulation techniques such as transcranial magnetic stimulation (e.g., Basso et al., 2010), (e) experiments that included children, adolescents, and older adults (e.g., Cheie et al., 2017; Zollig et al., 2007) given that previous research had demonstrated that PM follows an inverted U-shape developmental trajectory (Zimmermann & Meier, 2006; Zuber & Kliegel, 2020). Thus, by including only young and middle-age adults, age effects were somewhat restricted to this developmental stage.

3.3.3. ***Selection of studies***

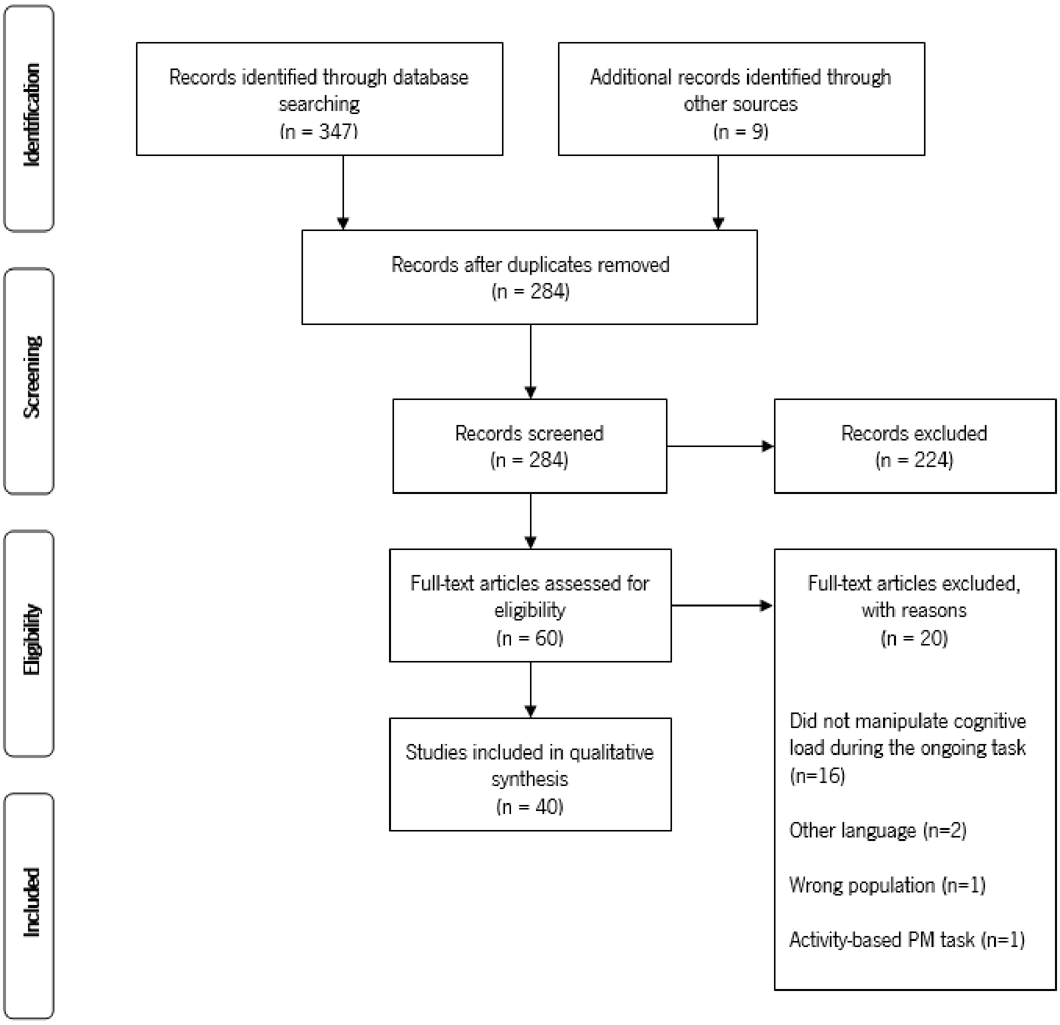
Figure 12 displays the PRISMA flow diagram showing a total of 356 articles identified. We found 328 articles through the initial database search (i.e., 199 articles in Web of Science, 92 in Scopus, and 37 in PubMed) and 19 articles in an updated search since April 2018 to the end of January 2020 (i.e., 13 articles in Web of Science, four in Scopus, and two in PubMed). In addition, nine articles were identified through other sources (i.e., hand-searching reference lists). The articles were exported to Zotero® to eliminate duplicates (n = 72). Title and abstract screening led to the identification of 60 articles. The main reasons for exclusion at this stage were papers unrelated to PM or the inclusion of clinical samples, children or elderly participants. In the case of any doubt concerning the application of the inclusion or exclusion criteria, the manuscripts were included in the "full-text reading" phase. After the full texts were screened, 40 articles were found to meet the inclusion criteria and 20 articles were excluded (see details in Figure 12). Of note, we did not conduct a meta-analysis because the articles differed methodologically in several ways (e.g., study design, OT, and PM tasks), which may lead to meaningless results according to Cochrane recommendation for systematic reviews (Higgins & Green, 2011). Instead, results were organized and described following a systematic narrative approach.

3.3.4. ***Coding procedure***

For each article included in the systematic review, the following details were extracted for each experiment: The author(s) and year of publication; the number and mean age of the sample; design (between-subjects, within-subjects); the OT used and the number of trials and blocks; the PM task; the cue type (e.g., word, image, letter), including whether the cue was specific or categorical (e.g., a specific word or a word from the animal category); the number of cues; cue focality (focal, non-focal), that is, the degree of overlap between the processing required by the PM cues and the OT; cue saliency, that is, the distinctiveness of the cue in relation to the OT (e.g., the PM cue stands out perceptually from the OT stimuli); data regarding the PM performance (accuracy) and OT performance (accuracy and RTs); and key findings that summarize how the load manipulation influenced both PM and OT performance. The information was initially extracted by the first author and then thoroughly reviewed by the second author. Finally, it was organized by the type of PM task (EBPM and TBPM) and by the type of OT load manipulation (increasing the primary OT demands, adding a secondary OT, and task-switching procedures).

FIGURE 12

PRISMA flow diagram of the articles included in the review.



3.4. Results

To date, 40 articles met our research criteria in examining the role of OT load on prospective remembering. The SCImago Journal and Country Rank was used as an indicator of visibility in scientific domains by ranking the journals in which articles were published. The articles were published in journals with different quartiles: 22 in Q1 journals, 16 in Q2 journals and two in Q3 journals. These quartiles also indicated that most articles were published in higher impact factor journals. The earliest work with a direct association with cognitive load and PM was published by Einstein et al. (1995). Moreover, 22% of the records (n = 8) were published between 1995 and 2000, 46% (n = 17) were published between 2001 and 2010, and 38% (n = 15) were published between 2011 and 2020.

The 40 published articles, containing a total of 62 experiments, differed methodologically in several ways. Most of the experiments investigated EBPM tasks (56/62) rather than TBPM tasks (7/62). Since only three studies assessed the role of the OT load on PM commission errors, we decided to discuss these findings and suggest future work in the Discussion section. Thus, in the following sections, we describe the results (a) regarding EBPM tasks and TBPM tasks according to (b) the OT manipulation (i.e., increasing the primary OT demands, adding a secondary OT, or using a task-switching procedure). To shed some light on how increasing demands influence PM performance, we classified studies according to how the task demands were manipulated (i.e., WM tasks increasing storage or executive function demands, reasoning tasks, LTM, and other tasks). Lastly, we detail some other relevant features that seem to modulate the occurrence of PM omission failures.

3.4.1. ***EBPM tasks***

3.4.1.1. ***Increasing primary OT demands***

Some experiments directly manipulated the difficulty of the primary OT since they increased the cognitive demands required to perform the ongoing activities in which the PM cues were embedded (see Table 3). In five experiments the OT load was manipulated by requiring WM storage demands by using a color-matching task in which participants had to decide whether the color of a word matched any of the colors shown on previous trials. In such cases, no differences were found between groups with different levels of OT difficulty using focal and specific PM tasks were used (i.e., pressing a keyboard key when target words appear; Horn et al., 2011; Smith et al., 2012; Smith & Hunt, 2014). The same pattern was revealed by Otani et al. (1997) that used a task with three levels of storage demand. In their study, participants were asked to perform an articulatory suppression task and repeat three or six previously presented words. Conversely, even though Kidder et al. (1997) did not observe a decrement in identifying PM cues by increased WM storage (i.e., asking participants to recall words at unpredictable intervals), the qualitative processing required to identify the cue (i.e., press a key whenever a background pattern appears) differed from that required to perform the OT. Also, some other studies did not find a PM impairment when a LTM task (Rendell et al., 2007, Experiment 2) or a semantic processing task (Lee & McDaniel, 2013) were used.

By contrast, increasing the OT requirement of WM and attentional executive resources had a deleterious effect on the ability to execute a delayed intention. Lewis-Peacock et al. (2016) and West and Bowry (2005) used a *n*-back task. The former instructed participants to judge if the lexical status of a current probe matched one of the probes presented one or two trials before (1-back and 2-back, respectively). In the latter, participants judged whether a letter was repeated 1- or 3-items back in a list. The same impairment pattern of results was found recently by Möschl et al. (2019). It is worth noting that West et al. (2006) also asked participants to perform a demanding *n*-back task. Nonetheless, PM retrieval may have been promoted by the salient and focal PM cue used in their study (i.e., pressing the *V* when target letters appear while performing a *n*-back letters task), ensuring successful PM. Moreover, Marsh and Hicks (1998, Experiment 1) asked participants to count stars forward and backward to increment or decrement a running total, respectively. As this task required inhibiting one cognitive process in order to activate another, the authors found a PM impairment. Likewise, performing demanding planning tasks during the retention interval seems to limit the resources that can be devoted to the PM task (which, in the current case, also required planning skills) and, henceforth, participants fail to successfully perform the planned intention (Stone et al., 2001).

3.4.1.2. ***Adding a secondary OT***

Some studies added a secondary OT in order to mimic complex daily situations (see Table 4). First, in line with previous findings, signalling the appearance of three consecutive tones of the same pitch (tone-monitoring WM task) or the occurrence of two/three consecutive odd digits (digit-monitoring WM task) while performing a primary verbal OT and holding a focal intention to press a designated key when target words appeared, revealed no statistically significant between-group differences in PM performance (Boywitt et al., 2015, Experiment 1; Rummel et al., 2016, Experiment 2). Indeed, in the study by Marsh and Hicks (1998), the authors only reported lower PM performance using a visuospatial task when it demanded more central executive resources.

Additionally, a deleterious effect on PM performance was reported in experiments adding a secondary random number generation task (Harrison et al., 2014, Experiments 2 and 3; Marsh & Hicks, 1998, Experiment 2; McDaniel et al., 2008, Experiment 2; McDaniel & Scullin, 2010, Experiment 1 and 2; van den Berg et al., 2004, Experiment 1). In such cases, participants were asked to perform a primary verbal task (i.e., word-rating and LDTs) while also generating random numbers, along with the intended action to press a key whenever some words appeared (i.e., a specific and focal PM cue). A similar finding was reported by Logie et al. (2004) when participants were asked to say *animal* when target images were presented, while watching a video and performing a concurrent reasoning task. Finally, experiments adding a LTM task showed inconsistent results: Two of them indicated a disruptive effect on PM performance (Bisiacchi et al., 2008; Khan et al., 2008), while the others did not (d'Ydewalle et al., 1999; Einstein et al., 1995, Experiment 3). It is noteworthy, however, that three of the previous experiments (d'Ydewalle et al., 1999; Einstein et al., 1995, Experiment 3; Khan et al., 2008) did not clearly show an effective load manipulation as similar OT performance was obtained across groups.

3.4.1.3. ***Task-switching procedures***

The results concerning task-switching, that is, when participants had to engage in a single task versus when they had to switch between distinct activities, are shown in Table 5. Given that switching between different tasks is more demanding than repeating the same task across time (Monsell, 2003), the comparison between these experimental conditions it is also a way of exploring how cognitive load may affect PM performance (Pereira et al., 2018). All task-switching studies included here used an OT involving semantic processing. As a main finding, most of them revealed that young adults performed poorly in the EBPM task when they had to switch between tasks relative to when they had to repeat the same task (Marsh et al., 2002; McNerney & West, 2007; West et al., 2011, Experiment 1). Even so, Pereira et al. (2018) did not find a PM impairment.

Also, most of these experiments used focal and non-salient PM cues (i.e., press a designated key when target words appear while making judgments; Marsh et al, 2002; McNerney & West, 2007; West et al., 2011, Experiment 1). Even though focal PM cues were used, these experiments revealed a lower PM performance when participants were required to switch between tasks compared to when they were engaged in a single task (see Tables S1-S3 in the Supplementary Material, Appendix 1).

3.4.1.4. ***Other relevant features***

Besides the type of cognitive load manipulation (i.e., increasing the difficulty of the OT; adding a secondary OT; task-switching), other factors to consider are the type of design used to operationalize such manipulation (i.e., between-subjects or within-subjects), focality of the PM cue (i.e., focal or non-focal), and PM cue salience (i.e., salient or non-salient). In this regard, the effect of demanding OTs on EBPM omission errors was reported in both experiments using between-subjects (e.g., Logie et al., 2004; Marsh

TABLE 3

Experiments on the effect of cognitive load in EBPM omission errors, by varying OT difficulty.

Experiment	Sample N (age-*M*; *SD*)	OT	Key findings	
			PM	OT
WM storage				
Horn et al., 2011 - 1	64 (n/a)	Color-matching task	=	↓ % and RTs
Horn et al., 2011 - 2a	27 (n/a)	Color-matching task	=	↓ %
Horn et al., 2011 - 2b	29 (n/a)	Color-matching task	=	↓ %
Smith et al., 2012	29 (n/a)	Color-matching task	=	↓ %
Smith & Hunt, 2014	100 (19.3; .12)	Color-matching task	=	↓ %
Otani et al., 1997 - 1	60 (n/a)	HL: six words repetition; LL: three words repetition; NL: articulatory suppression task	=	↓ %
Otani et al., 1997 - 2	60 (n/a)	HL: six words repetition; LL: three words repetition; NL: articulatory suppression task (15s per trial)	=	↓ %
Kidder et al., 1997	90 (19.6; 2.1)	Recall words at unpredictable intervals	↓	↓ %
WM executive processing				
Fronda et al., 2020	21 (29; 8)	Mental arithmetic task	=	↓ %
Lewis-Peacock et al, 2016	25 (23.2; n/a)	*n*-back test and lexical decision task	↓	↓ %
West et al., 2006	18 (n/a)	*n* -back test (letters)	=	↓ % and RTs
West & Bowry, 2005	18 (19.78;.81)	*n* -back test (letters)	↓	↓ % and RTs
Barutchu et al., 2019	28 (25.04; 4.25)	*n* -back test (letters)	=	↑ FA
Möschl et al., 2019	80 (21.79; 3.16)	*n* -back test (letters)	↓	n/a
Marsh & Hicks, 1998 - 1	54 (n/a)	Star counting task	↓	↓ %
Other tasks				
Lee & McDaniel, 2013	112 (n/a)	Anagram task	=	↓ % and RTs
Rendell et al., 2007 - 2	60 (20.1; n/a)	Face-naming task (HL = recall the names of famous faces + write words beginning with a specific letter; LL = estimate the age of faces + write comments)	=	=
Gonneaud et al., 2011	YA: 29 (24.3; 4.5) MA: 20 (51; 7)	Mental addition task	=	n/a
Stone et al., 2001 – 1a	28 (n/a)	Planning aircraft routes through a circuit of waypoints	↓	↓ %
Stone et al., 2001 – 1b	28 (n/a)	Planning aircraft routes through a circuit of waypoints	↓	↓ %

Note. WM = Working memory; PM = Prospective memory; OT = Ongoing task; HL = High load; LL = Low load; NL = No load; YA = Younger adults; MA = Middle-age adults; FA = False alarms; ↓ = Worse performance; = Similar performance; n/a = not available.

TABLE 4

Experiments on the effect of cognitive load in EBPM omission errors, by adding a secondary OT.

Experiment	Sample N (age-*M*; *SD*)	Secondary OT	OT	Key findings	
				PM	OT
WM storage					
Harrison et al., 2014 - 1	56 (n/a)	Digit-monitoring task	Lexical decision task	=	↓ % and RTs
McDaniel et al., 1998 - 3	30 (n/a)	Digit-monitoring task	Pleasantness rating task	↓	↓ RTs
McGann et al., 2002 - 1	48 (n/a)	Digit-monitoring task	Sentence validity task	↓	=
McGann et al., 2002 - 2	48 (n/a)	Digit-monitoring task	Readability rating task	=	=
McGann et al., 2002 - 3	96 (n/a)	Digit-monitoring task	Readability rating task or pleasantness rating task	= (readability rating task)	=
McDaniel et al., 2004 - 2	63 (n/a)	Digit-monitoring task	Word-rating task	↓	n/a
McDaniel et al., 2008 - 1	34 (n/a)	Digit-monitoring task	Word-rating task	=	n/a
Guynn & McDaniel, 2007	82 (n/a)	Digit-monitoring task	Word-rating task	= (preexposed targets)	n/a
Einstein et al., 1997 - 1	64 (19.43; n/a)	Digit-monitoring task	Word-rating task	↓	n/a
Einstein et al., 1997 - 2	64 (19.50; n/a)	Digit-monitoring task	Word-rating task	=	n/a
Van den Berg et al., 2004 - 2	80 (22; 5.3)	Random interval generation task (fixed or random tapping intervals)	Short-term memory task + sentence construction task	=	↓ %
Boywitt et al., 2015 - 1	73 (21.86; 2.15)	Tone-monitoring task	Lexical decision task	=	↓ % and RTs
Rummel et al., 2016 - 2	68 (n/a)	Tone-monitoring task	Word-categorization task	=	= % and RTs
Marsh & Hicks, 1998 - 4	36 (n/a)	Visuospatial task (sequential tapping task)	Short-term memory task	↓	= %
Marsh & Hicks, 1998 - 5	36 (n/a)	Visuospatial task (colored square task)	Short-term memory task	=	= %
Marsh & Hicks, 1998 - 3	36 (n/a)	Rehearse aloud monosyllabic words	Short-term memory task	=	↓ %
Van den Berg et al., 2004 - 3	80 (21; 2.2)	Random interval generation task (fixed or random tapping intervals)	Short-term memory task + sentence construction task	=	↓ %

(Continued)

TABLE 4

Continued

Experiment	Sample N (age-*M*; *SD* or *SE*)	Secondary OT	OT	Key findings	
				PM	OT
WM executive processing					
McDaniel et al., 2008 - 2	128 (n/a)	Random number generation	Word-rating task	↓	↓ % and RTs
McDaniel & Scullin, 2010 – 2	72 (n/a)	Random number generation task	Category decision task	↓	↓ % and RTs
Harrison et al., 2014 - 2	56 (n/a)	Random number generation task	Lexical decision task	↓	↓ % and RTs
Harrison et al., 2014 - 3	64 (n/a)	Random number generation task	Lexical decision task	↓	↓ % and RTs
McDaniel & Scullin, 2010 - 1	64 (n/a)	Random number generation task	Lexical decision task + category decision task	↓	↓ % and RTs
Marsh & Hicks, 1998 - 2	54 (n/a)	Random number generation task	Short-term memory task (auditorily)	↓	↓ %
Van den Berg et al., 2004 - 1	91 (21; 2.1)	Random number generation task	Short-term memory task	=	= %
Reasoning tasks					
Logie et al., 2004	40 (21.50; 2.4)	Arithmetic verification task	Video watching for future questions	↓	n/a
Long term memory tasks					
Bisiacchi et al., 2008 – comparison between 1 and 2	40 (n/a)	LTM task (Memorize items for future recall)	Picture-naming task	↓	↓ RTs
Einstein et al., 1995 - 3	YA:36 (20.2; n/a) MA: 28 (42.5; n/a)	LTM task (Hear a story for future recall)	General knowledge questions	=	= %
Khan et al., 2008	80 (24.61; 3.01)	LTM task (Hear a story for future recall)	General knowledge questions	↓	= %
d'Ydewalle et al., 1999	60 (19.35; n/a)	LTM task (Memorize continuously the last five presented questions or slides)	Questions answering + face-identification task	=	= %

Note. WM = Working memory; PM = Prospective memory; OT = Ongoing task; ↓ = Worse performance; = Similar performance; YA = Younger adults; MA = Middle-age adults; n/a = not available.

TABLE 5

Experiments on the effect of cognitive load in EBPM omission errors in task-switching paradigms.

Experiment	Sample N (age-*M*; *SD*)	OT	Key findings	
			PM	OT
Marsh et al., 2002 - 1 and 2	157 (n/a)	Judgment word task (Experiment1: Long E-sound vs. animacy judgment; Experiment 2: Count the number of syllables vs. invert interchanged letters)	↓	↓ RTs
McNerney & West, 2007 - 1	20 (20.22; n/a)	Judgment word task (noun or verb vs. 1 or 2 vowels)	↓	↓ RTs
McNerney & West, 2007 - 2	32 (19.78; n/a)	Judgment word task (noun or verb vs. 1 or 2 vowels)	↓	↓ RTs
McNerney & West, 2007 - 3	26 (19.39; n/a)	Judgment word task (noun or verb vs. 1 or 2 vowels)	↓	↓ RTs
West et al., 2011 - 1	24 (21.70; 7.38)	Judgment word task (noun or verb vs. 1 or 2 vowels)	↓	↓ % and RTs
West et al., 2011 - 2	21 (19.55; 1.19)	Judgment word task (noun or verb vs. 1 or 2 vowels)	=	↓ RTs
Pereira et al., 2018	32 (21.75; 4.30)	Lexical decision task + capital decision task	=	↓ RTs

Note. PM = Prospective memory; OT = Ongoing task; ↓ = Worse performance; = Similar performance.

TABLE 6

Experiments on the effect of cognitive load in TBPM omission errors.

Experiment	Sample N (age-*M*; *SD*)	OT	Secondary OT	Key findings	
				PM	OT
Experiments varying OT difficulty					
Martin & Schumann-Hengsteler, 2001	90 (24.0; 3.77)	Mastermind task	–	↓	↓
Gonneaud et al., 2011	YA: 29 (24.3; 4.5) MA: 20 (51; 7)	Mental addition task	–	=	n/a
Fronda et al., 2020	21 (29; 8)	Mental arithmetic task	–	=	↓ %
Experiments adding a secondary OT					
Khan et al., 2008	80 (26.41; 3.01)	General knowledge questions	Hear a story for future recall	↓	=
Einstein et al., 1995 - 3	YA: 36 (20.2; n/a) MA: 28 (42.5; n/a)	General knowledge and problem-solving questions	Hear a story for future recall	=	=
Logie et al., 2004	40 (21.05; 2.4)	Long-term memory task (video watching for future questions)	Arithmetic verification task	↓	n/a
d'Ydewalle et al., 1999	60 (19.35; n/a)	Questions answering vs. face-identification task	Short-term memory task (memorize continuously the general theme of the last five questions)	=	=

Note. PM = Prospective memory; OT = Ongoing task; ↓ = Worse performance; = Similar performance; YA = Younger adults; MA = Middle-age adults; n/a = not available.

TABLE 7

Experiments on the effect of cognitive load in EBPM and TBPM commission errors.

