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FACULTÉ DE PSYCHOLOGIE
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Section de
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Sous la direction de Prof. Dr. Matthias Kliegel et Dr. Alexandra Hering

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STRATEGIC MONITORING AND TIME PERCEPTION IN TIME-BASED PROSPECTIVE MEMORY

THESE

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Faculté de psychologie et des sciences de l'éducation
de l'Université de Genève
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Docteur en Psychologie

par

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Pietro, Maria, and Monica.

Statement

The present work is a cumulative dissertation based on three articles (*Thèse sur dossier d'articles*) representing two empirical studies and one meta-analysis. It has been prepared as a self-contained work and all chapters were composed specifically for this dissertation. Furthermore, I wrote the three journal articles as first author according to the APA author guidelines with edits from my co-authors. The articles are included in the present thesis as they were submitted to the respective journals, with minor changes were made to adapt all articles to the context of the entire thesis. Terminological and formatting inconsistencies may occur due to the different journal publishing policies. This work benefited also from the support of the Swiss National Centre of Competence in Research LIVES – Overcoming vulnerability: Life course perspectives (NCCR LIVES), which was financed by the Swiss National Science Foundation (grant number: 51NF40-185901).

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Article 2 (Chapter 5): Laera, G., Borghese, F., Hering, A., Kliegel M., & Mioni G. (2023). Aging and time-based prospective memory in the laboratory: a meta-analysis on age-related differences and possible explanatory factors, *Memory*, 31:5, 747-766, DOI: 10.1080/09658211.2023.2191901.

Article 3 (Chapter 6): Laera, G., Borghese, F., Hering, A., Kliegel M., & Mioni G. (under review). The cost of monitoring in time-based prospective memory. *Scientific Reports*

Abstract

Time-based prospective memory is the ability to fulfil an intention at the appropriate future moment, such as meeting a friend at 7:00 p.m., or taking the medication at dinner. Time-based prospective memory is a complex cognitive function that can be influenced by a myriad of factors, including individual and contextual characteristics. Although in the last 30 years there has been a growing research interest in the literature, the neurocognitive processes underlying time-based prospective memory are still a matter of debate. Specifically, there is limited knowledge about how time perception affects strategic monitoring of the external time, which is essential to perform time-based prospective memory tasks on time. Indeed, research generally assumes reliable connections between time perception and strategic time monitoring, but such assumption has been investigated systematically not very often. Moreover, it is not clear the extent of the age impact on time monitoring in laboratory-based tasks, as well as the link between age effects with time-based prospective memory performance, and the cognitive modulation induced by task-specific factors, such as the frequency or the duration of the prospective memory tasks. Finally, it is unknown the influence of motivational mechanisms on time monitoring and time-based prospective memory failures.

Time-based prospective memory, as well as its relationship with time perception, can have serious implications for functional autonomy and well-being, because both are tightly connected to an individual's ability to adapt to the environment, and has been shown to be a predictor of future disease, which is particularly relevant in late adulthood. Thus, understanding how time perception affects strategic time monitoring is of utmost importance for the scientific and clinical communities interested in promoting quality of life in late adulthood as well as in vulnerable populations affected by diverse neurological and psychopathological disorders. Yet, despite the growing scientific interest in the topic of time-based prospective memory, it is surprising how little is known about the role of time perception, especially given the huge importance that time-based prospective memory can have in daily life (e.g., forgetting to pay bills on time can lead to fines, or forgetting to take medication can lead to serious health troubles).

To fill this research gap, the present work aimed to better understand the cognitive processes behind strategic time monitoring and time-based prospective memory, as well as to elucidate the state of the art concerning age effects and related cognitive processes in time monitoring and time-based prospective memory, and to investigate the potential modulation of the cognitive processes involved in time monitoring and time-based prospective memory that is driven by motivational incentives. Three main research questions were formulated: 1) How do participants monitor the target time in time-based prospective memory tasks? Do participants actively use internal timing processes? 2) What are the age-related differences in time monitoring assessed in the laboratory setting? How do specific task-related factors affect age-related differences in time-based prospective memory? 3) How do monetary costs affect time monitoring and time-based prospective memory, as well as their relationship? Do people change time monitoring strategy?

Two empirical studies and one meta-analysis were conducted. Study 1 aimed to answer to research question 1 manipulating the external time (i.e., clock-speed); in two experiments, participants performed two identical time-based prospective memory tasks: a first time-based prospective memory block with no clock-speed manipulation followed by a second time-based prospective memory block, where the clock-speed was manipulated as faster or slower (experimental conditions) or normal (control condition). Study 3 aimed to answer to research question 3 manipulating monetary deductions: in one group of participants, missed PM responses were penalized with a monetary deduction (single-cost condition); in a second experimental group (double-cost condition), not only missed PM responses, but also time monitoring resulted in deductions from the endowment; both groups were compared with a control group. The meta-analysis was carried out to answer research question 2.