Experiment	Sample N (age-*M*; *SD*)	OT	Secondary OT	Key findings	
				PM	OT
Event-based PM tasks					
Boywitt, et al., 2015 - 1	73 (21.86; 2.15)	Lexical decision task	Tone-monitoring task	↓	↓ % and RTs
Pink & Dodson, 2013 - 1a and 1b	96 in each experimental condition	Lexical decision task	Digit-monitoring task	↓	=
Matos et al., 2020	140 (21.22, 4.27)	Lexical decision task	Counting-recall task	↓	↓ %
Time-based PM tasks					
Einstein et al., 1998	63 (19.8; 2.58)	Different tasks (vocabulary; implicit memory; internal source monitoring; perceptual speed; action control; compulsivity)	Digit-monitoring task	=	n/a

Note. PM = Prospective memory; OT = Ongoing task; ↓ = Worse performance; = Similar performance; n/a = not available.

& Hicks, 1998, Experiments 1 and 3; McGann et al., 2002) and within-subjects designs (e.g., Harrison et al., 2014, Experiment 3 and 4; McDaniel et al., 2008; West & Bowry, 2005).

Given that focal and salient PM cues have been shown to promote an automatic retrieval of delayed intentions, leading to a better PM performance (McDaniel & Einstein, 2000), it was expected that PM performance under demanding conditions would be protected by using focal and salient PM cues. Although only a small number of studies fulfil these criteria, the ones available reported no PM impairment under complex task processing when both criteria were met (Boywitt et al., 2015; West et al., 2006). Still, salient and focal PM cues did not help to accurately perform a delayed intention in complex situations requiring WM and attentional executive processes (Harrison et al., 2014, Experiment 3). This finding, however, requires further examination in future studies and should be interpreted with caution as only a few experiments used salient and focal PM cues. Taken together, the evidence in this domain remains scarce and more studies are needed to explore possible interactive effects between the focality and/or the saliency of the PM cue and the OT load.

3.4.1.5. ***Summary of EBPM tasks***

To date, 26/56 experiments that used EBPM performance under demanding conditions showed a PM decrement, and 30/56 did not. There is substantial evidence suggesting a deleterious effect on young adults´ ability to execute a delayed intention when there is an increase in the primary OT difficulty, when a secondary task is added, or when participants are required to engage in task-switching conditions. The critical element that appears to be shared by the former tasks is the requirement of WM attentional executive resources during OT processing. Conversely, increasing the demands of the ongoing activities by overloading the WM storage does not seem to impair PM performance. Moreover, although salient and focal cues seem to support PM performance under demanding conditions, they do not help accurately perform a delayed intention in complex situations such as the ones implying more WM executive processes.

*3.4.2. **TBPM tasks***

Table 6 shows data regarding omission errors in TBPM tasks. Results demonstrate an impaired PM performance with reasoning tasks (Martin & Schumann-Hegsteler, 2001) or by adding a secondary arithmetic verification task (Logie et al., 2004) while monitoring to press the spacebar or to change the protocol sheet every three minutes, respectively. In contrast, d'Ydewalle et al. (1999) and Einstein et al. (1995, Experiment 3) also added a secondary task, yielding nonsignificant differences in PM performance. Even so, the OT performance did not differ across groups which may suggest that the ongoing manipulation did not increase the cognitive load to the point of affecting the ability to carry out the intended action. As an alternative, it could be the case in other experiments that participants maintained a stable OT execution by dampening their PM task response. Thus, PM performance was significantly affected due to a trade-off between PM and OTs (Khan et al., 2008; Logie et al., 2004).

Moreover, when the effect of OT load was observed, it was irrespective of the experimental design (between-subjects: Logie et al., 2004; Martin & Schumann-Hengsteler, 2001; within-subjects: Khan et al., 2008; see Table S4 in the Supplementary Material, Appendix 1). Also, it is worth mentioning that the analysis of time-checking frequency revealed that participants check the clock to remind themselves about the PM task more often in low-load conditions than in high-load conditions (Gonneaud et al., 2011; Khan et al., 2008).

*3.4.2.1. **Summary of TBPM tasks***

Overall, the same pattern of PM impairment was found in 3/7 experiments that investigated TBPM task performance under cognitively demanding activities. That is, regardless of OT manipulation, PM performance was hindered if participants were cognitively overloaded by ongoing activities that were more demanding in terms of executive WM resources.

3.5. Discussion

The present review aimed to synthetize the large body of literature on the role OT demands on PM performance and to interpret those findings while considering the nature of the OT load manipulation in order to identify directions for future research. There were two main findings. First, resource-demanding OT processing may pose serious threats to the execution of delayed EBPM and TBPM intentions (e.g., Harrison et al., 2014; Lewis-Peacock et al., 2016; Logie et al., 2004; McDaniel & Scullin, 2010). Second, it seems that the efficiency of PM is likely disturbed the more the OT recruits WM and executive resources (e.g., Marsh & Hicks, 1998).

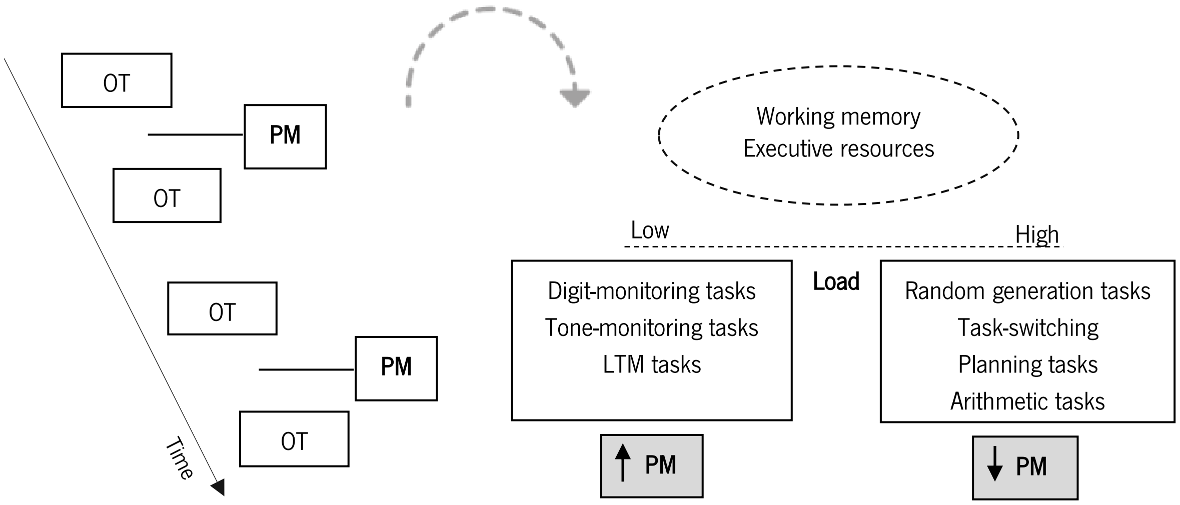
3.5.1. PM omission errors: Increasing OT complexity impairs PM cue detection

The evidence presented so far indicates that we are likely to forget to perform a previously planned intention whilst engaged in resource-demanding concurrent activities (see Figure 13). First, regarding EBPM tasks, OTs involving greater monitoring (e.g., arithmetic task, visuospatial monitoring, counting, and random number generation) or a planning component affected PM performance (Lewis-Peacock et al., 2016; Harrison et al., 2014, Experiments 2 and 3; Marsh & Hicks, 1998, Experiment 2; McDaniel et al., 2008, Experiment 2; McDaniel & Scullin, 2010, Experiments 1 and 2; Möschl et al., 2019; Stone et al., 2001; West & Bowry, 2005). These tasks likely overloaded WM and executive resources, particularly when participants were required to inhibit stereotypic sequences (e.g., 1-2-3, 2-4-6) while monitoring their output to comply with the randomness condition (Baddeley et al., 1998). These findings are consistent with prior research indicating that poor PM performance is linked to impaired WM (Arnold et al., 2015; Rose et al., 2010), planning (e.g., Shum et al., 2013), inhibition, or task-switching abilities (e.g., Schnitzspahn et al., 2013).

In contrast, the OT processing of visuospatial information (e.g., color-matching task; Horn et al., 2011; Lee & McDaniel, 2013; Smith et al., 2012; Smith & Hunt, 2014) or the maintenance of verbal information (e.g., word study and recall; Otani et al., 1997) did not yield significant differences on PM performance between low- and high-load conditions. The same pattern was documented in those experiments adding a digit-monitoring task to the primary OT (Boywitt et al., 2015, Experiment 1; Einstein et al., 1997, Experiment 2; Guynn & McDaniel, 2007; Harrison et al., 2014, Experiment 1; McDaniel et al., 2008, Experiment 1). In this case, although monitoring for odd numbers probably drew attentional resources, one could argue that this condition did not impose enough load on WM and executive abilities. Thus, this allowed for effective management of the available resources to accomplish the PM task.

FIGURE 13

Schematic diagram showing the effect of OT load on EBPM and TBPM performance.



Note. LTM = Long-term memory; PM = Prospective memory; OT = Ongoing task.

Moreover, the empirical evidence indicates that when the OT resource demands are varied within the context of a task-switching paradigm (i.e., with the idea that switch blocks would demand greater attentional resources than repetition of a single task across time) PM suffers (Marsh et al., 2002; McNerney & West, 2007; West et al., 2011). Yet, Pereira et al. (2018) did not replicate this result. In this case, the authors suggested that the cognitive load imposed by the two OTs used (i.e., perceptual task vs. LDT) may not have reached a similar level of demand as in previous studies. Thus, no effect on PM performance was detected in this case. The cognitive load imposed by task-switching conditions is based on the notion that additional cognitive processing resources are required to suppress responding to the OT and to execute the PM task. In this vein, McNerney and West (2007) argued that the effect of task-switching on PM might not result from the specific requirement to switch between task sets (i.e., different judgments made from one trial to the next). Instead, it may arise from the requirement to manage multiple task sets that are held in WM to guide task performance. For instance, in a task wherein participants must indicate whether a word is a noun or a verb or whether a word has one or two vowels, they must keep two different task sets online: The grammatical class task set, and the number of vowels task set. Arguably, this idea fits with the notion that increased load on central executive processes might contribute to the PM decrease in task-switching conditions.

Second, TBPM performance was also modulated by the demands imposed by the concurrent activities (Khan et al., 2008; Logie et al., 2004). That is, the successful recall and enactment of TBPM intentions may be disturbed when the intentions are not being retrieved or available in WM, but also when the ease of disengagement from the OT is affected. Nevertheless, this result should be treated with caution as only a few studies using TBPM tasks were included in the present review. Both EBPM and TBPM performance appear be sensitive to the type of demands placed on the cognitive system when an intention-related cue is encountered. Given that TBPM tasks rely more on shifting abilities (Kliegel et al., 2003) and on controlled and costly monitoring processes than EBPM tasks (Henry et al., 2004), it would be reasonable to assume that TBPM (as opposed to EBPM) tasks might be more affected by manipulations on OT load. Still, the dearth of evidence regarding the comparison between TBPM and EBPM performance (e.g., Fronda et al., 2020; Khan et al., 2008) highlight the need to further test this hypothesis.

Lastly, in addition to the overall demands that are required by an OT, we now consider how those processing manipulations interact with the processing that would be required to identify a PM cue (Marsh et al., 2000). As previously stated, focal and salient PM cues should increase the involvement of automatic processing in prospective remembering, rendering performance less susceptible to load effects. Kidder et al. (1997) used non-focal and non-salient PM cues, which likely imposed an active monitoring strategy as the cognitive resources required to perform the OT did not match the types of cognitive resources needed to identify the cue, nor did the OT make aspects of the PM cue salient. Hence, the lack of processing resources to retrieve the planned intention when the OT must be disengaged might explain why participants tended to fail PM execution during a verbal WM task that, theoretically, would impose a load on WM storage rather than on executive processes. In other cases, salience and/or focality of the PM cue may be able to counteract the deleterious effects of limited processing resources (Marsh et al., 2002; West et al., 2006; see also Marsh et al., 2000). For example, in the West et al. (2006) study, the PM cue was salient and focal which may have promoted PM retrieval even though participants performed a demanding *n*-back task. Still, despite using focal or salient PM cues, most studies revealed that PM was susceptible to OT regardless of the qualitative processing of PM cues. However, to determine how the content of a delayed intention may interact with different degrees of OT load is a question for future research.

3.5.2. **OT load and PM commission errors: A new research topic**

Less is known about the role of demanding OTs on PM deactivation. Surprisingly, there is growing evidence that, under conditions of heavy cognitive load or distraction, participants may continue to perform a previously planned intention when they no-longer have to do so (Boywitt et al., 2015, Experiment 1; Matos et al., 2020; Pink & Dodson, 2013). These memory failures, termed as PM commission errors, are thought to occur when participants spontaneously notice the PM cue and fail to inhibit PM execution (Bugg et al., 2016; Schaper & Grundgeiger, 2019; Scullin et al., 2012). This can be observed, for example, in some studies (Boywitt et al., 2015, Experiment 1; Matos et al., 2020; Pink & Dodson, 2013, Experiments 1a and 1b) adding tone-monitoring, digit-monitoring or counting recall tasks to a LDT in which focal PM cues were embedded (i.e., pressing a key when target words were detected). Thus, the finding that more participants make more commission errors as a function of increasing OT complexity is in line with the idea that an inefficient management of the available resources - that also serve to inhibit irrelevant information - is responsible for this type of PM failures (Bugg et al., 2016; Cowan, 2017; Engle, 2002). Moreover, the salience and focality of the PM cues might have also accounted for the increased number of commission errors observed (Bugg et al., 2016; Scullin & Bugg, 2013; see Table S5 in the Supplementary Material, Appendix 1). However, the scarce number of studies in this field underscores the need to better examine the role of cognitive load and PM cue salience on PM commission errors in order to clarify which conditions may be more prone to the occurrence of such memory failures.

3.5.3. Theoretical implications

Notably, the earliest studies on divided attention and PM pinpointed the importance of considering whether the OT demands impact the executive processing or whether they simply induce an increase in storage load (e.g., Marsh & Hicks, 1998; Otani et al., 1997). For instance, Marsh and Hicks (1998) reported that changing the difficulty of the OT without a deeper involvement of WM and executive control was insufficient to affect young adults' PM ability in EBPM tasks. The current systematic review provided support for this claim, which may shed some light on the discrepant findings reported in the literature.

As stated, cognitive load manipulations require participants to orient and manage their cognitive resources to respond effectively to both the ongoing and the PM task. To achieve that, WM resources and executive functions of inhibition are needed not only to hold information temporarily in a heightened state of availability for performing both tasks (see Cowan, 2017), but also to keep WM (i.e., the focus of attention) free from irrelevant information (see Hasher et al., 2007 for further details). However, WM capacity only allows hold a limited amount of information. Thus, imposing higher demands through arithmetic, random number generation (e.g., Harrison et al., 2014, Experiments 2 and 3; Logie et al., 2004; Marsh et al., 2002), planning (Stone et al., 2001), or task-switching tasks (Marsh et al., 2002; McNerney & West, 2007; West et al., 2011) has a deleterious effect on PM performance as there are fewer resources available to support PM retrieval when the associated PM cue is encountered. In such high-load conditions, the competition for WM and executive resources and the need for goal prioritization resulted in worse PM performance when compared to low-load conditions. On the contrary, when participants were engaged in less effortful tasks requiring storage of verbal or visual information, no PM decline was observed (e.g., Einstein et al., 1995, Experiment 3; Harrison et al., 2014, Experiment 1; Horn et al., 2011; Otani et al., 1997; Rendell et al., 2007, Experiment 2; Smith & Hunt, 2014).

Moreover, in a series of experiments, Baddeley et al. (1984) demonstrated that retrieval from LTM did not appear to depend heavily on executive resources. In line with this idea, cognitive load manipulations on LTM tasks did not influence PM performance (see Einstein et al., 1995, Experiment 3; d'Ydewalle et al., 1999; Rendell et al., 2007, Experiment 2). Indeed, different brain mechanisms appear to underly WM and episodic memory functions. Tasks relying on the central executive tend to recruit prefrontal and parietal brain regions (Collette & Van der Linden, 2002; Cona et al., 2015), whereas the encoding and successful retrieval of episodic memories require the additional involvement of medial temporal areas (Dickerson & Eichenbaum, 2010; Rugg & Vilberg, 2013). Taken together, the tasks that resulted in PM decrements required more difficult monitoring, planning, inhibition, and task-switching resources to avoid making errors. These results lend further support to the notion that PM requires resources of the same type that contribute to successful OT performance, presumably due to the contribution of the WM and executive control processes. When those demands are great enough, decrements in prospective responding are observed.

3.5.4. **Limitations and future directions**

First, some experiments reported a similar OT performance between low- and high-load conditions (e.g., Harrison et al., 2014, Experiment 1; Marsh & Hicks, 1998, Experiment 4 and 5; McGann et al., 2002, Experiment 3), which could be explained by an ineffective load manipulation. Even so, PM performance was impaired in some of the former studies (e.g., Marsh & Hicks, 1998, Experiment 4). Thus, as PM cues are always embedded in an OT, it is possible that a trade-off occurred between PM and OT performance. Put differently, if more resources were devoted to the ongoing activity, fewer would be available to execute the planned intention leading to a worse PM performance (e.g., d´Ydewalle et al., 1999). Yet, Marsh and Hicks (1998, Experiment 2) did not find that participants traded accuracy in the OT to better perform the PM task, as they performed at a similar level on both conditions. In this case, perhaps the focality of the PM cue (or the strength of the association between the cue and the intention) was able to counteract the deleterious effects of fewer processing resources (McDaniel & Einstein, 2007).

Thus, trade-off effects, as well as cue focality and salience, should be further considered in future studies. Moreover, since we observed no PM impairment despite cross-modality between PM and OT (e.g., Boywitt et al., 2015; Fronda et al., 2020; Otani et al., 1997), a better understanding of how congruent multisensory processes may up-regulate (or benefit) PM cue detection under complex conditions is another promising topic for future research (Barutchu et al., 2019; Bonnici et al., 2016).

Second, we did not include studies exploring the effects of cognitive load beyond EBPM and TBPM tasks, such as activity-based tasks. However, it is worth noting that the first two typically require the interruption of an OT, whereas activity-based intentions must be completed between tasks (e.g., return a book to the library immediately after the class; Brewer et al., 2011). Thus, future reviews should also probe the role of OT load on these activity-based intentions as its impact might differ according to the type of PM task. Finally, most of the studies included in this review implemented cognitive load manipulation within the timeframe required to carry out the intention (i.e., performance interval; see Ellis, 1996; Kliegel et al., 2002). In this context, an avenue for future research would be to examine whether PM performance is vulnerable to the interference prompted by demanding conditions placed during PM encoding or during the delay interval between encoding and PM retrieval.

3.5.5. Conclusions

The present study was the first systematic review exploring the effects of cognitive load on young and middle-aged adults´ prospective remembering. There was substantial evidence indicating that PM performance was hindered when cognitive resources were progressively captured by a difficult OT, by higher demands of a secondary task, or by task-switching conditions. A novel and counterintuitive finding was that, under demanding situations, one could also erroneously perform an intention which is no-longer-needed. Moreover, this review highlighted the crucial role of WM and executive demands required by OTs, as well as the characteristics of the PM cue, in predicting the successful accomplishment of PM intentions.

3.6. References

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CHAPTER 4

EMPIRICAL STUDIES

The work presented in Chapter 4 was submitted for publication to international peer-reviewed journals:

Matos, P., Santos, F. H., & Albuquerque, P. B. (2020). When we must forget: The role of cognitive load on prospective memory commission errors. *Memory, 28*(3), 374–385. https://doi.org/10.1080/09658211.2020.1726399
[Paper discussed on a peer-review session at the Summer School *Perspectives on human memory: Memory functioning and memory failures*, University of Bern, Switzerland]

Matos, P., & Albuquerque, P. B. (2020). *Moving forward: Exploring the role of retroactive interference on prospective memory deactivation* [Manuscript submitted for publication]. School of Psychology, University of Minho.

Also, the present studies were publicly presented at scientific meetings:

Matos, P., Santos, F. H., & Albuquerque, P. B. (2018, May 10–12). *Remember that you´ve already paid the bill: Finding prospective memory commission errors* [Poster presentation]. Psychonomic International Conference, Amsterdam, Netherlands.

Matos, P., Santos, F. H., & Albuquerque, P. B. (2018, April 13–14). *When we must forget: The role of ongoing task load on prospective memory commission errors* [Poster presentation]. 13rd Meeting of the Portuguese Association of Experimental Psychology, Braga, Portugal.

Matos, P., & Albuquerque, P. B. (2019, May 3–4). *Remember not to do it when you are busy: Understating prospective memory deactivation* [Conference presentation]. 14th Meeting of the Portuguese Association of Experimental Psychology, Évora, Portugal.

4.1 STUDY 1 | When we must forget:
The effect of cognitive load on PM commission errors

4.1.1. Abstract

Recent studies consistently show that PM intentions are not always deactivated when no-longer-needed and might be erroneously performed upon encountering the once relevant cue - termed PM commission errors. However, empirical evidence on the potential mechanisms that might lead to this kind of memory failure remains mostly unexplored. This study aimed to investigate the influence of the OT demands on PM deactivation of non-performed intentions. Younger adults, except for those in the no-PM condition, were asked to perform a PM task and were then told that the intention is cancelled. Later, they perform a LDT with some trials containing (irrelevant) PM cues while simultaneously carrying out a counting recall task with two levels of difficulty. The results showed a higher risk of PM commission errors under moderate cognitive load as compared to the no-load condition. Moreover, results also revealed that commission error risk did not increase in the high-load condition compared with the moderate-load condition. Besides, comparisons between a control no-PM condition and the other conditions with a PM task support that these failures might arise from a spontaneous PM retrieval. The implications of these findings are discussed within the dual-mechanisms account.

Keywords: prospective memory; unfulfilled intentions; commission errors; ongoing task load

4.1.2. Introduction

Prospective memory is an individual's ability to remember to perform an intended action at a later point in the future, such as remembering to buy medicines on the way home (Anderson et al., 2017; Einstein & McDaniel, 1990; Loftus, 1971). Indeed, forgetting to take an allergy medicine can result in health problems, but some (thankfully rarer) PM failures may have life-threatening consequences such as a parent forgetting an infant on the backseat of a car (e.g., Dismukes, 2008; El Haj et al., 2018; Loft et al., 2016). In everyday life, some intentions become irrelevant and thus should be deactivated; otherwise, PM commission errors may occur if those tasks are erroneously performed when no-longer-needed (e.g., Anderson & Einstein, 2017; Bugg et al., 2016; Schaper & Grundgeiger, 2019; Scullin & Bugg, 2013; Walser et al., 2017). For instance, taking medicines after lunch even though the prescription has ended or paying the same electricity bill twice (Kimmel et al., 2007).

The consistent finding that processing a salient (but irrelevant) cue can lead to commission errors challenged the linear idea that once an intention is completed, it is forgotten. However, knowledge is still lacking today about which factors influence PM deactivation. Crucially, the PM cues that signal it is the appropriate moment or time to perform a previously planned intention may reappear while individuals are engaged in daily activities (Einstein & McDaniel, 1990; McDaniel & Einstein, 2000). Yet, few studies address the question of how people manage to inhibit those (irrelevant) intentions (e.g., do not continue to take medicines) when encountering the associated retrieval cue (e.g., see the medicine box at the kitchen table), while busily engaged in demanding OTs (e.g., facing a busy working day while also attending a meeting, packing and arranging travel insurance just before vacation; see Boywitt et al., 2015; Pink & Dodson, 2013 for exceptions).

Moreover, PM research has mainly focused on completed PM tasks (e.g., Scullin et al., 2012; Walser et al., 2014, 2017). Nevertheless, many real-world situations require performing multiple intentions in rapid succession, some of which are updated and become irrelevant without being previously performed (Anderson & Einstein, 2017; Bugg & Scullin, 2013; Walser et al., 2017). We may initially form the intention to remember to set the house alarm before traveling, but it can become no-longer-needed because a relative is going to stay there. This is a requirement of everyday cognition, yet rarely addressed in research. Therefore, beyond its translational value, the OT load might help us to understand the cognitive mechanisms underlying PM commission errors.

4.1.2.1. *PM laboratory procedure*

The experimental task most used to investigate PM deactivation in the laboratory was proposed by Bugg and Scullin (2013), in which participants must inhibit performing an intention that becomes irrelevant. In the active-PM phase, they are engaged in an ongoing activity, and they are simultaneously asked to perform an EBPM (e.g., remember to press *Q* if they saw the word *corn* or *dancer* while performing a LDT). The PM task is declared finished afterward, and participants are told that they should no-longer respond to cues, which still occur later in the experiment (i.e., during the finished-PM phase). Moreover, control trials, which are trials matching (in this case, the frequency and length of the PM cues) but never served as retrieval cues, are presented.

By using this procedure, some studies have shown that both young and older adults were slower in response to OT trials containing PM cues compared to control trials (e.g., Pink & Dodson, 2013; Scullin & Bugg, 2013; Scullin et al., 2011, 2012; Walser et al., 2012, 2014). The idea is that PM intentions might continue to exhibit residual activation and the associated response competes with the performance on the OT. Many other studies have consistently shown that participants might often make commission errors (i.e., erroneously press *Q* in response to PM cues) despite being instructed that the PM task is completed or suspended (e.g., Anderson & Einstein, 2017; Boywitt et al., 2015; Bugg et al., 2013, 2016; Schaper & Grundgeiger, 2017).

Taken together, these findings suggest that PM intentions may not always be deactivated. Therefore, the study of factors that can modulate PM deactivation, such as cognitive load, is an important step to clarify which conditions may be more prone to the occurrence of PM commission errors. In the laboratory, the primary OT can be made more challenging by increasing its difficulty (e.g., a color-matching task with two complexity levels; e.g., Horn et al., 2011; Smith & Hunt, 2014) or by adding a secondary OT (e.g., perform a LDT while concurrently generating random numbers; e.g., Harrison et al., 2014; McDaniel & Scullin, 2010) in order to capture critical features of real-world situations with competing demands on cognitive resources.

4.1.2.2. **PM deactivation under cognitive load**

The tendency to be disrupted by distracting memories pervades daily life: We may retrieve an old intention and erroneously take medicines when we no-longer-needed because we see the old medicine package on the kitchen table. An example such as this highlights the need to control a memory system that is sometimes too able to deliver information, even when such memories conflict with current task goals. Thus, the processing demands of the OTs in which PM cues reappear may help us to understand

PM deactivation. If we increase the amount of resources needed for the OTs, it stands to reason that the resources leftover to perform the PM task might be reduced. Then, does performing difficult ongoing activities hamper PM performance compared to situations in which the OT is less demanding, and one can probably devote more resources to inhibit irrelevant PM tasks?

The theoretical advances explaining how our cognitive systems support PM forgetting stem from the PAM theory and the multiprocess theory. According to the PAM theory (Smith, 2003), the retrieval of an intention requires WM capacity and attentional resources to actively monitor the environment for an appropriate time or event to perform the PM task. Thereby, commission errors should occur if those monitoring processes have not been discontinued upon intention completion. However, some studies have shown that individuals did not unnecessarily monitor for PM cues in a context in which a PM task need not to be performed (e.g., Knight et al., 2011; Marsh et al., 2006) and, under some circumstances, PM intentions may be spontaneously retrieved according to the multiprocess theory (Einstein & McDaniel, 2005; Einstein et al., 2005). The multiprocess theory posits, for example, that PM retrieval occur more automatically when the PM cue is salient (e.g., stands out perceptually from the OT stimuli) or focal (i.e., the PM cue information may be easily decoded from the OT when there is a processing overlap between the PM and the OT).

In line with this reasoning, the dual-mechanisms account claim that this commission failures are thought to occur due to failed inhibition of a prepotent response following spontaneous retrieval of the PM intention (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2012). The idea is that the intention is correctly suppressed or, if the cognitive control (i.e., inhibition) is impaired, erroneously executed (see also Schnitzspahn et al., 2013 for the role of inhibition in PM). Support for this account is based on two key findings: Older adults, whose ability to override a prepotent response tendency is compromised (Lustig et al., 2007), show a higher commission error risk than younger adults (Bugg et al., 2016; Scullin et al., 2012), and their poorer inhibitory ability score is associated with a greater risk of making a commission error (Scullin et al., 2009, 2011). However, the effect of the inhibition measure was not replicated in a subsequent study using an implementation intention strategy condition which is known to foster spontaneous PM retrieval (Bugg et al., 2013) and it was only limited to older adults (Scullin et al., 2011).

Recently, Schaper and Grundgeiger (2019) also suggested that failed suppression of the PM intention is not necessary for commission error occurrence. In their study, participants were first instructed to perform the OT and the PM task, and, in a response lag condition, they could not enter their response until after a delay of 45 s. The reasoning behind this approach was that if PM suppression is critical to avoid commission errors, the additional time available for suppressing the associated action should prevent these errors compared with a condition where participants could respond immediately. Although a response lag had been introduced, results showed that commission error still occurred (Schaper & Grundgeiger, 2019). Therefore, the authors proposed that the recalled intention was directly implemented if the person fails to correctly evaluate the PM cue as no-longer relevant; otherwise, it will be tagged for suppression if the previously relevant cue is correctly processed.

In fact, our cognitive control ability allows us to form a plan, to maintain it in the face of distraction, and to adjust our behavior appropriately in case of cognitive conflict (Botvinick et al., 2001; Posner & Snyder, 1975). Critically, then, at the time of PM retrieval, the availability of cognitive resources should influence PM deactivation because inhibitory mechanisms are either not available to prevent making a response to an irrelevant PM intention or to tag the PM task for suppression. Hence, assuming that people's resources are overloaded by the OT demands, commission errors may arise upon the occurrence of former PM cues. Yet, empirical evidence on this issue is still scarce.

To the best of our knowledge, only two studies have focused on the question of whether PM deactivation is affected by OT demands. More specifically, Pink and Dodson (2013) provided the first evidence that young adults occasionally made more commission errors if engaged in difficult OTs. In their study, participants showed a significantly worse PM performance (i.e., more commission errors) if additionally performing a digit-monitoring task, compared with those who did not have to perform the concurrent task. It should be noted, however, that this finding might have been exacerbated by failures of source monitoring, because participants need to remember whether the cue belongs to the no-longer relevant cues from the first block or to the new relevant cues of the second block. A more recent study brings additional support for the impact of OT load on PM deactivation by showing higher rates of PM commission errors both in younger and older adults when they must perform an additional tone-monitoring task (Boywitt et al., 2015, Experiment 1). It is worth mentioning that in this study, young adults' PM performance was explored for intentions that were still active but performed in inappropriate situations. That is, participants made commission errors if they pressed a specific key in response to animal names in the wrong context (e.g., press *7* when they saw an animal name in a green background instead of a yellow background).

Importantly, some other pieces of evidence support the notion that OT demands should directly influence PM deactivation. First, it is becoming increasingly consensual that executive attention modulates the ongoing processing in accordance with WM rule-constrains or goal-oriented constraints in order to maintain some aspects of the incoming information and other task goals and, thus, support complex thought (e.g., Cowan, 2005, 2017). Second, Lavie et al. (2004) showed that under high-load conditions, WM and task coordination control mechanisms might not be available to ensure that selective attention rejects irrelevant stimuli and OT performance remains in accordance with current priorities. More, during a recognition task, young adults under divided attention showed a bias toward responding "old" when test items are presented simultaneously with to-be-ignored distracters (e.g., Anderson et al., 2011). This last result suggests that divided attention may reduce top–down constraint over retrieval, enabling irrelevant stimuli to be spontaneously retrieved.

In sum, the previous findings led to the idea that the deactivation of PM intentions may not be automatic and may require available cognitive resources. Following this reasoning, PM commission errors in an EBPM task should depend on the concurrent cognitive processing that is taking place when a PM cue (no-longer relevant) reappears.

4.1.2.3. **The present research**

The main goals of the present study were to investigate whether being engaged in demanding cognitive activities influences PM commission error risk for unfulfilled intentions and to explore the role of spontaneous versus strategic processes in PM deactivation. While two relevant studies primarily addressed the role of OT load on PM deactivation, they have explored participants' ability to update and maintain active PM intentions (Boywitt et al., 2015; Pink & Dodson, 2013). We, however, were interested in whether PM commission errors would occur after the PM intention is declared finished and the PM task is no-longer active when the PM cue (for a previously relevant intention) reappears under cognitive loaded conditions.

First, given that the cognitive demands required to perform the ongoing activities might be an important moderator of PM performance, we tested participants in situations that differed only in how difficult the OT processing was by using an innovative three-level load manipulation (no-load, moderate-load, and high-load). Based on the previous literature, if suppressing commission errors for unperformed intentions draws on inhibition (Bugg et al., 2016; Schaper & Grundgeiger, 2019), then a reduced cognitive processing capacity should affect the ability to inhibit the PM response or to tag the PM intention for suppression and, thus, increase the rate of commission errors as a function of OT demands.

Second, given the scarce evidence supporting the dual-process theory suggesting that commission errors occur due to spontaneous retrieval and failed inhibition, additional research is needed. To address this issue, we add a no-PM condition to determine if participants were spontaneously retrieving versus monitoring for a finished-PM intention under cognitive load (inferred from slowed lexical decision responding; Smith, 2003; see also Scullin & Bugg, 2013). Thereby, if PM commission errors arise from a spontaneous PM retrieval, we reasoned that the OT performance (in terms of lexical decision RT) in the no-PM condition should not differ compared to the no-load, moderate- and high-load conditions. Finally, a further aim was to investigate which factors may influence PM deactivation in situations in which an intention becomes irrelevant without being formerly executed. Since the PM cues never appear in the active-PM phase, we predicted that participants would make commission errors regardless of the cognitive load condition, given the Zeigarnik-like tension that keeps unfulfilled intentions more accessible.

4.1.3. Method

*4.1.3.1. **Participants***

Our sample size was based on previous research (Bugg & Scullin, 2013; Bugg et al., 2016). A total of 166 students at the University of Minho participated in the current study in exchange for course credits. Twenty-six participants ($N_{\text{No-load}} = 7$; $N_{\textit{Moderate-load}} = 6$; $N_{\text{High-load}} = 13$) were excluded due to a retrospective memory failure (*n* = 7), failed to follow the instructions to perform the secondary task (*n* = 4), or have anxiety and depressive symptoms (*n* = 15), which has been shown to influence PM ability (e.g., Arnold et al., 2015). Thus, 140 participants (22 male, $M_{\text{age}} = 21.22$, *SD* = 4.27) were included for further analyses. All participants had a normal or corrected vision and were Portuguese native speakers. Participants were randomly assigned to no-PM (*n* = 35), no-load (*n* = 35), moderate-load (*n* = 35), and high-load (*n* = 35) conditions. The local ethical committee for Research in Social and Human Sciences approved this study (SECSH 016/2018; see Appendix 4).

*4.1.3.2. **Design***

The experiment applied a 4 × 2 mixed bi-factorial design with group (no-PM, no-load, moderate-load, and high-load) as the between-subject independent variable and PM-phase (active-PM and finished-PM) as the within-subject independent variable. The main dependent variable was the percentage of participants who made PM commission errors[4]. In addition, we collected data on the frequency of PM commission errors per participant, on accuracy and RTs to the ongoing LDT, and on counting recall task accuracy.

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[4] This criterion has been used in previous studies (e.g., Bugg et al., 2013, 2016; Scullin & Bugg, 2013), since the primary goal of PM aftereffects research is to identify whether a participant will ever repeat a PM response after they have been instructed that the PM task is finished.

4.1.3.3. ***Materials***

The experiment was programmed using SuperLab 5.0 stimulus presentation software (Cedrus, 2013). Using the Portuguese-European norms (The Minho Word Pool; Soares et al., 2019, 2017), words and pseudo-words (i.e., letter strings that although do not have any meaning are combined according to the linguistic rules of a given language) for the LDT ranged between 5–8 characters, word frequency was higher than 75 occurrences per million, and RTs were between 550-750 ms. Four words between 4–6 characters in length (i.e., *phase/wait* or, in counterbalance, *high/title*[5]) served as PM target cues, which signalled the appropriate moment to press the key *Q* (see Appendix 2 and 3). The two words not used as targets served as control words, that is, they matched the PM cues on frequency and length and was also presented during the LDT. The pseudo-words were created by changing the order of the syllables of the 48 new words. Forty words and pseudo-words (20 each) were selected for Phase 1, and every item was presented twice. Forty-eight words and pseudo-words were selected for Phase 2 (24 each) and every item was presented five times. However, half of the words in Phase 2 were repeated from Phase 1 and a half were new. To match the number of presentations, the PM target/control pairs were also presented five times each.

During the first delay interval, depressive and anxiety symptoms were evaluated with the Beck Depression Inventory (BDI; Beck et al., 1961; Portuguese version Vaz Serra & Pio da Costa Abreu, 1973) and the State-Trait Anxiety Disorder (STAI; Spielberger et al., 1983; Portuguese version Silva, 2003), respectively. The BDI is a 21-item, self-report rating inventory that measures characteristic attitudes and symptoms of depression; the STAI-State Scale is 20-item, self-report rating inventory measuring symptoms of state-anxiety.

Finally, our cognitive load manipulation occurred during both the active- and finished-PM phase by adding a secondary counting recall task. Except for the no-load condition, participants were asked to additionally count the number of yellow screens (a total of 16) in the moderate-load condition, and 16 counterbalanced colored screens (e.g., 7 yellow, 5 white, 4 green) in the high-load condition. Based on previous studies, we reasoned that moderate- and high-load conditions would rely on different WM resources (Logie et al., 1994). Whereas the moderate-load condition requires temporary storage in WM (i.e., a mental rehearsal assists retention of accurate running totals), the high-load condition placed a heavy load on WM since a more general-purpose executive resource was involved in implementing the calculation procedure of different colored screens.

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[5] From Portuguese, *fase/espera* and *alto/titulo*.

4.1.3.4. ***Procedure***

At the beginning of the procedure, participants provided written informed consent. Following the procedure of Bugg and Scullin (2013), participants first practiced a LDT in which they were instructed to quickly and accurately make word/non-word judgments by pressing keyboard keys 5 and 6, respectively (see Figure 9). After 10 practice trials, participants in the no-load, moderate- and high-load condition, but not in the no-PM condition, were informed that if they saw either the words *phase* or *wait* (or, in counterbalance, *high* or *title*) on a red (or, in the counterbalanced procedure, blue) background during the LDT, they should press the *Q* key immediately. The PM instruction encoding was confirmed or corrected by having participants write down the PM intention and then repeat it to the experimenter. To approximate highly demanding settings, except for the no-PM and the no-load condition, participants were next asked to additionally count the number of yellow screens throughout the experience in the moderate-load condition, and to count counterbalanced colored screens in the high-load condition.

All stimuli were presented in 24-point Arial white font on a black background. As in Bugg and Scullin (2013), control words (i.e., the two words not used as target cues) appeared against the background color not used for target cues (i.e., red or blue). On each lexical decision trial, a fixation cross appeared for 300 ms followed by the stimulus, which was presented until the participant responded by pressing the 5, 6, *Q* key, or after 2500 ms have elapsed. To provide a short delay between the encoding and test phases (Einstein & McDaniel, 1990), participants completed anxiety and depressive symptomology inventories, which took approximately 6 min. They performed the active-PM phase (i.e., 80 trials of the LDT), in which the PM cues did not appear and, therefore, participants did not have the opportunity to perform the PM intention. Next, participants were instructed that “You have completed the *Q* press task. This task is finished and should not be performed again”.

After a 10 min delay, during which participants performed the Wechsler Adult Intelligence Scale vocabulary test (Wechsler, 2008) and a 24 LDT as filler tasks, which were not analysed, the finished-PM phase begun. They were further instructed that they would perform a LDT and their sole aim was to respond as quickly as possible. This second test phase contained 240 lexical decision trials (list A and list B), in which half of the words and pseudo-words were new, and the other half were repeated from the active-PM phase. The lists were counterbalanced between participants. Target and control words (10 trials each) were grouped, such that all four words were seen before any was repeated. A commission error occurs when a participant performs the PM task (i.e., pressed *Q* again) during the finished-PM despite being instructed that the task was finished.

At debriefing, participants were informed about the experience goals and were then asked (1) to describe the instructions received during the experiment to confirm their understanding of the OTs instructions; (2) to recall the target words and target key; (3) to recall whether they received the instruction that the PM task was finished (if participants did not spontaneously recall that instruction) and, if so, when; and (4) whether they ever pressed *Q* after they were instructed not to, and if so, to describe why. The entire experiment, implemented individually, lasted approximately 45 min.

4.1.3.5. Statistical analyses

The JASP software package was used for standard NHST (Null Hypothesis Significance Testing; JASP Team, 2018, Version 0.9.0.1), considering an alpha level of .05. In addition, we ran Bayes-factor analysis (henceforth *BF)* calculated according to Dienes (2014; see also Wagenmakers et al., 2018). This analysis allows evidence for the null hypothesis and the alternative hypothesis to be directly compared, with a larger *BF* value indicating more support for H_1 and smaller *BF* values offering more support for H_0. In short, the *BF* allows updating the beliefs about the data with evidence collected after the analysis. For instance, if the null hypothesis is that $M_1 = M_2$, and the alternative hypothesis is that $M_1 \neq M_2$, a $BF = 3$ shows moderate evidence in favour of H_1. Simply put, we had a prior belief that $M_1 = M_2$ (H_0). However, after the observation of the data we have to update that belief because it is three times more likely that $M_1 \neq M_2$ than $M_1 = M_2$. Here we will follow the recommendation of the JASP Team (2016): A *BF* of 1 shows no evidence in support of either hypothesis. Evidence accumulated in favour of H_1 when *BF* increases and in favour of H_0 when it decreases. A *BF* from 1 to 3 is interpreted as anecdotal evidence in favour of H_1, from 3 to 10 is moderate evidence, from 10 to 30 is strong, and more than 30 shows extreme evidence in support of H_1. A *BF* from 0.33 to 1 indicates anecdotal evidence in support of H_0, from 0.10 to 0.33 is moderate evidence, from 0.03 to 0.10 is strong evidence, and lower than 0.03 is considered extreme evidence in support of H_0. Results concerning PM performance is presented first, followed by LDT performance, and counting recall task performance.

4.1.4. Results

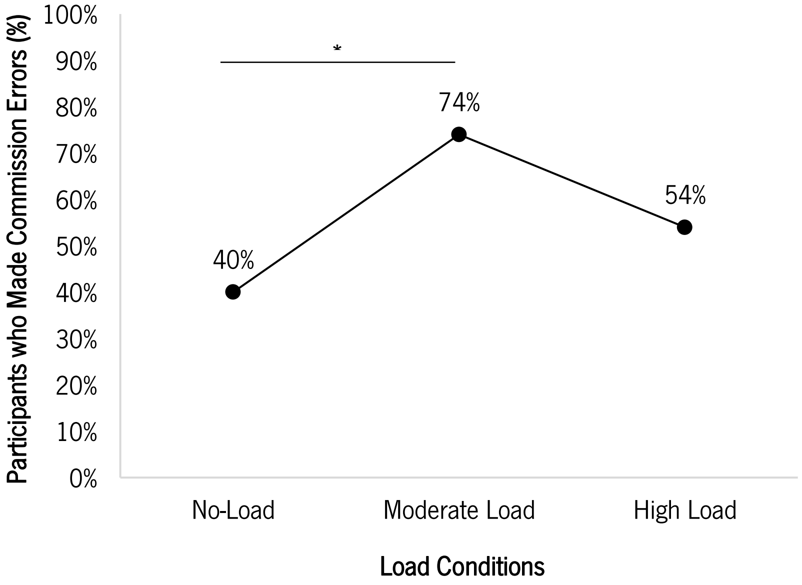
4.1.4.1. PM commission errors

Firstly, we analysed the number of participants who made commission errors (i.e., defined as a *Q* press during the finished-PM phase). Participants were significantly more likely to make a commission error under moderate load (26 out of 35; 74%) than in the no-load condition (14 out of 35; 40%), χ^2 =

8.43, $p = .015$, $\phi = -.28$ (see Figure 14)[6]. Our power to detect this medium-sized effect was .83. The previous analyses showed that a higher percentage of participants made a commission error in the moderate-load condition and Bayesian analyses provided support for that finding. The Bayes factor of $BF_{10} = 4.55$ indicates moderate evidence for the H_1, that is, that there is a different percentage of participants making commission errors in the moderate-load compared with the no-load condition. There were no other significant effects, all $ps \geq .08$. The Bayes factor of $BF_{10} = 0.58$ shows anedoctal evidence in favour of the null hypothesis that the percentage of participants who make a commission error did not differ between the no-load and the high-load condition.

FIGURE 14

Percentage of participants who did at least one commission error as a function of OT load.



Note. *p < .05

Next, we also analysed the proportion of commission errors made per participant (i.e., the total number of *Q* presses/10 targets). A one-way ANOVA showed a significant effect of group, $F(2, 102) = 5.67$, $p = .005$, $\eta_p^2 = .10$. The power to detect this medium-sized effect was .85. Post-hoc Tukey tests showed that the proportion of commission errors was significantly lower in the no-load ($M = .29$, $SD = .42$) than under a moderate-load condition ($M = .64$, $SD = .43$), $p = .003$, *Cohen´s d* = .82, 95% CI [-

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[6] Participants were only included if they recall the target words and target key, as well as the instruction that the PM task was finished (either spontaneously or if they recall the episodic event after a prompt). Importantly, participants were not significantly more likely to make a commission error if they recall the cancelled instructions spontaneously ($n = 71$) or with a prompt ($n = 34$), $\chi2 = 2.68$, $p = .10$, $\phi = .16$. Thus, participants who only recall the instruction that the PM task was finished when given a prompt did not raise the risk of making commission errors. Moreover, when excluding those participants ($n = 34$), we still observe the group effect, $\chi2 = 11.96$, $p = .003$, $\phi = .41$.

.61, -.10]. The former medium-sized effect has a significant statistical power, .96. Bayesian *t* tests revealed extreme evidence in favour of H_1, BF_{10} = 39.88, that is, a different proportion of commission errors was committed between the no-load and the moderate-load condition. The proportion of commission errors did not differ between the no-load (*M* = .29, *SD* = .42) and the high-load condition (*M* = .47, *SD* = .47), *p* = .24, *Cohen´s d* = .40, 95% CI [-.44, .07]; as well as between the moderate-load (*M* = .64, *SD* = .43) and high-load condition (*M* = .47, *SD* = .47), *p* = .34, *Cohen´s d* = .38, 95% CI [-.09, .61].

4.1.4.2. *Lexical decision task*

Separate analyses of variance were conducted for OT accuracy and RTs to investigate the presence of preparatory monitoring or spontaneous PM retrieval processes. Ongoing task accuracy and RTs analyses were performed to words and pseudo-words, excluding target and control trials, trials immediately following each target cue, and each colored screen. This decision is supported by recent studies that have demonstrated that responding to PM targets slows subsequent OT performance and must be considered as an additional source of costs (Marsh, Hicks, et al., 2002; Meier & Rey-Mermet, 2018; Smith & Hunt, 2014). Also, only accurate responses, slower than 300 ms but faster than 3 SDs above each participant´s individual mean, and calculated separately for each phase (i.e., active-PM and finished-PM), were included in the analyses to control for aberrant RTs (Ratcliff, 1993; Smith, 2010).