The results from the two empirical studies showed that participants used internal timing processes especially when exposed to the slower clock, benefiting strategic monitoring and time-based prospective memory performance; faster clocks hindered self-initiated monitoring and time-based prospective memory performance, disrupting internal time processing. Participants with a slower clock perhaps anticipated the PM target time earlier, having implicitly more time to complete the task. Moreover, such internal time processes seem to affect time monitoring differently as a function of the monetary losses related to time-based prospective memory performance and/or time monitoring: when monitoring was associated with money losses, participants checked the clock less frequently overall (thus minimizing money losses) but at the same time concentrated most clock checks closer to the PM target time (maximizing the chances of optimal time-based prospective memory performance). Conversely, when monitoring wasn't costly, the time-based prospective memory task required less strategic monitoring, and internal time processes had a beneficial effect on the self-initiated processes per se, rather than on the monitoring strategicness, allowing participants to prevent money losses linked to the time-based prospective memory performance. In Study 2, the age effects in time-based prospective memory were reviewed and meta-analyzed, revealing that younger adults performed better than older adults in time-based prospective memory tasks – in line with the previous meta-analysis – and checked the clock more often than older adults; the two age effects were positively related with each other. Moreover, especially for shorter intervals (i.e., less than 4 minutes), younger adults were more accurate at the time-based prospective memory task and checked the clock more frequently. This was in line with the empirical body of evidence suggesting that age differences for shorter intervals might be due to the involvement of attentional control processes, particularly impaired with aging, while longer PM tasks may facilitate the engagement of time estimation abilities, which are relatively spared with aging, thus reducing the age differences in time monitoring and time-based prospective memory accuracy.

In summary, the results comprehensively suggested that the involvement of time estimation is facilitated with longer PM tasks and can compensate age differences during these tasks (perhaps involving also learning processes), and when time monitoring is affected by consequences related to money losses. The relationship between time perception and time-based prospective memory is a complex phenomenon shaped by several factors. The present work provides an updated account of the literature, new insights, and data from two experimental studies investigating the cognitive and motivational mechanisms of time monitoring, as well as a quantitative account of the age effects through a meta-analysis. To have a more comprehensive understanding of how time perception influences strategic time monitoring, it is crucial to start integrating knowledge that so far has been developed in isolation and has been scattered over different literature.

French Abstract – Résumé en Français

La mémoire prospective basée sur le temps est la capacité à réaliser une intention au moment opportun, par exemple en rencontrant un ami à 19 heures précises ou en prenant ses médicaments au cours du dîner. La mémoire prospective basée sur le temps est une fonction cognitive complexe qui peut être influencée par une myriade de facteurs, y compris des caractéristiques individuelles et contextuelles. Malgré l'intérêt croissant de la recherche au cours des 30 dernières années, les processus neurocognitifs qui sous-tendent la mémoire prospective basée sur le temps font toujours l'objet d'un débat. Plus précisément, nous en savons peu sur la manière dont la perception du temps affecte le contrôle stratégique du temps externe, qui est essentiel pour effectuer à temps des tâches de mémoire prospective basée sur le temps. En effet, la recherche suppose généralement l'existence de liens potentiels entre la perception du temps et le suivi stratégique du temps, mais cette hypothèse n'a pas fait l'objet d'études systématiques très fréquentes. En outre, l'ampleur de l'impact de l'âge sur le contrôle du temps dans les tâches de laboratoire n'est pas claire, pas plus que le lien entre les effets de l'âge et les performances en mémoire prospective basée sur le temps, et la modulation cognitive induite par des facteurs spécifiques à la tâche, tels que la fréquence ou la durée des tâches de mémoire prospective. Enfin, on ne connaît pas l'influence des mécanismes de motivation sur la surveillance du temps et les échecs de la mémoire prospective basée sur le temps.

La mémoire prospective basée sur le temps, ainsi que sa relation avec la perception du temps, peut avoir de sérieuses implications pour l'autonomie fonctionnelle et le bien-être, car ces deux aspects sont étroitement liés à la capacité d'un individu à s'adapter à l'environnement, et il a été démontré qu'elle est un prédicteur de

maladies futures, ce qui est particulièrement pertinent chez les personnes âgées. Ainsi, comprendre comment la perception du temps affecte le contrôle stratégique du temps est de la plus haute importance pour les communautés scientifique et clinique intéressées par la promotion de la qualité de vie lors du vieillissement, ainsi que pour les populations vulnérables affectées par divers troubles neurologiques et psychopathologiques. Pourtant, malgré l'intérêt scientifique croissant pour le thème de la mémoire prospective basée sur le temps, il est surprenant de constater à quel point le rôle de la perception du temps est peu connu, surtout si l'on considère l'importance considérable que la mémoire prospective basée sur le temps peut avoir dans la vie quotidienne (par exemple, oublier de payer ses factures à temps peut conduire à des amendes, ou oublier de prendre ses médicaments peut conduire à de graves problèmes de santé).