We ran two 4 × 2 mixed ANOVAs with PM-phase (active and finished) as the within-subjects factor and group (no-PM, no-load, moderate-load, and high-load) as the between-subjects factor. The idea is that if participants were spontaneously retrieving the PM intention there should be no differences in the LDT performance in the no-load, moderate- or high cognitive load conditions compared to the no-PM condition. The results for OT accuracy are given in the first columns of each condition in Table 8. There was no significant differences between the two PM-phases, *F*(1, 136) = 2.32, *p* = .63, η_p^2 = .00, or a main effect of group, *F*(1, 136) = .97, *p* = .41, η_p^2 = .01. Thus, the introduction of a PM task did not impact the accuracy of response in the OT, even when associated with distinct levels of cognitive load. The interaction between PM-phase × group was also not significant, *F*(1, 136) = .56, *p* = .70, η_p^2 = .02. Regarding OT RTs (see Table 8), there was a main effect of PM-phase, indicating that participants were slower in the active-PM phase (*M* = 885, *SD* = 189) compared to the finished-PM phase (*M* = 687, *SD* = 105), *F*(1, 136) = 297.84, *p* <.001, η_p^2 = .69. The main effect of group was not significant, *F*(1, 136) = 1.52, *p* = .21, η_p^2 = .03, but the main effect of phase was qualified by a significant interaction with group, *F*(1, 136) = 3.68, *p* = .014, η^2 = .08. Pairwise comparisons did not reveal any significant effect, all *ps* > .29.

TABLE 8

Means (M) and standard deviations (SD) of LDT performance as a function of OT load.

	Commission error		No-load		Moderate-load		High-load	
	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*
PM-phase								
Active-PM	.95 (.07)	924 (178)	.96 (.03)	866 (216)	.94 (.11)	822 (134)	.95 (.06)	926 (205)
Finished-PM	.96 (.03)	692 (94)	.95 (.03)	680 (141)	.94 (.10)	681 (76)	.94 (.05)	693 (100)

TABLE 9

Means (M) and standard deviations (SD) of LDT performance as a function of participants who did versus did not make commission errors.

	Commission error		No-commission error	
	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*
PM-phase				
Active-PM	.95 (.09)	839 (181)	.95 (.06)	913 (199)
Finished-PM	.94 (.08)	676 (107)	.95 (.03)	697 (111)

With the same assumption, we next analysed OT performance between participants who did versus did not make commission errors. We ran two 2 × 2 mixed ANOVAs with PM phase (active and finished) as the within-subjects factor and group (commission error and no-commission error) as the between-subjects factor. The results are detailed in Table 9. Considering LDT accuracy, there was no significant differences between the two PM-phases, $F(1, 103) = .19$, $p = .65$, $\eta_p^2 = .00$. There was no group or commission error-related differences for lexical decision accuracy, $F(1, 103) = .39$, $p = .53$, $\eta_p^2 = .00$, neither the interaction between PM-phase × group was significant, $F(1, 103) = .19$, $p = .67$, $\eta_p^2 = .00$. Concerning OT RTs, there was a main effect of PM-phase. Participants were slower in the active-PM phase ($M = 872$, $SD = 192$) compared to the finished-PM phase ($M = 685$, $SD = 109$), $F(1, 103) = 182.91$, $p < .001$, $\eta_p^2 = .64$. There were no RTs differences between those who made a commission error and those who did not, $F(1, 103) = 3.05$, $p = .08$, $\eta_p^2 = .03$, and the interaction PM-phase × group did not reach significance, $F(1, 103) = 3.46$, $p = .06$, $\eta^2 = .03$. In addition, Bayesian *t* tests, $BF_{10} = 0.28$, indicates moderate evidence in favour of the null hypothesis. That is, a similar LDT accuracy in the finished-PM phase between participants who did versus did not make commission errors. Likewise, Bayesian *t* tests revealed anedoctal evidence in favour of the null hypothesis, BF_{10}= 0.32. Simply put, LDT RTs in the finished-PM phase did not differ between participants who did versus did not make commission errors. Collectively, these results suggest that adding a PM task did not have an indirect cost in the primary OT performance, supporting the idea that participants were not monitoring to detect the PM cues, but retrieving the PM intention more automatically

*4.1.4.3. **Counting recall task***

To assess possible differences between the proportion of correct responses in the secondary OT across the moderate- and high-load condition, we applied an independent sample Student´s *t* test which showed significant statistical differences. That is, participants assigned to the moderate-load condition (*M* = .91, *SD* =.18) were more accurate in the counting recall task compared to participants under high-load (*M* = .75, *SD* =.13), *t*(68) = 4.35, $p < .001$, *Cohen´s d* = 1.02, IC 95% [.09, .23]. The Bayes factor of BF_{10} = 436.67 indicates extreme evidence for the H_1 that there is a different counting recall accuracy between the moderate- and high-load condition. This finding supports that the secondary OT manipulation to create low and high concurrent demands was effective.

4.1.5 Discussion

The experimental study of PM commission errors under cognitively demanding activities has very recently been a fruitful path to test theoretical predictions about PM deactivation. In this context, the main aims of this study were twofold: (1) To evaluate if the difficulty of the OT can influence the ability to deactivate a PM intention no-longer relevant and (2) to further explore spontaneous versus strategic PM retrieval. As far as we know, this is the first study that has examined PM commission errors under demanding activities that does not require a constant memory updating of the status of the PM intention (i.e., the PM task was declared finished, and there was no longer any new-PM task to accomplish). It is also the first study to use an innovative procedure based on Bugg and Scullin's (2013) paradigm, including three groups that differ in the amount of resources required by the background tasks.

When PM deactivation failures happen outside the laboratory, they occur for specific reasons. The present study suggests that one reason might be the concurrent cognitive processing that takes place when a PM cue is encountered. To foreshadow, consistent with prior research, our results support the assumption that a PM intention might be spontaneously retrieved and erroneously executed when the (no-longer relevant) PM cue reappears under more difficult OTs. Yet, our results did not indicate an increased rate of commission errors when the overall OT demands were made highly difficult. Finally, we observed PM commission errors regardless of the cognitive load based on the idea that an unperformed intention is maintained at a heightened level of activation and is, therefore, more easily recalled. We will discuss each finding in turn.

To the best of our knowledge, this experiment provides the first demonstration that the overall demands of the OT situation influence the deactivation of unperformed PM intentions when there is no-longer any PM task to perform in the future. First, as hypothesised, younger adults were more vulnerable to PM commission errors if engaged in challenging cognitive ongoing activities. In line with past work (Boywitt et al., 2015; Pink & Dodson, 2013), we found that more participants make commission errors under moderate-resource demanding conditions (74%) compared to the no-load condition (40%). This result is also consistent with previous work showing that an intention might remain active and accessible for a minimum of 48 hr (Dasse & Scullin, 2016). Noteworthy, a recent systematic review also indicates that, if the WM demands required by the OT processing did not engage a deeper degree of central executive processing (e.g., tone- or digit-monitoring tasks), the PM retrieval still occur although under more difficult conditions (Matos et al., 2020). In such cases, even when the PM task has been declared finished, it can continue to be retrieved and, if not successfully inhibited, PM commission errors can occur.

Theoretically, interpreting PM as a multitasking situation links into the assumption that the processing requirements play a crucial role in the overall task situation (Anderson et al., 2018; Martin & Schumann-Hengsteler, 2001). The idea is that the availability of WM capacity and executive attention resources to reject stimuli irrelevant to the task at hand and, importantly, to inhibit the irrelevant PM intention is decreased when the cognitive system is subjected to incremental and concurrent loading of demanding activities (Cowan, 2005, 2017; Hasher et al., 2007). Conversely, less demanding conditions in our study could have facilitated cognitive control such that when the PM intention was retrieved in response to the target cue, a no-go response was reactively applied. Regardless of whether such inhibitory mechanism was intentional (i.e., conscious) or was a more automatic result of an executive-link resource of WM, the result is the same: Event-based PM tasks deactivation suffers under cognitively demanding conditions.

Another finding was that the number of participants who made commission errors did not significantly increase in the high-cognitive load compared to the moderate-load condition. A possible explanation is that, in the high-load condition, the OT load interfered with the full processing of the PM cue and/or with the retrieval of the intention into awareness (Harrison et al., 2014; Marsh et al., 2002), thereby decreasing the vulnerability to perform an irrelevant intention. However, since we used salient and focal PM cues, which has been shown to promote spontaneous PM retrieval, this idea seems counterintuitive. A lack of commission errors may not necessarily indicate PM deactivation and allows us to shed light on the theoretical explanations of PM commission errors. According to the dual-mechanisms account (Bugg et al., 2016), taxing cognitive resources should have disturbed the inhibitory capacity to suppress the associated response upon spontaneously retrieving the former PM intention as a function of the OT load. Yet, in a highly demanding situation, an inhibitory restraint mechanism (Hasher et al., 2007) might have made it easier for participants to restrain the strong but inappropriate response after the interfering PM information was activated. Simply put, an inhibitory function may have helped to tag it for suppression when the intention was spontaneously retrieved in response to PM cues (Schaper & Grundgeiger, 2019; see also Posner & Snyder, 1975 for a conceptualisation of cognitive control as effortful and strategic). Remarkably, for example, a previous study conducted in our laboratory showed that participants with low-span WM capacity were able to allocate top-down processing strategies, which facilitated the effect of the inhibitory function of restraint (Oliveira & Albuquerque, 2013). Future studies may benefit from using thought probe procedures to examine whether encountering PM cues under such complex conditions leads to a conscious retrieval of thoughts related to the PM inhibition.

Further, the current study (see also Boywitt et al., 2015; Pink & Dodson, 2013) contributes to better understand contradicting results arguing for minimal failures in PM forgetting when cognitive resources are also devoted to accurately performing demanding activities. For example, Schaper and Grundgeiger (2017), who used an activity-based PM task (i.e., the PM response had to be performed after a task has finished), and Walser et al. (2014), who manipulated the type of processing between the instruction that the intention is finished and the finished-PM phase found that commission errors do not necessarily increase under load. Two possible explanations, respectively, are that the impact of cognitive load might differ according to the type of PM task since activity-based intentions must be completed between tasks; and, another crucial aspect seems to be whether the PM cue reappears under the demanding OT instead of in the interval between the finished-PM instruction and the appearance of the PM cue.

Regarding our second hypothesis, we found that lexical decision response time was similar between participants in the no-load, moderate-load, high-load, and the no-PM condition. Further, we also found that participants who did make commission errors were not slower in the LDT compared to those who did not make a commission error. Thus, a second theoretical implication is that our results are consistent with a spontaneous PM retrieval instead of a monitoring view, which argues that PM retrieval should not occur in the absence of strategic and effortful processes (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2009). The following issues also support this interpretation. We strengthened the associative cue-action link by having participants write down the instructions and repeat them out loud (i.e., implementation intention strategy), which has been shown to increase the likelihood of spontaneous retrieval (Bugg et al., 2013; McDaniel et al., 2008; Rummel et al., 2012). Moreover, the PM cue trials appeared on blue and red backgrounds (i.e., salient cues), and the defining features of the PM cues are part of the information being extracted to perform the OT (i.e., focal cues). As mentioned earlier, existing evidence shows that a salient or focal cue will spontaneously trigger the retrieval of the associated action from LTM (McDaniel & Einstein, 2000).

Surprisingly, a more demanding condition did not impair the overall LDT performance. Our result is inconsistent with Boywitt et al.'s (2015) finding of poorer LDT performance when a tone-monitoring task was added to the primary OT (LDT performance scores were not available in the Pink and Dodson study, 2013). In Boywitt et al.'s (2015) study, however, participants were asked to press the *7* key on the keyboard when one out of 12 animal names appeared in a specific context color. Hence, it may well be argued that the higher PM load (i.e., imposed by the number of potential PM cues or PM categories) could have enhanced costs in the OT due to additional monitoring requirements (Meier & Zimmermann, 2015). Apart from this, it seems reasonable to suggest that participants may have prioritised the LDT since this was the task that had to be performed on each and almost every trial. Importantly, the lexical decision is a cognitive process where a reader automatically accesses knowledge about a familiar written word (Castles & Nation, 2008) and, unlike other perceptual tasks, appears unaffected by a difficult divided-attention task (Mulligan & Peterson, 2008). In this respect, previous research shows that the relationship between available WM resources and individuals' performance on concurrent tasks competing for available attentional/WM resources is not straightforward. Recently, for instance, Cheie et al. (2017) observed the counterintuitive finding that children's arithmetic performance was superior in the WM plus a PM condition, compared to their performance on the PM condition in which the additional WM requirement was absent. Taken together, these findings may help us to understand why there is overall high LDT performance across conditions, despite load manipulation taxing young adults' cognitive resources. Noteworthy, an important finding was that participants under high-cognitive load had worse counting recall accuracy than those in the moderate-load condition, rendering support to the OT load manipulation.

Finally, our results replicated a previous finding that an unfulfilled intention might be accessible and easily recalled (Bugg et al., 2016; Bugg & Scullin, 2013). We found that an unfulfilled intention is still accessible and likely to be performed regardless of OT load, even when participants have been explicitly instructed not to do so. From a theoretical perspective, this result seems to favour the recent modified dual-mechanisms account (Schaper & Grundgeiger, 2019) since from the dual-mechanisms view it should be harder to inhibit a repeatedly performed intention (Pink & Dodson, 2013). Nevertheless, research verifying the specific inhibitory mechanism involved in PM deactivation is needed to disentangle between the two theoretical proposals.

4.1.6. Conclusions

In sum, our cognitive system is constantly required to perform but also to inhibit multiple intentions daily. This study was the first to investigate the impact of OT load on the ability to deactivate unperformed intentions when any new-PM task has to be executed next. First, we observed that a former PM cue might promote a spontaneous retrieval of the irrelevant intention. This point is nontrivial given people's intuition that once an intention is cancelled, it is forgotten. Second, this study highlights that the PM deactivation mechanism seems to involve a specific disengagement process which implies available cognitive resources. For instance, being busily engaged in finishing an important report while performing complex statistical analyses increases the probability of taking medicines (that was never taken but is no longer prescribed) from a package that is right on our desk. Theoretically, the current research provides therefore strong support for a dual-mechanisms account underlying this memory failure (Bugg et al., 2016; Schaper & Grundgeiger, 2019). Finally, the ability to deactivate PM intentions is highly relevant because a failure to disengage from finished intentions might incur not only commission errors but also impair the retrieval and execution of current and new goals. This, of course, is an avenue for future research.

4.1.7 References

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4.2 STUDY 2 | Moving forward:
Exploring the role of interference on prospective memory deactivation

4.2.1. Abstract

Recent PM studies have shown that an intention may be erroneously executed despite no-longer-needed (i.e., commission errors), mainly under demanding ongoing activities. In the current study, we examined whether PM deactivation benefits from an RI mechanism under such environments. In two experiments, we set up a procedure in which participants first learned about a PM task and were then told that the task is cancelled. Next, they encoded a new, dissimilar and more complex PM intention to accomplish later (Experiment 2) or performed filler WM tasks with increased difficulty levels (Experiment 3). Lastly, all participants encountered several (but irrelevant) PM cues. Results showed that encoding a dissimilar and more taxing PM intention or new WM contents, respectively, prevented the occurrence of PM commission errors. These findings are discussed in terms of strategic or spontaneous retrieval processes and linked to an RI which might help to overwrite or deteriorate the old-PM task representation.

Keywords: prospective memory deactivation; commission errors; retroactive interference; unperformed intentions

4.2.2 Introduction

Anyone who has tried to remember to send an important report the next day has experienced what researchers refer to as PM (Einstein & McDaniel, 1990; Loftus, 1971; Rummel & McDaniel, 2019). Prospective memory intentions are frequently updated and some of them become no-longer-needed. The idea is that those irrelevant prospective memories rapidly decay or are otherwise deactivated (i.e., actively suppressed). However, several studies have shown that individuals may not deactivate them (e.g., Anderson & Einstein, 2017; Bugg et al., 2016; Matos et al., 2020; Schaper & Grundgeiger, 2019; Walser et al., 2017). For instance, we should not send that report, after all, because we will have a face-to-face meeting by the end of the week. Yet, the environmental cue (e.g., see the computer) that may trigger retrieval of that previously PM intention (e.g., send the report) often reappear. Then, commission errors might occur if a PM task is erroneously executed despite there is no need to do so.

Prospective memory commission errors are usually investigated by asking participants to perform a PM task during an ongoing activity (e.g., press *Q* when an infrequent PM cue - the word *dancer* - is presented during a LDT). Upon this active-PM phase, they are then told that the PM intention (1) is temporarily suspended (Einstein et al., 2005; Scullin et al., 2009), or (2) is finished and therefore no-longer relevant (i.e., finished intentions; Scullin et al., 2012). Moreover, PM tasks might be declared finished without being previously executed (termed zero-target conditions, because participants never see PM cues while the intention is still active; Bugg et al., 2013, 2016). Critically, during the finished-PM phase that follows, unexpected (former) PM cues occur embedded in a new OT (Phase 2). Several studies have shown that both younger and older adults are slower in response to those (re)presented PM cues relative to control trials, which is inferred as a spontaneous, but erroneous, PM retrieval or even made commission errors (e.g., press *Q* in response to *dancer*; Anderson & Einstein, 2017; Bugg et al., 2016; Matos et al., 2020; Pink & Dodson, 2013; Schaper & Grundgeiger, 2019; Scullin et al. 2009; Walser et al., 2017; for a review see Möschl et al., 2020).

Different theoretical accounts have been proposed to explain the occurrence of such memory failures. First, we may hold an intention in mind and actively monitor the environment for a cue that signals that is the appropriate moment to fulfil the PM task. This process requires available cognitive resources and so it may incur costs to the performance of the other ongoing activities (e.g., Einstein & McDaniel, 2005; Einstein et al., 2005; Smith, 2003). A somewhat different perspective is taken by a theory of delay suggesting that the OT costs reflect people slowing down their responding to allow more time for PM-related information to accumulate and, thus, notice the PM cue (Heathcote et al., 2015;

Strickland et al., 2018). From this viewpoint, commission errors occur if those monitoring processes or accumulation process have not been discontinued upon intention completion (possibly due to confusion since there is no motive for participants to commit resources toward monitoring for PM cues; Scullin & Bugg, 2013).

Second, the dual-mechanisms account posits that commission errors result from a spontaneous PM retrieval and a subsequent failure to inhibit the execution of the intention (Bugg et al., 2016; Scullin & Bugg, 2013). So far, the evidence strongly suggests that the PM cue occurrence within an OT context might trigger a more automatic retrieval without any decline in the OT, such as when the cue is salient (e.g., perceptually deviate from standard trials) or focal (i.e., the OT encourages processing of the attributes of the PM cue that was processed during initial encoding; Einstein et al., 2005; McDaniel & Einstein, 2000). On the one hand, the empirical support for this view stems from the finding that participants who held a PM task that becomes no-longer-needed have a similar OT performance when compared to a control condition without any PM task to accomplish (Scullin & Bugg, 2013; see also Matos et al, 2020). That is, participants were not allocating cognitive resources to monitor for their old-PM intentions[7]. On the other hand, some studies recently showed that young adults are more vulnerable to execute a previous PM intention under conditions of heavy cognitive load or distraction which become unnecessary[8] (Boywitt et al., 2015, Experiment 1; Matos et al., 2020; Pink & Dodson, 2013). According to the executive attention theory (Engle et al., 1995; see also Cowan, 2005), WM capacity also depends on an attentional control mechanism (executive attention) that allows us to critically inhibit contextual information irrelevant to the OT at hand. Thus, it is arguable that if cognitive resources are divided between tasks and inhibitory mechanisms are being tapped out, it could be hard to activate the relevant information to perform the OT, eliminate the old-PM task representation, or even suppress the salient but irrelevant PM cue information (Hasher & Zacks, 1998). Simply put, the sparse resources leftover under such demanding environments might lead to a cognitive control failure and, then, impair the deactivation process to work sufficiently.

However, it would seem sub-optimal to continually inhibit internal PM representations in everyday situations. Moreover, in real-life, we must constantly form, maintain, retrieve, and execute several intentions rather than single intentions in isolation and regardless of whether other old intentions have been completed. On this promise, we can argue that a potential mechanism of RI (by which newly

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[7] Hereafter, we use the term old-PM intention to refer to the PM task which was declared finished.

[8] Schaper and Grundgeiger (2017, Experiment 2) and Einstein et al. (1998) did not found increased aftereffects of PM intentions as a function of cognitive load. However, these studies used an activity-based PM task and a TBPM task, respectively. In such cases, target cues do not appear during the OT.

encoded memories help to overwrite or degrade an existing memory trace; Barnes & Underwood, 1959), that has long been held to cause forgetting, may apply to PM deactivation, too. More specifically, memories appeared to decay over a retention interval because they are interfered with by additional memories that the subjects have learned (Nairne, 2002; Wixted, 2010). Thus, it is reasonable that a new-PM task representation might help to deactivate older prospective memories, that is, that commission errors may be reduced while we manage to respond to the changing demands of our environment.

Therefore, an important issue is to examine whether PM deactivation may be a function of newly PM tasks replacing or interfering with the memory representation of an old-PM intention. To the best of our knowledge, only a few studies empirically tested this idea (Anderson & Einstein, 2017; Walser et al., 2012, 2017). Anderson and Einstein (2017) conducted an experiment in which they asked participants to encode a new-PM intention to perform later during a finished-PM phase (i.e., when unexpected irrelevant cues associated with an old-PM intention still occur as OT stimuli). Yet, the authors did not find that such a strategy significantly reduced PM deactivation failures. However, Walser et al. (2017) observed that encoding a new intention in which no components of the old-PM task representation are needed for performing it helped to reduce commission error risk. In their procedure, new-PM tasks were encoded over several blocks (i.e., respond to specific words rather of symbols as in an old-PM condition) after former intentions are declared finished (termed repeated-cycles paradigm; Walser et al., 2012, 2017). It is also worthy to note that commission errors seem to decrease by encoding novel memory representations in the interval between the instruction that a former PM task is finished and the later appearance of irrelevant PM cues (Walser et al., 2014).

The aim of the present study was then to extend previous work by examining two questions: Do individuals show less intention deactivation failures if engaging novel intentions to fulfil in the future? Does performing cognitively demanding tasks after an intention becomes no-longer relevant helps to override the old-PM task set and support PM deactivation? This could be how we update our PM demands, such that moving to address new and dissimilar contents deactivates the old-PM intention, reducing commission error risk. A novel aspect of our research is that it explores this issue in contexts in which participants never fulfil the intention due to the absence of PM cues while it was still active (i.e., zero-target conditions). These unfilled intentions might be harder to forget due to the lack of episodic traces (of prior responding) or its heightened activation (Bugg et al., 2016). Yet, it is arguable that prospective remembering might benefit from an interference mechanism that helps to deactivate such unperformed, but irrelevant intentions.

Moreover, in the repeated-cycles paradigm used in some of the abovementioned studies, participants must regularly update their representations of which intention is currently relevant since they shift from one intention to the next throughout several blocks (e.g., Walser et al., 2012, 2014). Here, we have focused on manipulations that may decrease commission errors when there is a single active-PM phase and the PM task is declared finished afterward by telling participants that they should no-longer respond to PM cues. In convergence with the prominent dual-mechanisms account, we also added a no-PM control condition to examine whether PM retrieval and, therefore, commission errors result from an automatic rather than a controlled process. Finally, to the best of our knowledge, there is no evidence concerning which factors prevent PM commission errors under cognitively demanding environments. For instance, consider the earlier example of sending a report. We might have to do so during a day in which one must pack and is also the deadline for primary school enrolment. For that reason, we added a secondary OT (i.e., a counting recall task) to increase the overall demands. That is, the total amount of WM (i.e., to process and retain information temporarily) and attentional control resources deployed by the cognitive system increase to meet task demands (Conway et al., 2005).

4.2.3. **Experiment 2**

The role of RI on PM deactivation remains unclear. Besides, the procedure used in the studies on this topic does not capture many real-world situations in which PM tasks are updated and new dissimilar intentions must be carried out under loaded conditions. Thus, in Experiment 2, we manipulated whether a new and dissimilar PM intention must be fulfilled after the old-PM intention is declared finished using a finished-PM paradigm. To explore this possibility, we adapted the procedure proposed by Scullin and Bugg (2013). As noted, participants encoded a PM task, namely, pressing *Q* if the target cue *high* or *title*[9] in a red background appears while performing an ongoing LDT (i.e., active-PM phase). Later, participants are told that the PM intention is finished and, thus, they should no-longer respond to cues. Critically, they were asked to perform a new-PM task subsequently during the same ongoing LDT. As a reminder, participants make a commission error by pressing the *Q* key when cues associated with the old-PM task are presented during the finished-PM phase.

The main goal of Experiment 2 was to understand if introducing a new-PM task under a demanding OT processing reduces the level of activation associated with the old-PM representation to diminish its accessibility. Thus, reducing the number of participants who make commission errors. We expected that the *new-PM task condition* should result in fewer commission errors compared with the *no*

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[9] From Portuguese, *alto* or *título.*

new-PM condition, in line with an earlier work indicating few PM lapses when the category of both intentions differed (Walser et al., 2017). Furthermore, we explored the type of PM retrieval process that is taking place. Thus, as a third critical condition, we included a *no-PM condition* without any PM task. Examining the effect of having to perform a PM intention on the OT processing provides additional leverage for informing the theoretical views of PM retrieval stated above. According to previous work (Matos et al., 2020; Schaper & Grundgeiger, 2019; Scullin & Bugg, 2013), we reasoned that commission errors might result from a spontaneous retrieval process and so there should be no differences in the OT performance between the no-PM and each of no new-PM and new-PM conditions. If, on the contrary, participants are devoting cognitive resources to monitor for PM cues, it should be expected a worse OT performance in the two experimental conditions compared to the no-PM group.

4.2.3.1. Method

*4.2.3.1.1. **Participants***

An a priori power analysis (based on $p_{1\ (\text{No-load})} = 0.40$ and $p_{2\ (\text{Moderate-load})} = 0.74$ and sample size N = 70 of our previous work, Matos et al., 2020) indicated that a sample of 3 × 42 participants was needed (two-tailed, α = .05, power = .90; conducted for a Chi-Square test of independence using PS-Power and Sample Size Calculation, Dupont & Plummer, 1990). Thus, 137 students of the University of Minho participated in an exchange of course credits. All participants had a normal or corrected vision, reported no psychiatric history and were Portuguese native speakers. Fourteen (10%) participants were excluded from the analyses ($N_{\text{No new-PM}} = 8$; $N_{\textit{New-}\text{PM}} = 6$), either because they could not correctly recall the PM task or the finished-PM instruction at the end of the experiment (n = 8), or due to depression and anxiety symptoms (n = 6; see Bowman et al., 2019). The 123 participants (14 male, $M_{\text{age}} = 21.50$, SD = 4.23) were randomly assigned to the no-PM (n = 39), no new-PM (n = 42), and new-PM (n = 42) conditions. The local ethical committee for Research in Social and Human Sciences approved this study (SECSH 016/2018; see Appendix 4).

*4.2.3.1.2. **Design***

The design was a 2 × 3 mixed-factorial, with PM-phase (active and finished) as the within-subject variable and PM condition (no-PM, no new-PM, and new-PM) as the between-subjects variable. The main dependent variable was the percentage of participants who made commission errors. In addition, we assessed the frequency of PM commission errors per participant, LDT performance (accuracy and RTs), and counting recall task accuracy.

4.2.3.1.3. ***Materials***

Sixty-eight words were extracted from the Minho Word Pool (Soares et al., 2017, 2019). For the LDT, 36 words ranged between five to eight letters long, word frequency higher than 75 occurrences per million, and RTs between 550-750 ms. The pseudo-words (i.e., letter strings that although do not have any meaning are combined according to the linguistic rules of a given language) were created by changing one or to syllables of 32 new words with 5-8 length. Further, two out of four words between four to six letters (i.e., *phase/wait; high/title*[10]) served as PM targets (i.e., signalled the appropriate moment to execute the PM task) or, in counterbalance, control words (i.e., matched PM cues in frequency and length; see Appendix 2 and 3). Forty words and pseudo-words (20 each) were selected for Phase 1, and every item was presented twice. Forty-eight words and pseudo-words were selected for Phase 2 (24 each), in which half of the words were repeated from Phase 1 and a half were new. Every item was presented five times to match the frequency of target/control words.

During the first delay interval, depressive and anxiety symptoms were evaluated with the BDI (Beck et al., 1961; Portuguese version Vaz Serra & Pio-Abreu, 1973) and the STAI (Spielberger et al., 1983; Portuguese version Silva, 2003), respectively. The BDI is a 21-item, self-report rating inventory that measures attitudes and symptoms of depression; and, the STAI-State Scale is 20-item, self-report rating inventory measuring symptoms of state-anxiety. Finally, the Vocabulary Test (Wechsler, 2008), which is a verbal comprehension task in which participants must define the words presented, was performed during the second delay interval.

4.2.3.1.4. ***Procedure***

The procedure had four main sections: (1) Instructions, (2) active-PM phase, (3) finished-PM phase, and (4) debriefing. First, participants in all conditions were informed about the OT, namely, a LDT in which they had to quickly and accurately make word/non-word judgments by pressing keyboard keys “5” and “6”, respectively (see Figure 15). All words and pseudo-words were presented in white, Arial, 24-point font on a black background. Participants were instructed to use their index fingers and to keep them on the keys throughout the experiment. Each lexical decision trial started with a fixation cross presented for 300 ms followed by the stimulus, which was presented until the participant responded by pressing the 5, 6, *Q* key, or after 2500 ms.

In the active-PM phase that follows, they perform 80 lexical decision trials without PM cues or control trials, so they did not have the opportunity to perform the PM intention. Then, the PM task was

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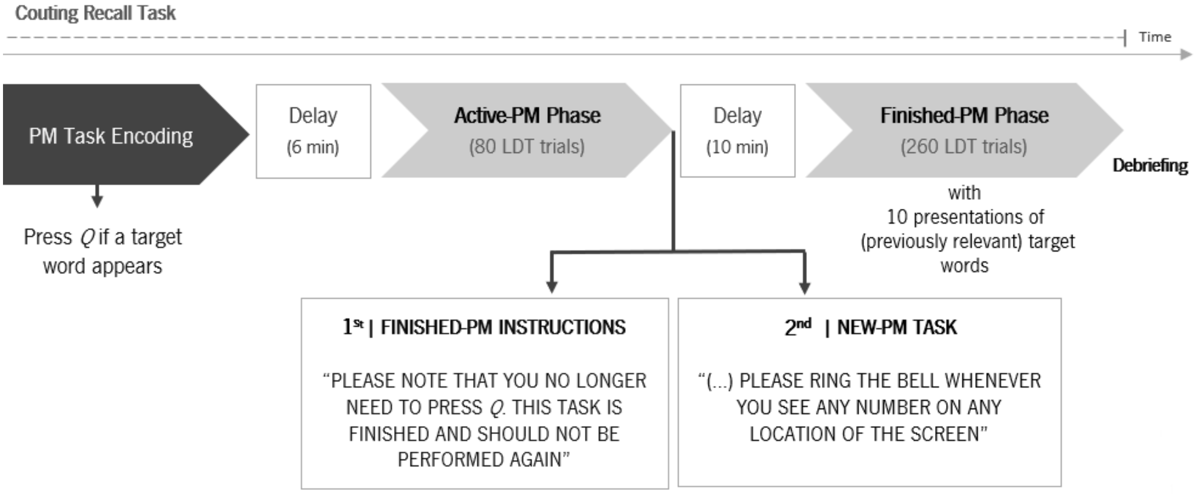
[10] From Portuguese, *fase/espera* and *alto/título*.

FIGURE 15

Schematic representation of the adapted Bugg and Scullin´s paradigm (2013) used in this study.



declared finished by telling participants that they no-longer-needed to press the *Q* key. That task was declared finished and should not be performed. In the new-PM task condition, participants were immediately asked to press a bell (placed next to the keyboard) whenever they saw numbers in any location of the screen either in the presented words/pseudo-words or in the background screen. Note that, in the new-PM condition, the numbers were never presented so there was no opportunity to perform the new-PM task. We used a new-PM task that presumed to place greater demands on attention and planning (Bugg & Ball, 2017; Meier & Zimmermann, 2015). To ensure that the new-PM task had the same encoding as the old-intention, participants were again asked to reproduce the instructions in writing and orally.

After a 10 min delay during which both groups performed a vocabulary test (Wechsler, 2008) and a 24 LDT as filler tasks, the finished-PM phase begun. They were further instructed that their sole aim was to respond as quickly as possible to a LDT containing 260 lexical decision trials (including 10 trials with the former PM cues and 10 control trials presented in the salient background, as in the active-PM phase). A commission error occurs when participants perform the PM task (i.e., pressed *Q*) despite being instructed that the PM task was finished.

Finally, participants were asked to describe all the instructions received during the experiment. If participants did not do it spontaneously, we asked them to (1) recall the target words and target key; (2) if they received the instruction that the PM task was finished and, if so, when did that happen; and (3) whether they ever press *Q* after they were instructed not to, and if so, to describe why. The entire experiment was implemented individually and lasted approximately 45 minutes.

4.2.3.1.5. ***Statistical analyses***

As in Study 1, to test our hypotheses, we ran standard NHST considering an alpha level of .05, using JASP (JASP Team, 2018, Version 9.0.1). To support these results, a Bayesian analysis were also implemented which can provide evidence in support of either the null or the alternative hypothesis (Wagenmakers et al., 2018). In short, the *BF* allows updating the beliefs about the data with evidence collected after the analysis. As stated, for instance, if the null hypothesis is that $M_1 = M_2$, and the alternative hypothesis is that $M_1 \neq M_2$, a $BF = 3$ shows moderate evidence in favour of H_1. Simply put, we had a prior belief that $M_1 = M_2$ (H_0). However, after the observation of the data we have to update that belief because it is three times more likely that $M_1 \neq M_2$ than $M_1 = M_2$. Here we will follow the recommendation of the JASP Team (2016): A *BF* of 1 shows no evidence in support of either hypothesis. Evidence accumulated in favour of H_1 when *BF* increases and in favour of H_0 when it decreases. A *BF* from 1 to 3 is interpreted as anecdotal evidence in favour of H_1, from 3 to 10 is moderate evidence, from 10 to 30 is strong, and more than 30 shows extreme evidence in support of H_1. A *BF* from 0.33 to 1 indicates anecdotal evidence in support of H_0, from 0.10 to 0.33 is moderate evidence, from 0.03 to 0.10 is strong evidence, and lower than 0.03 is considered extreme evidence in support of H_0. Results concerning PM commission errors are presented first, followed by LDT performance and, then, by the counting recall task performance.

4.2.3.2. Results

4.2.3.2.1. ***PM commission errors***

A PM commission error was defined as at least one *Q* press in the trial with the PM cue during the finished-PM phase. The no-PM condition was excluded from the analyses because participants did not have any PM task to accomplish. There was a higher percentage of participants making a PM commission error in the no new-PM (30/42; 71.43 %) than in the new-PM task condition (14/42; 33.33 %), $\chi^2 = 12.22$, $p < .001$, $\phi = -.38$[11] (see Figure 16A). To further explore the effect of interference by a new-PM task, the *BF* was calculated and examined using the dichotomic variable of whether participants made a commission error. There was extreme evidence for H_1 ($BF_{10} = 120.44$), that is, a different proportion of participants making commission errors in the no new-PM relative to the new-PM task

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[11] Participants were only included if, at the end of the procedure, they recall the target words and target key, as well as the instruction that the PM task was finished (either spontaneously or if they recall the episodic event after a prompt). Importantly, participants were not significantly more likely to make a commission error if they recall the finished-PM instructions spontaneously ($n = 57$) or with a prompt ($n = 27$), $\chi^2 = 3.25$, $p = .071$, $\phi = .20$. Moreover, when excluding those participants ($n = 27$), we still observe significantly more commission errors under cognitive load, $\chi^2 = 7.41$, $p = .006$, $\phi = -.36$.

condition (see Figure 17A). Taken together, results showed that fewer participants made a commission error in the new-PM task condition and Bayesian analyses provided support for that finding.

Next, we also analysed the frequency of commission errors made per participant (i.e., the total number of *Q*-presses/10 targets). An independent sample Student´s *t* test indicated that the frequency of commission errors per participant was significantly higher in the no new-PM (*M* = .59, *SD* = .44) than in the new-PM task condition (*M* = .26, *SD* = .41), $t(82) = 3.56$, $p < .001$, *Cohen´s d* = .77, 95% CI [.15, .52]. Bayesian *t* tests support the previous finding revealing extreme evidence in favour of H_1, $BF_{10} = 39.88$. That is, a different frequency of commission errors committed by participants in the no new-PM than in the new-PM task condition.

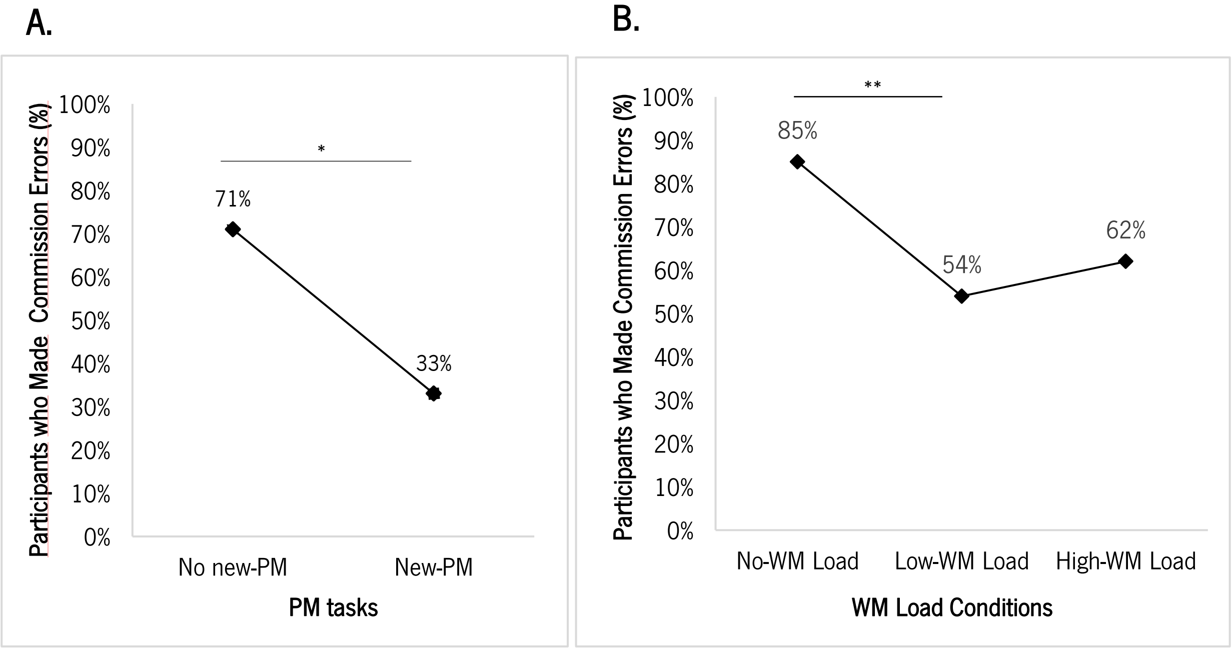
4.2.3.2.2. ***Lexical decision task***

Another interest was comparing OT performance across conditions in the active- and finished-PM phases. As a reminder, the idea was that if participants were spontaneously retrieving the PM intention there should be no differences in the LDT between the no-PM control condition and each of the experimental conditions. For LDT accuracy and RTs analyses, the target and control trials, the trials immediately following each target cue were excluded as responding to PM targets may slow subsequent OT performance and must be considered as an additional source of costs (Meier & Rey-Mermet, 2018; Smith & Hunt, 2014). Likewise, the trials immediately following each colored screen were excluded. Accuracy and RTs analyses were conducted on correct trials, slower than 300 ms, and were trimmed at 3 standard deviations from each participant´s mean (Ratcliff, 1993) calculated separately for each active-PM and finished-PM phases (Smith, 2010).

Results are summarised in Table 10. Mean accuracy and RTs were submitted to a 2 (PM-phase: active and finished) × 3 (PM condition: no-PM, no new-PM, and new-PM) separate mixed-factorial analyses of variance (ANOVA). For OT accuracy, participants were less accurate in the active-PM phase (*M* = .93, *SD* = .07) compared with the finished-PM phase (*M* = .95, *SD* = .06), $F(1, 120) = 15.63$, $p < .001$, $\eta^2 = .12$. There was no main effect of PM condition, $F(1, 120) = 2.64$, $p = .08$, $\eta^2 = .04$, but there was a significant interaction between PM-phase and PM condition, $F(1, 120) = 8.11$, $p < .001$, $\eta^2 = .12$. Pairwise comparisons showed that the interaction arises from the observation that participants in the new-PM task condition were less accurate (*M* = .91, *SD* = .04) than those in the no-PM task condition (*M* = .95, *SD* = .05) during the active-PM phase, $p = .010$, IC 95% [.01, .09]. There were no other significant effects all $ps \geq .37$. There were also no significant differences in their LDT accuracy in the finished-PM phase across conditions, all $ps \geq .08$.

FIGURE 16

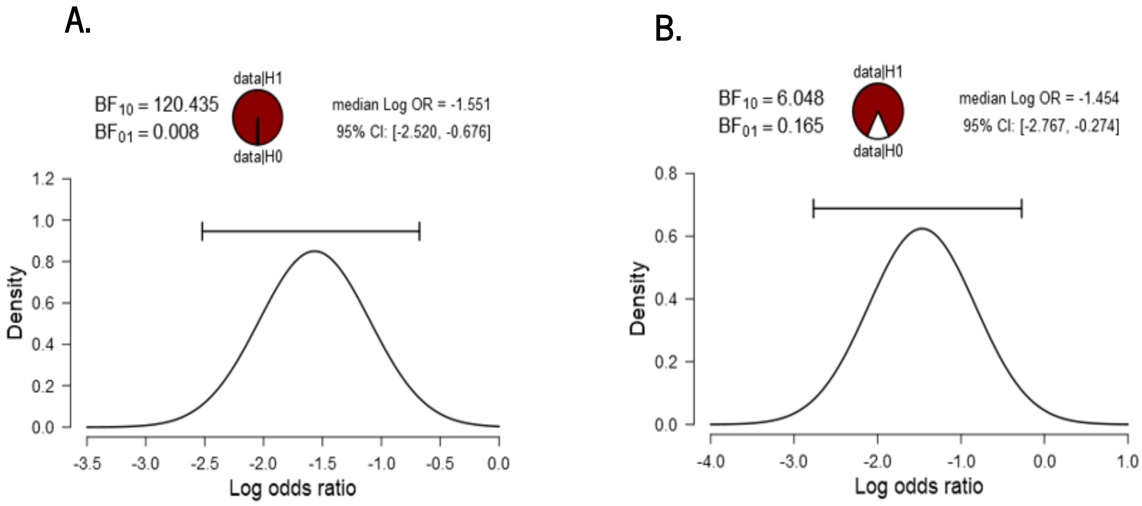
Percentage of participants who made at least one PM commission error across conditions. Panel A displays the results of Experiment 2 and panel B displays the results of Experiment 3.



Note. *p < .001; ** p < .05.

FIGURE 17

Posterior distribution for the Chi-Square Test for the proportion of participants who made commission errors across conditions. Panel A displays the results of Experiment 2 and panel B displays the results of Experiment 3.



Note. Panel A displays the default two-sided Bayes factor which is visualised by the ratio between the prior and posterior ordinate at ρ = 0 and equals 120.44 in favour of the alternative hypothesis over the null hypothesis. Panel B displays the default two-sided Bayes factor which is visualised by the ratio between the prior and posterior ordinate at ρ = 0 and equals 6.05 in favour of the alternative hypothesis over the null hypothesis. Figures from JASP.

Regarding OT RTs, participants reacted more slowly in the active-PM (*M* = 873, *SD* = 164) compared to the finished-PM phase (*M* = 708, *SD* = 102), *F*(1, 120) = 309.75, $p < .001$, $\eta^2 = .72$. There was no significant main effect between PM conditions, *F*(1, 120) = 1.20, *p* = .31, $\eta^2 = .02$, but the interaction between PM-phase and PM condition was significant, *F*(1, 120) = 7.55, *p* = 001, $\eta^2 = .11$. Pairwise comparisons showed no significant differences in their RTs in the active-PM phase across conditions, all *ps* ≥ .25, while in the finished-PM phase participants in the new-PM task condition were slower (*M* = 740, *SD* = 119) compared to those in the no-PM condition (*M* = 683, *SD* = 97), *p* = .034, IC 95% [3.20, 110.81]. There were no other significant effects, all *ps* ≥ .18.

TABLE 10

Experiment 2 means (M) and standard deviations (SD) of LDT performance (accuracy and RTs).

	No-PM		No new-PM		New-PM	
	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*
PM-phase						
Active-PM	.95 (.05)	901 (188)	.93 (.10)	838 (139)	.91 (.04)	881 (162)
Finished-PM	.96 (.03)	683 (97)	.93 (.09)	699 (80)	.96 (.04)	740 (119)

4.2.3.2.3. ***Counting recall task***

Counting recall accuracy was computed as the proportion of correct responses (in a total of 16) per participant. Importantly, we did not found significant differences between the no new-PM (*M* = .91, *SD* =.16) and the new-PM task conditions (*M* = .92, *SD* =.12), *t*(82) = -.04, *p* = .97, *Cohen´s d* = .07, IC 95% [-.06, .06]. Bayesian *t* tests revealed moderate evidence in favour of the null hypothesis, $BF_{10} = .22$, i.e., a similar counting recall accuracy across conditions. We also examined whether there were no differences in the lexical decision trials immediately following the counting recall task. A 2 (PM-phase: active and finished) × 2 (PM condition: no new-PM and new-PM) mixed-factorial ANOVA was conducted for OT RTs[12]. There was a main effect of PM-phase, indicating that participants were slower in the active-PM (*M* = 1018, *SD* = 271) compared to the finished-PM phase (*M* = 785, *SD* = 166), *F*(1, 82) = 2.29, *p* = .13, $\eta^2 = .03$. There was not a main effect of PM condition, *F*(1, 82) = 10.72, $p < .001$, $\eta^2 = .20$., nor an interaction between PM-phase and PM condition, *F*(1, 82) = .57, *p* = .45, $\eta^2 = .01$. These results

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[12] We elected not to trim responses to avoid the problem of having a low number of observations.

demonstrate that the effect on PM commission errors is due to the new-PM task set and not due to a differential attention allocation strategy.

4.2.3.3. Discussion

The main goal of Experiment 2 was to assess whether a reduction of PM commission errors is evidenced when new intentions must be accomplished. This question was addressed by means of a new and dissimilar PM task to perform during the finished-PM phase. The key finding was that fewer participants made commission errors in the new-PM task (33%) compared to those in the no new-PM task condition (71%). According with our first hypothesis, this result provided initial evidence that encoding a novel and dissimilar intention might overwrite or degrade the old-PM representation (Barnes & Underwood, 1959; Wixted, 2010). Additionally, we observed a similar counting recall task accuracy between participants in the no new-PM and new-PM task conditions. Thus, we believe it is reasonable to propose that this result strengthens the evidence that the lower number of commission errors was due to the new-PM task set and not driven by a general differential attention allocation strategy.