Pour combler cette lacune, le présent travail visait à mieux comprendre les processus cognitifs qui sous-tendent le contrôle stratégique du temps et la mémoire prospective basée sur le temps, ainsi qu'à éclaircir l'état de la littérature concernant les effets de l'âge et les processus cognitifs liés au contrôle du temps et à la mémoire prospective basée sur le temps, et à étudier la modulation potentielle des processus cognitifs impliqués dans le contrôle du temps et la mémoire prospective basée sur le temps sous l'effet d'incitations motivationnelles. Trois questions de recherche principales ont été formulées : 1) Comment les participants surveillent-ils le temps cible dans les tâches de mémoire prospective basée sur le temps ? Les participants utilisent-ils activement des processus de synchronisation internes ? 2) Quelles sont les différences liées à l'âge dans le suivi du temps évalué en laboratoire ? Comment les facteurs spécifiques liés à la tâche affectent-ils les différences liées à l'âge dans la mémoire prospective basée sur le temps ? 3) Comment les récompenses monétaires affectent-ils le contrôle du temps et la mémoire prospective basée sur le temps, ainsi que leur relation ? Les individus changent-ils de stratégie de contrôle du temps ?

Deux études empiriques et une méta-analyse ont été réalisées. L'étude 1 visait à répondre à la question de recherche 1 en manipulant le temps externe (c'est-à-dire la vitesse de l'horloge) ; dans deux expériences, les participants ont effectué deux tâches identiques de mémoire prospective basée sur le temps : un premier bloc de mémoire prospective basée sur le temps sans manipulation de la vitesse de l'horloge, suivi d'un second bloc de mémoire prospective basée sur le temps, où la vitesse de l'horloge était manipulée comme plus rapide ou plus lente (conditions expérimentales) ou comme normale (condition de contrôle). L'étude 3 visait à répondre à la question de recherche 3 en manipulant les déductions monétaires : dans un groupe de participants, les réponses de mémoire prospective manquées étaient pénalisées par une déduction monétaire (condition à coût unique) ; dans un second groupe expérimental (condition à double coût), non seulement les réponses mémoire prospective manquées, mais aussi le contrôle du temps entraînaient des déductions de la récompense monétaire ; les deux groupes ont été comparés à un groupe témoin. La méta-analyse a été réalisée pour répondre à la question de recherche 2.

Les résultats des deux études empiriques ont montré que les participants utilisaient les processus temporels internes surtout lorsqu'ils étaient exposés à l'horloge la plus lente, ce qui favorisait la surveillance stratégique et les performances de la mémoire prospective basée sur le temps ; les horloges plus rapides entravaient la surveillance auto-initiée et les performances en mémoire prospective basée sur le temps, ce qui perturbait le traitement interne du temps. Les participants dont l'horloge est plus lente ont peut-être anticipé l'heure cible des PM plus tôt, disposant

implicitement de plus de temps pour accomplir la tâche. En outre, ces processus temporels internes semblent affecter différemment le contrôle du temps en fonction des pertes monétaires liées à la performance de la mémoire prospective basée sur le temps et/ou au contrôle du temps : lorsque le contrôle était associé à des pertes monétaires, les participants vérifiaient l'horloge moins fréquemment dans l'ensemble (minimisant ainsi les pertes monétaires) mais concentraient en même temps la plupart des vérifications de l'horloge plus près de l'heure cible de l'après-midi (maximisant les chances d'une performance optimale de la mémoire prospective basée sur le temps). Inversement, lorsque le contrôle n'était pas coûteux, la tâche de mémoire prospective basée sur le temps nécessitait un contrôle moins stratégique, et les processus temporels internes avaient un effet bénéfique sur les processus auto-initiés en soi, plutôt que sur le caractère stratégique du contrôle, permettant aux participants d'éviter les pertes d'argent liées à la performance de la mémoire prospective basée sur le temps. Dans l'Étude 2, les effets de l'âge sur la mémoire prospective basée sur le temps ont été examinés et méta-analysés, ce qui a révélé que les jeunes adultes étaient plus performants que les adultes plus âgés dans ce type de tâche - conformément à la méta-analyse précédente - et qu'ils vérifiaient l'horloge plus souvent que les adultes plus âgés ; les deux effets de l'âge étaient positivement liés l'un à l'autre. En outre, en particulier pour les intervalles plus courts (c'est-à-dire inférieurs à 4 minutes), les jeunes adultes étaient plus précis dans la tâche de mémoire prospective basée sur le temps et vérifiaient l'horloge plus souvent. Ces résultats sont conformes à l'ensemble des données empiriques suggérant que les différences entre les âges pour les intervalles plus courts sont dues à l'implication des processus de contrôle attentionnel, particulièrement altérés avec le vieillissement, tandis que les tâches de mémoire prospective plus longues peuvent faciliter l'engagement des capacités d'estimation du

temps, qui sont relativement épargnées avec le vieillissement, réduisant ainsi les différences entre les âges dans la surveillance du temps et la précision de la mémoire prospective basée sur le temps.