Moreover, based on previous work (Bugg et al., 2016; Scullin & Bugg, 2013), PM commission errors occur due to a combination of spontaneous retrieval of a previously relevant intention and a subsequent failure to exert cognitive control over performing it. For that reason, we reasoned that there should be no differences in the OT performance between the no-PM condition and each of the experimental conditions. Interestingly, we found that OT performance regarding (both accuracy and RTs) did not differ between the no-PM and the no new-PM condition. As previously hypothesised, this finding indicates that it is likely that in the no new-PM task condition participants were spontaneously retrieving the old-PM task despite it was no-longer necessary (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2012). On the contrary, the new-PM group performed the OT in the finished phase slower than the no new-PM group showing potential monitoring costs or response delays (Smith. 2003; Strickland et al., 2018). It is arguable to consider that participants in the new-PM task condition may have monitored heavily for the new PM task or strategically delayed their ongoing-task responding and, hence, could ignore the old-PM cues more easily (Schaper & Grundgeiger, 2019; Smith, 2003).

In sum, findings from Experiment 2 bring additional evidence that, while performing demanding ongoing activities, an old-PM intention might be spontaneously retrieved and, most importantly, the memory trace of an old and irrelevant PM task might be degraded by a new and dissimilar PM intention. Consequently, it reduced the probability of making PM commission errors.

4.2.4. Experiment 3

In Experiment 3, we further explored the role of RI on PM deactivation reasoning that the old-PM task memory should also be disrupted or interfered with by new information subsequently encoded in WM. The limited amount of information on this question appears to suggest that it may help to deactivate an old memory task representation. For instance, Walser et al. (2014) investigated the effect of intervening activities showing that performing a high WM demanding task (i.e., read letter strings aloud in backward order) after the active-PM phase reduced intention interference (i.e., slowing in response to PM cues relative to control trials) compared to a control condition (i.e., in which they had to read letter strings aloud). Their finding supports the role of an overwriting-like mechanism that might facilitate PM deactivation.

Although it seems possible to reduce PM commission errors by encoding novel memory representations before the appearance of irrelevant cues during a finished-PM phase, the mechanisms underlying this effect are not clear. Thus, we thought it was valuable to further investigate the beneficial effect of RI in prospective remembering (Dewar et al., 2007; Wixted, 2004) by manipulating the filler task difficulty. For this purpose, three conditions were implemented in a between-subjects design: A no-WM load, a low-WM load, and a high-WM load condition. As in Experiment 2, participants performed a LDT and were then informed that they should no longer perform the PM task. However, we crucially manipulated the task demands during the following delay interval. Specifically, in the *no-WM load condition* participants performed a verbal comprehension task requiring semantic knowledge and retrieval of information from LTM, without posing cognitive load. Conversely, in the *low-WM* and *high-WM load conditions*, they were asked to perform a *n*-back task with two increasing difficulty levels (1- and 3-back, respectively). Previous work has shown that increasing *n*-back load should limit WM capacity since it required a higher ability to maintain, continuously update and process information (Braver et al., 1997; Lewis-Peacock et al., 2016). Finally, in the finished-PM phase, they performed a new LDT with 10 former PM cues (except for the no-PM condition in which they did not had any PM task to accomplish). If this idea has merit, then we would expect fewer commission errors as a function of the increased WM demands of the filler activities which are expected to retroactively interfere with the old-PM task representation.

Moreover, we included a condition without any PM task in order to examine OT performance (Scullin & Bugg, 2013) as additional research is needed to support the that a spontaneous PM retrieval contributes to the occurrence of PM commission errors (e.g., Scullin & Bugg, 2013; Scullin et al., 2012). Considering the dual-mechanisms account, we reasoned to find no difference in the LDT performance regardless of PM condition (no-PM, no-WM load, low-WM load, high-WM load) assuming a spontaneous PM retrieval, replicating results from Experiment 2.

4.2.4.1. Method

The method for Experiment 3 followed the method of Experiment 2. Therefore, only deviations are described.

4.2.4.1.1. ***Participants***

An a priori power analysis (based on the proportions of Experiment 2, $p_{1\ (\text{New-PM})} = .33$ and $p_{2\ (\text{No new-PM})} = .74$, and sample size $N = 84$) a sample of 4 × 26 participants was recruited (two-tailed, $\alpha = .05$, power = .80; Dupont & Plummer, 1990). Thus, 131 students of the University of Minho participated in the current study in exchange of course credits. Twenty-seven participants (20%) participants were excluded from the analyses ($N_{\text{No-WM load}} = 4$; $N_{\text{Low-WM load}} = 9$; $N_{\textit{High-WM load}} = 14$) because they could not correctly recall the PM task or the finished-PM instructions at the end of the experiment (n = 22), or due to depression and anxiety symptoms (n = 5). Therefore, 104 young adults (15 male, $M_{\text{age}} = 21.22$, SD = 3.86) were randomly assigned to no-PM (n = 26), no-WM load (n = 26), low-WM load (n = 26), and high-WM load (n = 26) conditions.

4.2.4.1.2. ***Design***

The design was a 2 × 4 mixed-factorial, with PM-phase (active and finished) as the within-subject variable and PM condition (no-PM, no-WM load, low-WM load, and high-WM load) as the between-subjects variable. The dependent variables were the same as Experiment 2 except for the additional *n*-back task accuracy using d-prime (d').

4.2.4.1.3. ***Materials***

The materials were the same as in Experiment 2, except for the *n*-back task which was programmed in E-Prime (software package, version 3.0, Schneider et al., 2002). The *n*-back task was a WM test in which participants were asked to compare the current stimulus to the one presented *n* steps earlier in a continuous sequence (Kirchner, 1958). The items to be updated were the following 15 letters: A, B, C, D, H, I, K, L, M, O, P, R, S, T. Stimuli were presented one by one in the centre of the screen (font: Arial bold; size: 30). Participants had to press the spacebar when the currently presented letter (i.e., target) matched the letter presented one step before (low-WM load) or three steps before (high-WM load). The first three trials of each block were always non-targets. Each stimulus appeared on the screen for 500 ms, separated by a 1500 ms intertrial interval (regardless of whether the participant pressed a key or not) during which participants must press the target response key.

After a first practice phase that consisted of 32 trials, an additional practice block was administered if participants did not have any doubts. Next, there were three test blocks of 60 letters each (totalling 180 trials) separated by two breaks of 1 min each in order to prevent fatigue. In each block, 25% of all the stimuli presented were hit items (i.e., 8 in the practice phase and 15 per block in the test phase). The number of hits and false alarms was recorded.

*4.2.4.1.4. **Procedure***

The procedure was identical to Experiment 2 with the following exceptions. In Experiment 3, all participants also performed filler tasks in the second delay interval for approximately 10 min. Participants in the no-WM load condition were asked to provide a definition to the presented words of a vocabulary test. In the low-WM load condition, they were asked to judge whether a letter is a repetition from the previous step (e.g., L P P), while in the high-WM load condition they were told to judge whether a letter was repeated three steps back in the list (e.g., S D E S).

4.2.4.2. Results

*4.2.4.2.1. **PM commission errors***

PM commission errors were significantly higher in the no-WM load (22/26; 85 %) compared to the low-WM load condition (14/26; 54 %), $\chi^2 = 5.78$, $p = .016$, $\phi = -.33$[13] (Figure 16B), with a moderate statistical power, .69. Bayesian contingency analysis support the previous results revealing a strong evidence in favour of the alternative hypothesis, $BF_{10} = 6.05$ (Figure 17B). Moreover, commission errors were marginally higher in the no-WM load in comparison to the high-WM load condition (16/26; 62 %), $\chi^2 = 3.52$, $p = .061$, $\phi = -.26$. In turn, bayesian analysis were conducted and showed anedoctal evidence in favour of H_1, ($BF_{10} = 2.02$), suggesting that that the number of participants making commission errors differ between the no-WM load and the high-WM load condition. Lastly, the low-WM and high-load conditions did not differ, $\chi^2 = .32$, $p = .58$, $\phi = .08$, as also indicated by the $BF_{10} = 0.39$ showing moderate evidence in favour of H_0.

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[13] In this experiment, participants were significantly more likely to make a commission error if they recall the finished-PM instruction with a prompt ($n = 25$) than those who did that spontaneously ($n = 5$), $\chi2 = 19.10$, $p < .001$, $\phi = .60$.

We further analysed the frequency of commission errors made per participant (i.e., the total number of *Q* presses/10 targets). A one-way ANOVA showed a marginal statistical difference in the frequency of commission errors between the no-WM load (*M* = .72, *SD* = .47), low-WM load (*M* = .50, *SD* = .47), and high-WM load conditions (*M* = .47, *SD* = .49), *F*(1, 77) = 2.41, *p* = .09, η_p^2 = .47.

4.2.4.2.2. ***Lexical decision task***

Trimming procedures for accuracy and RTs analyses were identical to those of Experiment 2. Mean accuracy and RTs were submitted to a 2 (PM-Phase: active and finished) × 4 (PM condition: no-PM, no-WM load, low-WM load, and high-WM load) separate mixed-factorial ANOVAs. As illustrated in Table 11, the main effect of PM-phase for OT accuracy was not significant, *F*(1, 100) = 1.07, *p* = .30, η^2 = .01. The main effect of PM condition was also not significant*,* *F*(1, 100) = 1.32, *p* = .27, η^2 = .04, neither the interaction between PM-phase and PM condition *F*(1, 100) = .20, *p* = .90, η^2 = .01. For OT RTs, there was a main effect of PM-phase with participants being slower in the active-PM phase (*M* = 843, *SD* = 155) compared to the finished-PM phase (*M* = 659, *SD* = 77), *F*(1, 100) = 264.05, *p* < .001, η^2 = .73. There was not a main effect of PM condition, *F*(1, 100) = .94, *p* = .42, η^2 = .03, and the interaction between PM-phase and PM condition was only marginally significant, *F*(1, 100) = 2.26, *p* = .08, η^2 = .06.

TABLE 11

Experiment 3 means (M) and standard deviations (SD) of LDT performance (accuracy and RTs).

	No-PM		No-load		Moderate-load		High-load	
	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*	Accuracy *M (SD)*	RTs (ms) *M (SD)*
PM-phase								
Active-PM	.96 (.03)	881 (172)	.95 (.09)	823 (145)	.96 (.04)	830 (144)	.95 (.06)	836 (159)
Finished-PM	.97 (.03)	674 (73)	.95 (.08)	684 (86)	.95 (.03)	654 (75)	.94 (.04)	623 (60)

4.2.4.2.3. ***Counting recall task***

A one-way ANOVA showed that counting recall accuracy did not differ across conditions, *F*(1, 78) = 3.02, *p* = .06, η^2 = .07 (no-WM load: *M* = .82, *SD* =.06; low-WM load: *M* = .93, *SD* =.09; high-WM load: *M* = .94, *SD* =.08. The BF_{10} = 1.01 value from the Bayesian ANOVA showed no evidence in support of either hypothesis.

4.2.4.2.4. ***n-back task***

We next analysed the sensitivity of the participants to discriminate items as previously presented (or not) *n* steps back using the signal-detection parameter d', which was estimated as $d' = Z_{Hits} - Z_{FalseAlarms}$. The method of MacMillan and Creelman (2005) was used to avoid that d' might be undetermined when the hit or the false-alarm rate was equal to 0 or 1. Specifically, scores equal to 0 were replaced by (false-alarms + 0.5) / (maximum number of false alarms +1) and scores equal to 1 were replaced by (hits + 0.5) / (maximum number of hits +1). An independent sample Student´s *t* test revealed a higher d' in the low-WM load ($M = 4.41$, $SD = .74$) compared to the high-WM load condition ($M = 2.30$, $SD = .95$), $t(50) = 8.85$, $p < .001$, *Cohen´s d = 2*.48, 95% CI [1.63, 2.59]. A Bayesian *t* test indicated moderate evidence for the H_1 that *n*-back task performance differed between the low-WM and the high-WM load, $BF_{10} = 6.75$. This result gives us confidence that filler task manipulation was effective at inducing different levels of WM demands.

4.2.4.3. Discussion

The main purpose of Experiment 3 was to examine to what extent the demands imposed by the activities performed right after the finished-PM instruction might reduce intention deactivation failures. In accordance with previous studies (Walser et al., 2014), our results indicated that successfully deactivating an intention seems to depend on WM demands incurred before the finished-PM phase begins. This interpretation is supported by the evidence of a lower commission error risk in the low-WM load condition (54%) compared to the no-WM load (85%). Moreover, we found a marginal trend and Bayesian support that fewer participants make commission errors in the no-WM load compared to the high-WM load (62%).

Hence, this result seemed to indicate that the vulnerability to PM commission errors is reduced by the interference caused by a subsequent mentally effortful task requiring WM abilities at a moderate level. Recent studies bring additional support for this claim (Craig et al., 2014; Dewar et al., 2007; Wixted, 2004, 2010). As previously noted, yet is generally assumed that similarity between original and new memories may be particularly damaging, there is evidence that an interfering activity that is not similar to the previously learned material (i.e., *mental effort per se*, as originally defined by Müller and Pilzecker, 1900) can produce forgetting, too.

Importantly, our results also reveal a clear effect of the filler task´ difficulty since the discrimination index d' in the *n*-back task was higher on the low-WM load (i.e., 1-back) than on the high-WM load (i.e., 3-back). This result supports the assumption that the filler task was more demanding in the 3-back compared the 1-back condition. Finally, as in Experiment 1, counting recall performance was similar across conditions supporting the idea that PM commission error risk is due to the experimental manipulation and not due to a differential attention allocation strategy.

Another interesting finding stemmed from the OT performance. Consistent with our prediction, and replicating Experiment 2, we observed a similar accuracy and RTs between the no-PM and the three other experimental conditions with a PM task (i.e., the no-WM, low-MW, and high-WM load conditions). Therefore, Experiment 3 provided more substantial evidence that participants automatically retrieve the (irrelevant) intention upon encountering the associated PM cue, excluding confounding factors in the occurrence of commission errors such as monitoring for PM cues.

4.2.5 General discussion

The present study explored a prominent topic in PM research: Does forgetting irrelevant intentions occur because these memory traces are degraded or destabilized by interfering information? In two experiments we have shown that an RI mechanism seems to play a crucial role in PM deactivation. Recent research has pointed in this direction (Anderson & Einstein, 2017; Walser et al., 2017). However, an advantage of our experimental task (vs. Walser et al., 2012, 2017) is that we have taken a different approach to tackle PM deactivation: We have analysed the occurrence of PM commission errors and by using a finished-PM paradigm (i.e., not by repeating PM and OT blocks in which commission errors can occur due to a source monitoring failure - because participants have to continuously update the relevance of the PM cue and response throughout several blocks). We also have innovatively added a no-PM group. As previously theorised, we sought to understand if PM commission errors occur due to a failure to inhibit a spontaneous retrieved PM task or, instead, because subjects continue to strategically monitor for PM cues.

Replicating previous work (Boywitt et al., 2015; Matos et al., 2020; Pink & Dodson, 2013; Shaper & Grundgeiger, 2017), we found that young adults are prone to erroneously execute an unperformed intention when they no-longer must do so if the OT is cognitively demanding. A novel finding was that, in such cases, commission errors were reduced by the requirement to perform a new and dissimilar PM task after the old one is declared finished (Experiment 2). Consistent with prior work (Walser et al., 2014), in Experiment 3 we also observed that fewer participants make commission errors if immediately prior they performed a task with a moderate and high WM load than in a no-WM load condition. Taken together, our results can be theoretically interpreted based on an RI mechanism (Barnes & Underwood, 1959; Wixted, 2010). Applied to the present data, encoding dissimilar new intentions or WM contents seems to overwrite, deteriorate or even restrain the old-PM trace (Engle et al., 1995; Hasher & Zacks, 1998). Hence, the old-PM intention becomes less accessible and, consequently, more easily inhibited upon encountering the associated (but irrelevant) cue during the finished-PM phase.

In Experiment 2, participants in the new-PM task condition were slower in response to the LDT during the finished-PM phase compared to the no-PM condition. The new-PM intention required checking the environment for the appropriate moment to perform it given that the OT did not encourage focal processing of the PM cues (i.e., participants had to press a bell whenever they saw numbers in the context of a LDT; see also Walser et al., 2017). By this, we mean that this monitoring strategy, or people´s decision to slow down their responding, may have incurred costs to the OT performance (Einstein et al., 2005; Heathcote et al., 2015; Smith, 2003; Strickland et al., 2018). One could easily argue that participants monitored heavily for the new-PM task reducing commission error risk for an old-PM task. In previous works, monitoring for novel PM cues during finished phases seemed to exacerbate PM aftereffects but using a repeated-cycles paradigm (Walser et al., 2017). On the one hand, their findings may then also reflect a source monitoring failure because participants have to continuously update the relevance of the PM cue and response throughout several blocks. On the other hand, as they must perform many PM tasks in several blocks this may have helped to establish a general PM task set or retrieval mode that biased attention towards the detection of PM cues and, thus, increase the likelihood that no-longer relevant PM cues triggered intention retrieval (Bugg & Streeper, 2019). Alternatively, this slowing may reflect the idea of Schaper and Grundgeiger (2019) that participants might have had more time for prepare a response in the sense that they correctly evaluated the PM cue and tagged it for suppression (i.e., with the knowledge that the intention should not be executed).

Importantly, we found fewer commission errors by using a new-PM intention with a different PM-category (i.e. saw numbers in any location of the screen instead of a specific word) and PM-response (i.e., press a bell rather than the *Q* press on the keyboard). One possible interpretation of this inconsistent result seems to be intention´s similarity. For instance, Walser et al. (2017) showed that PM aftereffects were reduced when the category of both intentions differed (e.g., symbols vs. words) compared to when PM cues belonged to the same category (e.g., symbols vs. symbols). One proposal is that the deactivation of old and irrelevant PM tasks depends on the similarity between irrelevant and current intentions. From this perspective, like other aspects (e.g., the existence of a strong link between retrieval and intended action, salient PM cues encountered during the same OT context or impaired cognitive control; Bugg et al., 2013, 2016; Matos et al., 2020; Schaper & Grundgeiger, 2019; Scullin & Bugg, 2013), pursuing another intention of a similar/dissimilar type after completion may affect intention deactivation. Second, the empirical evidence that memory loss is not merely caused by interference of highly similar material but also by nonspecific RI (Dewar et al., 2007; Müller & Pilzecker, 1900; Wixted, 2010) provide support for this reasoning. The idea is that the greater and more variable the new learning is, the greater the interfering effect will be since it may elicit the most hippocampal activity and, consequently, the greatest rate of new memory formation (Wixted, 2004, 2010). A further noteworthy finding is that the reduced pattern of commission errors in the new-PM task condition could also have benefited from a cumulative mechanism of release from PI (Wickens et al., 1963). That is, this kind of interference by which older memories impair the retrieval of new memories is known to builds up over time until people are given information that differs from the old knowledge. At that point, memory improves. In our study, we should highlight that there was a reduced overlap between intentions (i.e., no components of the old-PM representation were needed for performing the new intention).

Another aspect merit consideration. Although our results appear contradictory to previous studies (when compared to performing only an OT; Anderson & Einstein, 2017; Walser et al., 2017) one has to take into account, as reasoned by the authors, that the new intention might have been very simple (i.e., press a specific key if a target word appears; Anderson & Einstein, 2017) or not sufficiently demanding (i.e., press X/Y in response to a specific word/symbolic features; Walser et al., 2017) to detect possible effects of overwriting on the old-task representation. A promising avenue for future research would be to test the impact of PM task difficulty on the extent of overwriting.

Regarding OT performance, the current research is one of the few studies adding a no-PM condition to bring additional leverage on the PM retrieval process. The rationale here is that the ability to remember to perform delayed intentions might occur due to top-down effortful self-reminders or to a bottom-up reactivation in response to external cues. The later form of retrieval has the advantage of supporting PM without effortful processes. Yet, since PM is cue-dependent, processing a strong retrieval cue might spontaneously retrieve an old and irrelevant PM intention to consciousness, which may lead, in some situations, to PM commission errors (Bugg et al., 2016; Matos et al., 2020; Scullin & Bugg, 2013; Scullin et al., 2012). So, the present finding that there were no differences in the OT performance between the no-PM and each the experimental conditions on both experiments (except for those in the new-PM task condition in Experiment 2) supports the dual-mechanisms theory´s prediction of a spontaneous PM retrieval (Bugg et al., 2016; Scullin & Bugg, 2013).

In conclusion, an irrelevant intention might be spontaneously retrieved despite no-longer-needed when greater demands are placed on the cognitive system. Interestingly, our results add significant evidence to the claim that, in such cases, encoding new dissimilar memories (i.e., new intentions or new WM contents) seems to provide an overwriting-like mechanism that facilitates PM deactivation. A remaining outstanding theoretical issue concerns which specific interfering dissimilar information (e.g., verbal or visual information) are potentially at play, as well as the impact of WM individual differences on PM deactivation.

4.2.6 References

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CHAPTER 5

FINAL CONSIDERATIONS

5.1. Introduction

"Life can only be understood backwards; but it must be lived forwards."

(Kierkegaard, 1855)

Inhibition is "(...) not an occasional accident; it is an essential and unremitting element of our cerebral life? (...)"

(James, 1890, p. 583)

For long a neglected topic, scientists have sought to understand how our episodic memory allows us to schedule, establish, and maintain memory for intentions over extended periods. The so-called prospective memories influence our behavior and define how we process our environment while performing a variety of ongoing activities. An important question for research on PM and goal-directed behavior is whether this influence stops after a PM is no-longer-needed. In fact, memory errors can provide a window into the mechanisms of memory. For example, in Bartlett´s classical study, with the Indian folktale *The War of the Ghosts* (1932), he found that the recollections of the folktale reflected the participants´ interpretations of the stories, suffering the influence of their own cultural and logical expectations. In a similar vein, researchers have also observed that eyewitnesses sometimes report confident, but inaccurate memories and that post-event suggestions or misinformation can easily taint eyewitness memory (Loftus, 1992; Loftus & Palmer, 1974). False memories might be produced internally, too. In 1995, Roediger and McDermott´s study impacted the scientific community by showing high rates of false memories, known as memory illusions.

In this scenario, the strong support for persisting activation of irrelevant PM intentions caught researchers´ attention and fostered numerous studies. Since studying PM commission errors may provide new insights about the functioning of human memory, efforts have been made to design research paradigms that allowed a systematic study on this effect and a clearer comprehension of its underlying mechanisms. However, until now, the issue of whether this influence stops after intention completion, and if so, under what conditions, has not been extensively settled.

This counterintuitive finding then inspired the present dissertation: Completing a PM task does not necessarily lead to a direct deactivation of these memory representations. In fact, this can impair subsequent task performance or even trigger the erroneous performance of irrelevant intentions (Bugg & Streeper, 2019; Möschl et al., 2020). We find it critical to have a deeper knowledge of the cognitive mechanisms underlying these memory failures as intention deactivation should make it possible to flexibly re-adjust our behavior according to novel intentions or current environmental demands. It was also built upon an intellectual curiosity to understand which conditions could lead to or, otherwise, prevent PM commission errors. This is exciting for theoretical reasons but also because of the translational value of these studies is promising.

After evaluating the existent empirical evidence (Chapter 2 and 3) and developing controlled tests in our experiments (Chapter 4), the general picture that emerges from the evidence of the studies reported in this dissertation support the notion that (1) PM commission errors seem to be mediated by cognitive control over the need to *letting go* of a no-longer relevant intention, but also that (2) these memory traces may be interfered with (i.e., forgotten) by new information relative to a new planned intention or more general WM contents. These findings allow us a better understanding of the phenomenon and provide a humble contribution to this research line.

Below, this final chapter is then devoted to discussing a central question: Are intentions´ representations deactivated from memory after no-longer-needed, and if so, how? We will summarise our main findings and provide an integrative discussion of key issues.

5.2. Are PM intentions deactivated from memory after no-longer-needed and, if so, how?

As Neisser (1978) emphasized in his seminal talk entitled *Memory: What are the Important Questions?*, "memory is also involved in many activities of daily life. We make a plan and have to remember to carry it out". Throughout this thesis, we were specifically motivated to pursue the goal of understanding why does irrelevant memories for future events continue to stick around (i.e., remain accessible) leading, in some cases, to the erroneous performance of those intentions (e.g., such as in the case of double-dosing).

As mentioned before, the dynamic multiprocess theory (Shelton et al., 2019) suggests that, in order to fulfil prospective intentions, individuals can flexibly adjust their control strategy (i.e., rely on top-down self-reminders or on bottom-up reactivation processes when encountering associated cues) in response to environmental factors (for dissociable neural correlates see Beck et al., 2014; Cona et al., 2014; Lewis-Peacock et al., 2016). Within this conceptualization, the strategic proactive control process is cognitively demanding and interferes with OT processing because it relies on WM to remember the goal and external attention to monitor the environment for cues to act (Smith & Bayen, 2004). In turn, a reactive spontaneous retrieval has the advantage of supporting PM without effortful processes since it relies on episodic memory to store the goal and the associated PM cues from the environment to trigger its timely retrieval (Anderson et al., 2017; Einstein & McDaniel, 2010). Regarding PM deactivation, since PM is cue-dependent, the dual-mechanisms theory proposes that PM commission errors occur due to a spontaneous retrieval upon encountering the associated (but irrelevant) PM cue and a subsequent failure of executive control in terms of response inhibition (Bugg et al., 2016; Scullin & Bugg, 2013; Scullin et al., 2012).

In Chapter 2, we first reviewed the literature on remembering and forgetting RM traces to put our research on PM deactivation into context and to later develop innovative theoretically supported empirical studies (Matos & Albuquerque, 2020a). Then, in Chapter 3, we systematically reviewed much of what we know about PM-related costs (Matos et al., 2020b). Our findings showed that there is presently compelling evidence of a detrimental effect of the OT load on the ability to retrieve and perform a planned intention. To be more precise, in high-demand environments, it may not be possible to successfully allocate controlled attentional and WM processes to maintain goal information and to strategically monitor the environment for PM cues, or resources are not available to spontaneously process the PM cue when it occurs.

However, we also systematically examined how the field has handled with the effect of the cognitive load on intentions deactivation revealing a preliminary boundary condition for PM commission errors: Individuals seem to more frequently execute an irrelevant PM intention when they no-longer must do so when their cognitive resources are taxed by demanding ongoing activities. Yet, it is still unclear exactly what circumstances are necessary for this impairment to occur.

To shed light on this question, in our first study (Experiment 1, Section 4.1), we conducted a conceptual replication, which is known to play a crucial role in the development of a theory or model (see Schmidt, 2009), with precise manipulation of theoretically-relevant parameters. Here, we examined an important testable prediction derived from the dual-mechanisms account: Under demanding cognitive tasks, an inhibitory failure should raise PM commission error risk. A novel finding estimated with high precision emerged. In line with our prediction, when a group of participants, who had been subjected to a no-load condition, is contrasted with a group of participants in a moderate OT load condition, we found that, in the later, participants were more vulnerable to carry out a PM intention when it no-longer needs to be completed (Matos et al., 2020c). In fact, under the assumption that PM and OT performance rely on shared resources, we reasoned more commission errors when resources for PM deactivation were limited by a demanding OT. This finding extends previous knowledge (Boywitt et al., 2015; Pink & Dodson, 2013) by showing that the cognitive requirements of daily ongoing activities can moderate the presence of PM commission errors.

Interestingly, the former finding is consistent with recent theoretical developments that have described a role of cognitive control over memory (Baddeley et al., 2015; Benoit & Anderson, 2012; Cowan, 2005, 2017; Engle & Kane, 2004; Miller & Cohen 2001; Posner & Snyder, 2004; Wierzba et al., 2018). More specifically, as a reminder, cognitive control allows us to behave flexibly, shift attention in a goal-directed fashion, and inhibit inappropriate response tendencies (Posner & Snyder, 2004). From this perspective, under conditions of higher cognitive load, attentional executive resources are divided among tasks and so maybe there are no resources available to activate the relevant information to OT performance in WM, eliminate the old-PM task representation, or even suppress the salient but irrelevant PM cue information to the OT at hand. More, inhibitory processes are critical in conditions where the presence of distracting or salient behavior interferes with the maintenance of information relevant to the OT (Engle & Kane, 2004), as it appears to be the case. Noteworthy, this idea of an inhibitory control failure would be further examined by testing whether and how PM aftereffects as well as the processes underlying prospective remembering are modulated by factors that are known to alter cognitive control functioning such as acute stress. This potential inhibitory mechanism for PM deactivation warrants further investigation. Doing that, as discussed below, may thereby allow us to disentangle between an inhibitory response which may override the prepotent tendency to execute the PM tasks after intention retrieval or a down-regulating suppression mechanism that helps to inhibit irrelevant information to successfully perform ongoing activities.

Still, it would appear sub-optimal or even disastrous to continuously inhibit prospective memories in everyday situations. Therefore, we turned our attention to the variables that could reduce PM commission errors under demanding conditions. Our work has been guided by the idea that the world around us is dynamic and, therefore, memory traces must also be dynamic if the organism is to be adaptive. In this context, it is worth no note that empirical research has been providing evidence that memories appear to decay over a retention interval because they are interfered with by additional memories that the subjects have learned (Nairne, 2002; Wixted, 2010). Although viewed as a troublesome phenomenon, several researchers have recognized the adaptive value of the ability to forget and, from our perspective, interference mechanisms might play a role in helping to diminish the influence of a memory trace of a previously relevant PM task to make way for the new intentions or goals that must be accomplished daily (Anderson & Hanslmayr, 2014; Baddeley et al., 2015; Bjork, 2011). In real-life situations, we scarcely perform one intention in isolation but rather continuously form, maintain, retrieve, and execute several intentions in parallel. Thus, in Study 2 (Section 4.2), our aim was to clarify the controversy of whether PM commission errors fade as a function of interference caused by encoding new information (Matos & Albuquerque, 2020d). We have collected some evidence that may work for this purpose.

In line with our expectation, Experiment 2 allowed us to conceivably argue that an old-PM task representation seems to be interfered with by the requirement to maintain and execute a novel intention. That is, that commission errors seem to be reduced while we manage to respond to our environment´s changing goal demands. Our results deviate from some previous findings, but in which the process of monitoring for new PM cues may have reactivated the old-intention representation when associated cues are encountered (Walser et al., 2017). Yet, our finding is consistent with the scarce research conducted on this issue that suggests that PM aftereffects may, in fact, depend on whether a new intention has or not to be performed in parallel and how much elements (PM cue, action, goals) of an irrelevant intention do or do not overlap (Walser et al., 2017).

In Experiment 2, we also observed slower responses to the ongoing activity when participants had a new intention to perform in the future. In fact, the new-PM intention required checking the environment for the appropriate moment to perform it since the OT did not encourage focal processing of the PM cues (i.e., participants had to press a bell whenever they saw numbers in the context of a LDT; see also Walser et al., 2017). By this, we mean that this monitoring strategy, or people´s decision to slow down their responding, may have incurred costs to the OT performance (McDaniel et al., 2015; Strickland et al., 2018). One could argue that participants monitored heavily for the new PM task reducing commission error risk for an old-PM task.

In principle, it is hard to see how does a system that constantly retrieves old and irrelevant memory representations, while having multiple other intentions to perform in the future in mind, could operate effectively in the natural world. Therefore, in the search for further evidence that could help us to examine the role of RI on PM deactivation, we conducted Experiment 3 in which we vary the OT load of the interval between the cancelled instructions and the measurement of PM commission errors in the finished-PM phase. Our results provide evidence to argue in favor of a beneficial effect of RI, strengthening the idea that this could be how we update PM demands. In this regard, future work should test the impact of PM task difficulty on the extent of overwriting of an old irrelevant.

In addition, to avoid theoretical confusion caused by ad hoc hypotheses, a critical test on the dual account was undertaken: We add no-PM control conditions in all of our behavioral studies (see also Scullin et al. 2013). We did not observe slower responses when participants performed the ongoing activity with an additional PM task compared to respond to the OT alone both in Study 1 and 2. Such a finding is frequently referred to as spontaneous PM retrieval (McDaniel et al., 2015) and, thereby, provide a good support for the dual-mechanisms view of PM commission errors occurrence (Bugg et al., 2016).

Overall, our studies followed a renewed interest in the time-honored concepts of cognitive control, interference, and inhibition, in which recent work has shed important new light on complex human behaviors. Along the same lines, considering that they add important evidence about some neglected mechanisms contributing to deactivating irrelevant prospective memories, we wish that these topics continue to instigate novel scientific endeavours.

5.3. Limitations and future directions

Altogether, the present set of studies not only provided new empirical support for the dual-mechanisms nature of PM commission errors but also suggest that encoding new intentions to perform subsequently or WM contents have the potential to reduce these memory lapses. Considering the potential theoretical and practical implications, these topics should continue to be of scientific inquiry. At present, disentangle intention suppression from an active intention deactivation warrant further investigation and some unanswered questions about the nature of inhibitory control over PM deactivation remain unclear.

First, at this point, the literature is relatively silent as whether the absence of commission errors reflects a direct deactivation of an irrelevant intention (i.e., it is not spontaneously retrieved) or, instead, reflect an intact cognitive control (i.e., inhibition) after intention retrieval. As the first step in this direction, future studies should examine RTs to the previously relevant targets using procedures in which it is unambiguous that a single PM task is finished (i.e., to exclude confounding factors such as monitoring for PM cues). If those participants who did not make commission errors exhibit significantly higher intention interference to PM target trials compared to control trials, then this may support that the irrelevant PM task is still spontaneously retrieved even when participants are told that they can forget them. Simply put, such spontaneous retrieval may slow down responding to a previously relevant cue, reflecting a failure to completely deactivate (turn-off or forget) the intention, although it may be successfully inhibited.

Clearly, as a complement, further research is required to examine whether there is a substantial proportion of PM-related thoughts after encountering associated PM cues indicating that participants may consciously rehearse the irrelevant PM intention (Anderson & Einstein, 2017). Put differently, by adopting thought-probe procedures, researchers may occasionally stop participants during the finished-PM phase and ask them to indicate their thoughts at that moment. Similarly, future work should address if participants are aware of their error by collecting information regarding individuals´ subjective evaluation (i.e., through self-rating measures) about their reaction in such trials (e.g., Bugg et al., 2013). More specifically, at debriefing, participants may complete a post-experimental questionnaire in which they are asked to recall the target words and target key, whether they believed that the PM task was finished when they received this instruction, rate how often they continued to think about the PM task, and answer whether they ever pressed *Q* after they were instructed not to, and if so, to describe why (e.g., Scullin & Bugg, 2013).

Second, considering our specific findings, we also acknowledge that currently it is still unclear which specific inhibitory mechanism may underlie commissions error risk in everyday life. The dual-mechanisms account (Bugg et al., 2016) argues that commission errors occur because participants are not able to exert control and override a prepotent PM response. However, Schaper and Grundgeiger (2019) suggested that these failures may not necessarily reflect failed response suppression. As noted, in their study, even though they have provided time for suppress a PM response after encountering a related PM cue, participants still made commission errors. Thus, the authors suggested that PM commission errors occur if the person fails to correctly evaluate the PM cue as no-longer relevant because the retrieved intention is directly implemented to be executed. Therefore, the key question concerns whether PM deactivation is accomplished through an inhibitory process that suppress the prepotent PM response or inhibitory mechanisms are instead recruited to override declarative memory retrieval. In this last case, it is worth to note that memory, like physical actions, sometimes need to be controlled. Without the capacity to override unwanted processes, we could not adapt behavior or thoughts to changes in our goals or circumstances. Importantly, it is currently recognized that a crucial role of the PFC is to support the goal-directed interruption of our behaviour and thoughts (Anderson et al., 2015). While the right inferior frontal gyrus (rIFG) seems to play a critical role in inhibitory control over motor responses by suppressing thalamocortical motor programs (e.g., Aron et al., 2014; Kelly et al., 2004), the right dorsolateral prefrontal cortex (rDLPFC) is specifically associated with the forgetting, and purportedly the inhibition, of competing memories (Kuhl et al., 2007; Penolazzi et al., 2014; Wimber et al., 2008).

Thus, moving forward, we believe that it is critical for researchers to consider if changes in PFC brain activity would mediate changes in PM commission error risk. This will hopefully provide additional evidence for the role of inhibitory processes on PM deactivation. In this context, so far, only two recent brain-oriented studies have explored PM commission errors despite its value for enhancing our understanding of the cognitive processes involved in prospective remembering (Cona et al., 2015, 2020, for PM omission errors). In an interesting and relevant work, Beck et al. (2014) contrasted blood-oxygen-level-dependent (BOLD) responses to PM target cues across several 70 s cycles of active and inactive phases. The authors observed brain activation during PM cue trials in areas that are also activated by those cue trials when PM intentions are still active. During inactive phases, the (although irrelevant) PM cue trials elicited increased transient BOLD responses in the ventral parietal, precuneus, posterior cingulate, and rostro-lateral pre-frontal regions. This finding was interpreted as indicating (erroneous) bottom-up spontaneous retrieval coupled with top-down control to avoid commission errors. Nevertheless, this study did not elicit any commission error (only increased RTs to target cues). In this vein, Scullin et al. (2020) recently found that that a small volume in the lateral orbito-frontal cortex was associated with a greater number of PM commission errors.

Notwithstanding these fruitful developments, imaging data are correlational in nature and cannot provide causal links on which regions play a crucial role in PM deactivation. Therefore, transcranial direct current stimulation (tDCS) has become the focus of recent interest as it allows for a useful method to test causal hypothesis about the cortical neural substrates that underlie memory functioning as well as if it can modulate its performance (Filmer et al., 2014). Transcranial direct current stimulation is a non-invasive method that is used to modulate the spontaneous cortical excitability by directing a weak electrical current (usually of 1-2 mA) through cortical tissue (Woods et al., 2016). It is generally assumed that during tDCS there is neuromodulatory effects through the voltage-gated channels. That is, a positive anodal current temporarily facilitates behaviors associated with the cortical region under the active electrode (i.e., the resting membrane potential of the neuron is depolarized, increasing the probability of action potentials occurring), while a negative cathodal current inhibits behaviors (i.e., the resting potential is hyperpolarized decreasing the probability of action potentials occurring; Nitsche & Paulus, 2000; Thair et al., 2017).

Importantly, as recent meta-analyses have shown, modification of the excitability of the DLPFC or the rIFG can significantly change inhibitory behavior (Dedoncker et al., 2019; Schroeder et al., 2020). In this vein, a more direct proof of the involvement and type of inhibitory mechanisms in the deactivation of irrelevant intentions would be established by testing if anodal, cathodal and sham tDCS (applied during the finished-PM instructions when inhibitory control is thought to be triggered) in the rDLPFC or in the rIFG can modulate inhibitory control, which are supposed to support PM deactivation.

Therefore, beyond the value of exploring innovative techniques for reducing PM commission failures, the suggested study also might provide an important test of current theoretical explanations. Besides, another main challenge would be to develop new paradigms more suited to provide indicators of inhibition or to capture spontaneous retrieval processes in the absence of commission errors (e.g., electroencephalography or neuroimaging techniques). Lastly, an arguable question is also whether we proactively maintain that a PM intention is no-longer-needed to prepare us for actions required to reach current goals. Or, whether we may reactively react and retrieve the goal and engage control at that point? Moving forward, it seems critical for researchers to consider develop new measures to possibly isolate these two adaptively mechanisms that allows us to behave in a goal-directed manner in response to external and internal demands (Braver, 2012).

5.4. Closing remarks

Decades of research from cognitive psychology has shown that human memory is susceptible to many kinds of errors, distortions and illusions (Bartlett, 1932; Gallo, 2006; Loftus & Palmer, 1974; Roediger & McDermott, 1995; Schacter, 2001). In this context, the current dissertation highlights the role of PM deactivation by means of an evaluation of the existing evidence of it and suggested empirical studies designed to offer strong tests to some predictions.

Overall, our studies indicate that forgetting irrelevant intentions is not a trivial task for the human cognitive system and, under demanding ongoing activities, people are at greater risk of making PM commission errors. For instance, see the medicine box is likely to prompt intention retrieval and those medicines might be mistakenly taken. Simply put, the current studies pinpointed that irrelevant or completed PM intentions might remain active and that measures taken in this regard may be useful to prevent PM commission errors. We suspect that people, in general, do not realize that these memories may not be immediately deactivated. Thus, it could be helpful, for example, to throw away finished-to-do lists or using a daily pill planner for one´s medication or to remove PM cues after an intention becomes no-longer-needed (Anderson & Einstein, 2017). Moreover, in work situations in which there are multiple and demanding cognitive tasks to accomplish, people should be warned of their effects on forgetting or inhibiting prospective memories that were previously relevant.

A remaining outstanding theoretical issue concerns the role of spontaneous retrieval and cognitive control. The reviewed studies could not unambiguously attribute the absence of commission errors to an effective elimination of spontaneous retrieval or an effective cognitive inhibitory control after retrieval of an irrelevant intention. This issue cannot be entirely resolved at the present dissertation but calls for further research along these lines. In our view, we have identified novel hypotheses that are worth being tested in the future, following the recent focus on the mechanisms of cognitive control over memory. Furthermore, at present, several researchers recognize the adaptive value of the ability to forget and we reason that some mechanisms known to cause interference might play a role in helping to diminish the influence of a memory trace of a previously relevant intention to make way for the new intentions that must be accomplished daily.

In sum, our findings provided consistent and solid evidence that once an intention became irrelevant, it may not be immediately forgotten, and that inhibition and interference mechanisms modulate PM commission error risk. In future research, a way of approaching a challenging and relevant question highlighted by William James's in the opening citation of this chapter would be to further explore the mechanisms of cognitive control over prospective remembering, which is likely to broaden our understanding of the utility of episodic memory in everyday life. This dissertation takes us a little further on approaching the fate of long-term memories for intentions that are no-longer-needed and, hopefully, encourages future studies on this enthralling field. In a broader sense, this might inform us about the mechanisms and modulators of goal-directed, yet flexible, behavior.

5.4. References

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APPENDICES

Tables. Appendix 1

Supplementary material of the systematic review of Chapter 3: Tables S1 – S5.

TABLE S1. *Experiments on the effect of cognitive load in EBPM omission errors, by varying OT difficulty.*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
WM storage											
Horn et al., 2011 - 1	B	78 trials	Press *1* key when target words appear	V	W (specific)	6 targets	NF	NS	HL = .57 (.34) LL = .66 (.34)	HL = .53 (.17) LL = .88 (.11)	HL = 1869 (593) LL = 1594 (435)
Horn et al., 2011 - 2a	W	4 blocks 62 trials	Press *1* key when target words appear	V	W (specific)	6 targets	NF	NS	HL = .51 (.36) LL = .52 (.31)	HL = .53 (.16) LL = .90 (.05)	HL = 1822 (405) LL = 1882 (592)
Horn et al., 2011 - 2b	W	4 blocks 62 trials	Press *1* key when target words appear	V	W (specific)	6 targets	NF	NS	HL = .75 (.22) LL = .76 (.22)	HL = .67 (.16) LL = .92 (.05)	HL = 2171 (640) LL = 2123 (635)
Smith et al., 2012	W	2 blocks 62 trials	Press *1* key when target words appear	V	W (specific)	6 targets	F	NS	HL = .59 (.27) LL = .63 (.32)	HL = .55 (.22) LL = .81 (.27)	HL = 1923 (538) LL = 1966 (651)
Smith & Hunt, 2014	B	78 trials	Press *1* key when target words appear	V	W (specific)	6 targets	F	NS	HL = .67 (.35) LL = .64 (.35)	HL = .65 (.21) LL = .90 (.14)	HL = 1667 (714) LL = 1531 (488)
Otani et al., 1997 - 1	B	26 trials	Press zero when target words appear	A + V	W (specific)	4 targets	F	NS	HL1 = .55 (.33) HL = .46 (.39) LL = .45 (.44) NL = .55 (.40)	HL1 = .47 (.08) HL = .58 (.09) LL = .60 (.11) NL = .70 (.11)	n/a
Otani et al., 1997 - 2	B	26 trials	Press zero when target words appear	A + V	W (specific and category)	4 targets	F	NS	HL = .40 (.37) LL = .48 (.37) NL = .48 (.41)	HL= .39 (.09) LL = .45 (.08) NL = .56 (.10)	n/a
Kidder et al., 1997	B	23 recall events	Press zero key on the keypad whenever a background pattern appears	V	I (specific)	6 targets	NF	NS	HL = .82 (.20) LL = .98 (.09) (one PM target)	HL = .75 (.16) LL = .99 (.02)	n/a

(Continued)

TABLE S1. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
WM executive processing											
Fronda et al., 2020[a]	W	6 blocks 95 or 150 trials	Subtract numbers when a specific sound appears	A + V	Sound (specific)	n/a	NF	S	HL = 1.00 LL = 1.00	HL = .92 LL = .96	n/a
Lewis-Peacock et al, 2016[a]	W	6 blocks 90 trials	Press a key when target images appear	V	I (specific)	8 faces or scene target per block	NF	NS	HL = .66 (.20) LL = .71 (.20)	HL = .68 (.05) LL = .78 (.05)	HL = 1127 (105) LL = 1126 (110)
West et al., 2006	W	blocks 100 trials	Press *V* when target letters appear	V	L (specific)	10 targets	F	S	HL = .63 (.22) LL = .72 (.16)	HL = .51 (.17) LL = .73 (.15)	HL = 795 (124) LL = 700 (98)
West & Bowry, 2005	W	4 blocks 100 trials	Press *V* when target letters appear	V	L (specific)	10 targets	F	S	HL = .59 (.22) LL = .69 (.18)	HL = .89 (.06) LL = .91 (.08)	HL = 738 (198) LL = 673 (132)
Barutchu et al., 2019	W	10 blocks 200 trials	Press a key when target letters appear	A + V	L (specific)	4 targets per block	F	NS	HL = 6.80 (15.27) LL = 1.92 (6.28)	HL = 52.06 (38.11) LL = 26.49 (39.18)	n/a
Möschl et al., 2019	W	10 blocks 64 trials	Release finger from *STRG* key when encountering circles of a specific color and type how many PM cues already appeared	V	I (specific)	3-5 targets	NF	NS	Errors: HL = 34.3 (25) LL = 19.7 (18.8)	Errors: HL = 10.6 (6.25) LL = 6.2 (3.58)	HL = 609 (108) LL = 537 (98)
Marsh & Hicks, 1998 - 1	B	40 trials	Press *F* key when target words appear	A + V	W (category)	2 targets	F	NS	HL = .50 (.42) LL = .75 (.25) NL = .78 (.25)	HL = .67 (.08) LL = .74 (.08) NL = .91 (.04)	n/a

(Continued)

TABLE S1. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Other tasks											
Lee & McDaniel, 2013	B	2 blocks 82 anagrams	Press *Q* key if they saw any anagrams of 2 specific words	V	W (specific)	2 targets	F	NS	HL = .95 (.26) LL = .89 (.26)	HL = .82 (.08) LL = .93 (.07)	HL = 4560 LL = 3047
Rendell et al., 2007 – 2	B	4 blocks 120 trials	Circling the item number whenever a face is wearing glasses	V	I (category)	8 targets	F	NS	HL = .76 LL = .72	HL = .56 (.19) LL = .53 (.22)	n/a
Gonneaud et al., 2011	W	n/a	Press *D* key when the answer was over 100 and the *L* key *w*hen the number was made up of two identical digits	V	N (category)	4 targets per load condition	F	NS	n/a	n/a	n/a
Stone et al., 2001 - 1a	W	12 trials	Send a plane to a specific point	V	Route (specific)	12 targets	F	NS	HL = 1-min delay: .80 (.17); 3-min delay: 87 (.17); 5-min delay: .85 (.17) LL = 1-min delay: .92 (.12); 3-min delay: .92 (.10); 5-min delay: .93 (.13)	HL = .72 (.12) LL = .77 (.09)	n/a

(Continued)

TABLE S1. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Stone et al., 2001 - 1b	W	12 trials	Send a plane to a specific point	A + V	Route (specific)	12 targets	F	NS	HL = 1-min delay: .59 (.26); 3-min delay: .67 (.25); 5-min delay: .64 (.24) LL = 1-min delay: .82 (.16); 3-min delay: 5-min delay: .79 (.21); .80 (.23)	HL = .70 (.09) LL = .81 (.06)	n/a

Note. WM = Working memory; PM = Prospective memory; OT = Ongoing task; B = Between-subjects; W = Within-subjects; A = Auditory; V = Visual; A + V = Auditory and visual; I = Image; L = Letter; N = Number; W = Word; F = Focal; NF = Non-focal; S = Salient; NS = Non-salient; HL = High load; LL = Low load; NL = No load; n/a = not available. [a]Estimated values using WebPlotDigitizer®.

TABLE S2. *Experiments on the effect of cognitive load in EBPM omission errors, by adding a secondary OT.*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
WM storage											
Harrison et al., 2014 - 1	W	4 blocks 320 trials	Press *Q* key when target words appear	A + V	W (specific)	4 targets per block	F	NS	HL = .60 LL = .65	HL = .95 (.03) LL = .96 (.03)	HL = 652 (110) LL = 546 (60)
McDaniel et al., 1998 - 3	B	60 trials	Press *F10* key when target words appeared	V	W (specific)	4 targets per block	F	NS	Adjective: HL = .28 (.39); LL = .55 (.39); Rhyme: HL = .18 (.33) LL = .40 (.39)	Adjective: HL = .27 (.42) LL = .28 (.28) Rhyme: HL = 2.9 (.47) LL = 2.8 (.34)	Adjective: HL = 3830 (1270) LL = 2750 (570) Rhyme: HL = 3490 (1080) LL = 2800 (630)
McGann et al., 2002 - 1	B	10 blocks 100 trials	Press *enter* key when target words appeared	A + V	W (specific)	4 targets	F	NS	HL = .22 LL = .58	n/a	n/a
McGann et al., 2002 - 2	B	10 blocks 100 trials	Press *enter* key when target words appeared	A + V	W (specific)	4 targets	F	NS	Same font: HL = .75 (.32) LL = .84 (31) Different font: HL = .42 (.36) LL = .52 (.41)	n/a	n/a
McGann et al., 2002 - 3	B	10 blocks 100 trials	Press *enter* key when target words appeared	A + V	W (specific)	4 targets	F	NS	Pleasantness rating: HL = .60 (.40) LL = .85 (.30) Readability rating: HL = .75 (.32) LL = .72 (.34)	n/a	n/a
McDaniel et al., 2004 - 2	W	104 trials	Write a particular response word when target word appears	A + V	W (specific)	4 targets	F	NS	HL = .76 (.35) LL = .86 (.28)	n/a	n/a
McDaniel et al., 2008 - 1	W	4 blocks 60 trials each	Press *Q* key when target words appear	A + V	W (specific)	2 targets per block	F	NS	n/a	n/a	n/a

Continued)

TABLE S2. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Guynn & McDaniel, 2007	W	100 trials	Write the response word when target appear	A + V	W (specific)	4 targets	F	NS	No target preexposure: HL = .59 (.43) LL = .69 (.40) Target preexposure: HL = .83 (.33) LL =.80 (.36)	n/a	n/a
Einstein et al., 1997 - 1	B	2 blocks 97 trials	Press *slash* key when target words appear	A + V	W (specific)	3 targets	F	NS	HL = .58 (.37) LL = .71 (.31)	n/a	n/a
Einstein et al., 1997 - 2	B	2 blocks 97 trials	Press *slash* key when target words appear	A + V	W (specific)	6 targets	F	NS	HL = .64 (.43) LL = .66 (.32)	n/a	n/a
Van den Berg et al., 2004 - 2	B	11 trials with 7 words each	Press *enter* key when target words appear	A + V	W (specific)	2 targets	F	NS	Typical target: HL = .28 LL = .40 Atypical target: HL = .15 LL = .25	HL = .65 LL = .69	n/a
Boywitt et al., 2015 - 1	B	192 trials	Press *7* key when target words appear	A + V	W (specific)	6 targets	F	S	HL = .95 (.11) LL = .97 (.06)	HL = .93 (.07) LL = .96 (.07)	HL = 955 (258) LL = 807 (254)
Rummel et al., 2016 - 2	B	300 trials	Press a colored key twice when target words appeared	A + V	W (specific)	12 targets	F	NS	HL = .33(.29) LL = .45 (.28)	HL = .91 (.06) LL = .93 (.06)	HL = 1048 (234) LL = 947 (226)
Marsh & Hicks, 1998 - 4	B	40 trials	Press *F* key when target words appear	V	W (category)	2 targets	F	NS	HL = .42 (.47) LL = .72 (.42)	HL = .94 (.04) LL =. 96 (.04)	n/a
Marsh & Hicks, 1998 - 5	B	40 trials	Press *F* key when target words appear	A + V	W (category)	2 targets	F	NS	HL = .81 (.30) LL = .78 (.25) NL = .67 (.38)	HL = .99 (.001) LL =. 99 (.001) NL = .99 (.002)	n/a

(Continued)

TABLE S2. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Marsh & Hicks, 1998 - 3	B	40 trials	Press *F* key when target words appear	A + V	W (category)	2 targets	F	NS	HL = .61 (.42) LL = .64 (.42)	HL = .54 (.34) LL = .82 (.34)	n/a
Van den Berg et al., 2004 - 3	B	11 trials with 7 words each	Press *enter* key when target words appear	A + V	W (specific)	2 targets	F	NS	Typical target: HL = .58 (.44) LL = .60 (.45) Atypical target: HL = .85 (.37) LL = .78 (.41)	HL = .68 LL = .72	n/a
WM executive functioning											
McDaniel et al., 2008 - 2	W	4 blocks 80 trials each	Press *Q* key when target words appear	A + V	W (specific)	2 targets per block	F	NS	HL = .84 LL = .94	HL = .88 LL = .98	HL = 2585 LL = 2239
McDaniel & Scullin, 2010 - 2	W	2 blocks 96 trials	Press *enter* key when target words appear	A + V	W (specific)	2 targets per block	F	NS	HL = .21 (.36) LL = .31 (.41)	HL = .91 (.04) LL = .95(.03)	HL = 2475 (851) LL = 1049 (134)
Harrison et al., 2014 - 2	W	4 blocks 320 trials	Press *Q* key when target words appear	A + V	W (specific)	4 targets per block	F	NS	HL = .53 LL = .37	HL = .92 (.05) LL = .96 (.03)	HL = 1063 (521) LL = 617 (157)
Harrison et al., 2014 - 3	W	4 blocks 320 trials	Press *Q* key when target words appear	A + V	W (specific)	4 targets per block	F	S	HL = .39 LL = .53	HL = .95 (.04) LL = .97 (.03)	HL = 1284 (577) LL = 625 (115)
McDaniel & Scullin, 2010 - 1	W	Lexical decision task: 274 trials Category decision task: 4 blocks; 100 trials	Press *7* key when target words appear	A + V	W (specific)	2 targets per block	F	NS	HL = .30 (.36) LL = .56 (.45)	HL = .86(.12) LL = .94(.05)	HL = 2255 (801) LL = 1117 (144)
Marsh & Hicks, 1998 - 2	B	40 trials	Press *F* key when target words appear	A + V	W (category)	2 targets	F	NS	HL = .36 (.42) LL = .67 (.34)	HL = .71 (.13) LL = .85 (.34)	n/a

(Continued)

TABLE S2. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Van den Berg et al., 2004 - 1	B	20 trials with 3 words each	Press *enter* key when target words appear or target category (fruits)	A + V	W (specific/ category)	1 target	F	NS	Specific: HL = .50 LL = .73 Category: HL = .35 LL = .45	Specific: HL = .65 LL = .69 Category: HL = .59 LL = .63	n/a
Reasoning tasks											
Logie et al., 2004	B	n/a	Say animal when target images appear	A + V	I (category)	5 targets	F	NS	HL = 4.8 (.42) LL = 5.0 (.00)	–	n/a
Long-term memory tasks											
Bisiacchi et al., 2008 - comparison between 1 and 2[a]	B	8 blocks 20 trials	Press the *spacebar* when target images appeared	V	I (specific)	1 target per block	F	NS	HL = .93 LL = .98	n/a	HL = 688 LL = 646
Einstein et al., 1995 - 3	W	160 trials	Press *F8* key whenever a question about the president was presented	A + V	Question (category)	6 targets	F	NS	n/a	HL = .59 LL = .60	n/a
Khan et al., 2008	W	120 trials	Double-click the left side of the mouse on the right side of the screen whenever target words appear	A + V	W (specific)	6 targets	F	NS	HL = 1.82 (.71) LL = .2.55 (.71)	n/a	n/a

(Continued)

TABLE S2. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
d'Ydewalle et al., 1999	B	46 trials each OT	Press *F1* key whenever a question about the Belgian royal family was presented or draw a circle around the number of the card when they saw a man with tie	V	Question (category)	3 target-events per each OT	F	NS	n/a	n/a	n/a

Note. WM = Working memory; PM = Prospective memory; OT = Ongoing task; B = Between-subjects; W = Within-subjects; A = Auditory; V = Visual; A + V = Auditory and visual; I = Image; W = Word; F = Focal; S = Salient; NS = Non-salient; HL = High load; LL = Low load; NL = No load; n/a = not available.

[a]Estimated values using WebPlotDigitizer®.

TABLE S3. *Experiments on the effect of cognitive load in EBPM omission errors in task-switching paradigms.*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Marsh et al., 2002 - 1 and 2	B	104 trials	Press */* key when target words appear	V	W (specific)	4 targets	F	NS	Experiment 1: HL = .56 (.31) LL = .71 (.25) Experiment 2: HL = .56 (.42) LL = .71 (.37)	n/a	Experiment 1: HL = 2515 (764) LL = 1529 (437) Experiment 2: HL = 2478 (842) LL = 1887 (625)
McNerney & West, 2007 - 1	W	8 blocks 100 trials each	Press *V* key when target words appear	V	W (specific)	16 targets	F	NS	HL = .29 (.25) LL = .47 (.36)	HL = .87 (.07) LL = .88 (.05) NL = .83 (.05)	HL = 1534 (452) LL = 1421 (358) NL = 1165 (291)
McNerney & West, 2007 - 2	W	8 blocks 100 trials each	Press *V* key when target words appear	V	W (category)	16 targets	F	NS	HL = .57 (.26) LL = .70 (.29)	HL = .91 (.06) LL = .91 (.05) NL = .91 (.02)	HL = 1628 (430) LL = 1475 (385) NL = 1151 (294)
McNerney & West, 2007 - 3	W	8 blocks 100 trials each	Press *V* key when target words appear	V	W (category)	16 targets	F	NS	HL = .50 (.28) LL = .68 (.27)	HL = .98 (.02) LL = .99 (.07)	HL = 1945 (397) LL = 1263 (271)
West et al., 2011 - 1	W	8 blocks 100 trials each	Press *V* key when target words appear	V	W (category)	16 targets	F	NS	HL = .55 (.34) LL = .61 (.31)	HL = .83 (.09) LL = .84 (.08) NL = .78 (.08)	HL = 1441 (315) LL = 1389 (322) NL = 1140 (242)
West et al., 2011 - 2	W	8 blocks 100 trials each	Press *V* key when target words appear	V	W (category)	16 targets	F	NS	HL = .42 (.28) LL = .60 (.21)	HL =.81 (.10) LL = .81 (.10) NL = .77 (.08)	HL = 1481 (391) LL = 1426 (344) NL = 1239 (269)

(Continued)

TABLE S3. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Pereira et al., 2018	W	12 blocks 52 trials	Press *Q* key when target words appear	V	W (category)	4 targets	F	NS	HL = PTR: .75 (.32); ITR: .63 (.32) LL = PTR: .74 (.32); ITR: .72 (.28)	HL = PTR: .91 (.06); ITR: .93 (.07) LL = PTR: .92 (.07); ITR: .94 (.04) NL = PTR: .94 (.05); ITR: .95 (.04)	HL = PTR: 1102 (279); ITR: 1172 (315) LL = PTR: 1072 (287); ITR:136 (304) NL = PTR: 882 (216); ITR: 999 (223)

Note. PM = Prospective memory; OT = Ongoing task; B = Between-subjects; W = Within-subjects; A = Auditory; V = Visual; A + V = Auditory and visual; W = Word; F = Focal; NS = Non-salient; HL = High Load; LL = Low load; NL = No load; PTR = Postponed target response; ITR = Immediate target response; n/a = not available.

TABLE S4. *Experiments on the effect of cognitive load in TBPM omission errors.*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Number of PM cues	Cue saliency	PM performance	OT performance	
							Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Experiments varying OT difficulty									
Martin & Schumann-Hengsteler, 2001	B	n/a	Change the protocol sheet every three minutes	V	Maximum 6 targets	NS	HL = 3.9 LL = 4.5 NL = 5.4	Number of games: HL = 1.83 LL = 9.57 NL = 27.53	n/a
Gonneaud et al., 2011	W	n/a	Press *D* and *L* every 3 minutes	V	4 targets per load condition	NS	n/a	n/a	n/a
Fronda et al., 2020[a]	W	6 blocks 95 or 150 trials	Subtract numbers every 3 minutes from the beginning of the task	A + V	3 targets	NS	HL = .95 LL = .91	HL = .92 LL = .96	n/a
Experiments adding a secondary OT									
Khan et al., 2008	W	120 trials	Click the left side of the mouse on the right side of the screen every 5 minutes		5 targets	NS	HL = 1.23 (.89) LL = 2.45 (.64)	n/a	n/a
Einstein et al., 1995 - 3	W	160 trials	Press *F8* key every 5 minutes (6 times)	A + V	6 targets	NS	n/a	HL = .59 LL = .60	n/a
Logie et al., 2004	B	n/a	Press the *spacebar* every 3 minutes	A + V	Maximum 6 targets	NS	HL = 4.8 (.42) LL = 5.0 (.00)	n/a	n/a

TABLE S4. *Continued*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Number of PM cues	Cue saliency	PM performance	OT performance	
							Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
d'Ydewalle et al., 1999	B	46 trials each OT	Press *F1* when clock showed 4, 9, and 12 minutes (question answering); draw a circle around the number of a card when clock showed 3, 8, and 10 minutes (face identification)	V	3 target each OT	NS	n/a	n/a	n/a

Note. PM = Prospective memory; OT = Ongoing task; B = Between-subjects; W = Within-subjects; A = Auditory; V = Visual; A + V = Auditory and visual; NS = Non-salient; HL = High load; LL = Low load; NL = No load; n/a = not available. [a]Estimated values using WebPlotDigitizer®.

TABLE S5. *Experiments on the effect of cognitive load in EBPM and TBPM commission errors.*

Experiment	Design	OT Number of blocks/trials	PM task	Modality	Cue type	Number of cues	Cue focality	Cue saliency	PM performance	OT performance	
									Accuracy *M* (*SD*)	Accuracy *M* (*SD*)	RTs *M* (*SD*)
Event-based PM tasks											
Boywitt, et al., 2015 - 1	B	186 trials	Press *7* key when target words appear	A + V	W (category)	16 targets	F	S	HL = .08 (.11) LL = .19 (.23)	HL = .93 (.04) LL = .96 (.04)	HL = 955 (287) LL = 805(283)
Pink & Dodson, 2013 - 1a and 1b	B	400 trials	Press *shift* key when target words appear	A + V	W (specific)	16 targets	F	NS	n/a	n/a	n/a
Matos et al., 2020	B	240 trials	Press *Q* when target words appear	A + V	W (specific)	10 targets	F	S	n/a	HL = .94 (.05) ML = .94 (.10) LL = .95 (.03)	HL = 693 (100) ML = 681 (76) LL = 692 (94)
Time-based PM tasks											
Einstein et al., 1998	B	11 blocks 1-3 trials each	Press *F1* in the appropriate moment	A + V	n/a	11 targets	–	–	No cue: HL = .06 LL = .03 Cue: HL = .05 LL = .08	n/a	n/a

Note. PM = Prospective memory; OT = Ongoing task; B = Between-subjects; A = Auditory; V = Visual; A + V = Auditory and visual; W = Word; F = Focal; NS = Non-salient; HL = High load; LL = Low load; NL = No load; n/a = not available.

Table. Appendix 2

List of words and pseudo-words used in the LDT of Phase 1 and Phase 2 (extracted from the Portuguese-European Norms - The Minho Word Pool; Soares et al., 2017, 2019).

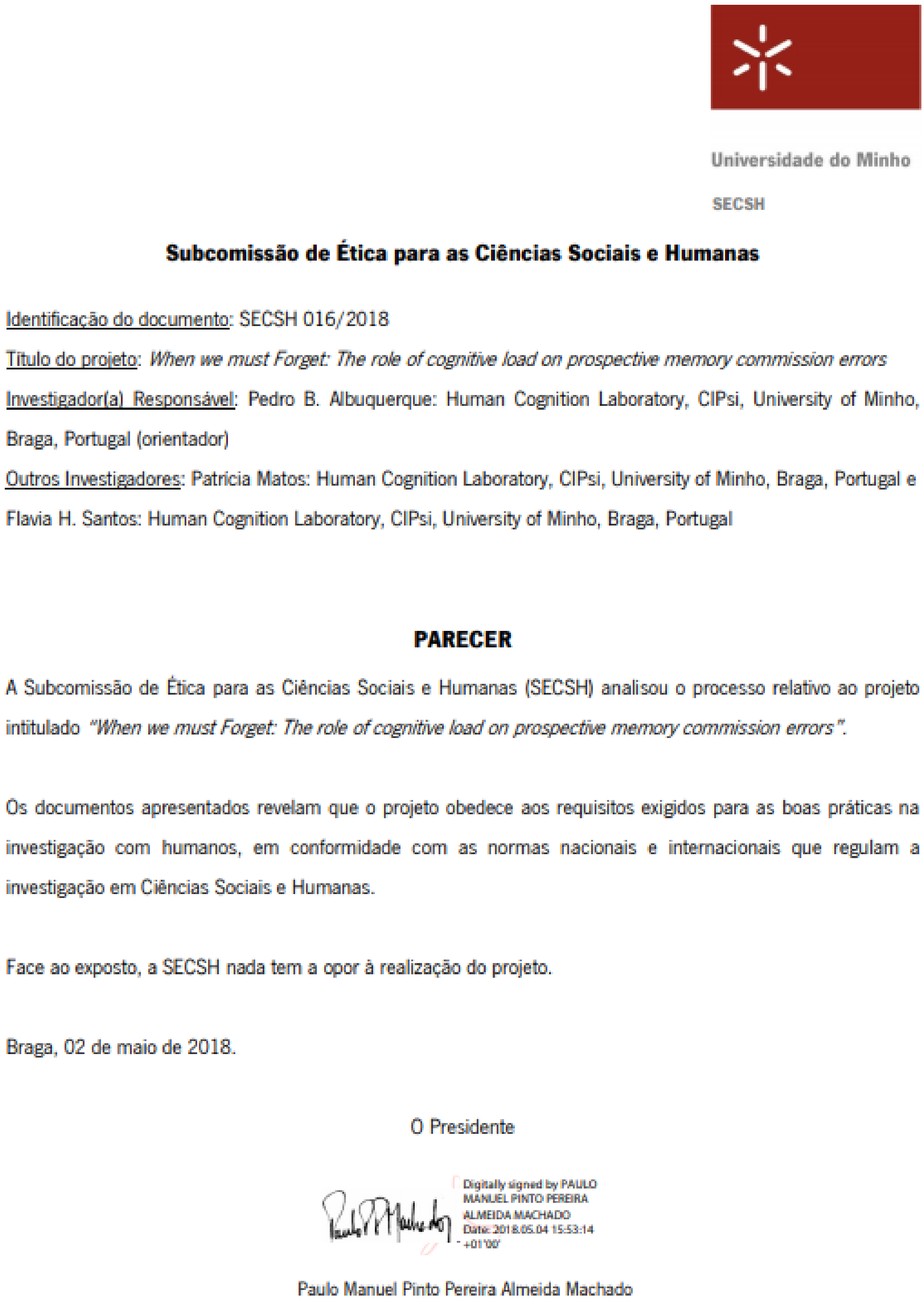
Words	Lenght	RT	Word Frequency	Pseudo-Words	Lenght
Curso	5	550	132	donho	5
Livre	5	553	102	necha	5
Longo	5	553	236	pelha	5
Resto	5	566	143	couga	5
Sinal	5	558	87	panta	5
Visto	5	551	298	ladota	6
Actual	6	560	298	tedola	6
Enorme	6	551	91	nolato	6
Estado	6	565	85	sofote	6
Início	6	552	318	paquigo	7
Mínimo	6	581	88	telhoto	7
Parque	6	553	85	lonebilo	7
Subida	6	585	79	telhoto	7
Atitude	7	555	110	mitogue	7
Entrada	7	557	190	sumides	7
Estrada	7	553	93	taplanto	8
Jogador	7	559	104	sotecoda	8
Maneira	7	558	145	riabates	8
Notícia	7	559	80	lanimaço	8
Questão	7	555	371	dacoteso	8
Sentido	7	551	311	touto	5
Sucesso	7	555	110	morma	5
Anterior	8	576	179	tebabo	6
Direcção	8	553	265	coteda	6
Edifício	8	560	118	codico	6
Encontro	8	558	290	cotenso	7
Hipótese	8	572	123	doritio	7
Intenção	8	559	93	macação	7
Interior	8	553	141	ladagio	7
Ministro	8	565	433	lapenato	8
Natureza	8	559	99	tanitaso	8
Política	8	578	147	lamajapa	8
M	6,73	559,58	168,39	***M***	6,59
SD	1,10	9,22	98,17	***SD***	1,10

Table. Appendix 3

List of target and control words trials (extracted from the Portuguese-European Norms - The Minho Word Pool; Soares et al., 2017, 2019).

Words	Lenght	RT	Word Frequency
Alto	4	554	113
Fase	4	551	223
Título	6	567	196
Espera	6	557	194
M	5,00	557,25	181,50
SD	1,15	6,95	47,54

Ethical Approval. Appendix 4



Universidade do Minho

SECSH

Subcomissão de Ética para as Ciências Sociais e Humanas

Identificação do documento: SECSH 016/2018

Título do projeto: *When we must Forget: The role of cognitive load on prospective memory commission errors*

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PARECER

A Subcomissão de Ética para as Ciências Sociais e Humanas (SECSH) analisou o processo relativo ao projeto intitulado *"When we must Forget: The role of cognitive load on prospective memory commission errors"*.

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na investigação com humanos, em conformidade com as normas nacionais e internacionais que regulam a investigação em Ciências Sociais e Humanas.

Face ao exposto, a SECSH nada tem a opor à realização do projeto.

Braga, 02 de maio de 2018.

O Presidente

Digitally signed by PAULO MANUEL PINTO PEREIRA ALMEIDA MACHADO
Date: 2018.05.04 15:53:14 +01'00'

Paulo Manuel Pinto Pereira Almeida Machado