En résumé, les résultats suggèrent que l'implication de l'estimation du temps est facilitée par des tâches de mémoire prospective plus longues et peut compenser les différences d'âge au cours de ces tâches (impliquant peut-être aussi des processus d'apprentissage), et lorsque la surveillance du temps est affectée par des conséquences liées à des pertes d'argent. La relation entre la perception du temps et la mémoire prospective basée sur le temps est un phénomène complexe qui dépend de plusieurs facteurs. Le présent travail fournit un compte rendu actualisé de la littérature, de nouvelles perspectives et des données issues de deux études expérimentales portant sur les mécanismes cognitifs et motivationnels du contrôle du temps, ainsi qu'un compte rendu quantitatif des effets de l'âge par le biais d'une méta-analyse. Pour mieux comprendre comment la perception du temps influence le contrôle stratégique du temps, il est essentiel de commencer à intégrer les connaissances qui, jusqu'à présent, ont été développées de manière isolée et dispersées dans différentes publications.

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Abbreviations

TBPM: Time-based prospective memory

OT: Ongoing task

RTs: reaction times

TWTE: Test-Wait-Text-Exit

TWTE-r: Test-Wait-Text-Exit (revised)

AGM: Attentional-gate model

IR-AGM: Attentional-gate model (intention-retrieval version)

TBS: Time-based strategy

EBS: Event-based strategy

"We should begin thinking of events as the primary realities and of time as an abstraction from them – a concept derived mainly from regular repeating events, such as the ticking of clocks. Events are perceived, but time is not."

James J. Gibson, 1979, p. 93

“Most daily activities […] involve tacitly ‘using’ event timing to track events in real time. […] We are too busy involuntarily using time to guide anticipatory attending to forthcoming happenings, than to ‘pay attention’ to time, qua time, as discrete intervals. In tacit acknowledgment of this, societies over millennia developed clocks and wristwatches to precisely correct for this common human deficiency involving time perception.”

Mari R. Jones, 2019, p. 12

“We saw that the brain can use the dynamics of neural networks to establish correlations between internal network states and changes happening in the external world. So the task of tapping your finger every second ultimately comes down to matching changes within your brain to those of a man-made clock. In the end this is essentially all we mean when we say that the brain is telling time.”

Dean Buonomano, 2017, p. 139

1. General introduction

As you will read in the present work, time-based prospective memory is extremely important in daily life and can be influenced by a myriad of both individual and contextual factors. Research in prospective memory is flourishing, and during the last 30 years the field has advanced consistently in the understanding of how participant use time to fulfil delayed intentions at the right future moment; yet the cognitive mechanisms supporting time monitoring and time-based prospective memory are still a matter of debate. Indeed, studying the cognitive processes underlying time-based prospective memory can be particularly challenging because of the remarkably intricated interactions between internal time processes and attentional mechanisms that occur when we check the clock time and attend delayed intentions at specific future time-points. In this regard, one aspect that came as a surprise at the beginning of my PhD was the lack of communication between theoretical models and empirical evidence across the fields of time perception and time-based prospective memory and, consequently, the scarcity of the knowledge on the role of internal time processes in clock-checking behavior. In fact, one of the caveats of the time-based prospective memory research is that it generally assumes a connection between time perception and time monitoring behavior, but this assumption was not tested empirically in most part of the studies. As you will read in the present work, however, it is possible to experimentally and meta-analytically disentangle the role of time perception in time-based prospective memory.

Attending delayed intentions at the right future moment is tightly connected to an individual's ability to adapt to the environment and has been shown to be a predictor of functional autonomy and well-being in older adults and in several clinical populations affected by different neurological and psychopathological disorders. Thus, understanding how time perception affects time-based prospective memory is of uttermost importance for the scientific and clinical communities interested in promoting quality of life, especially in late adulthood. In addition, gaining better insight into the effect of internal time processes on time-based prospective memory might shed light onto vulnerabilities in time perception and help preventing, or reducing, the damaging long-term effects of such impairments in daily life. The overarching goal of the present work was to contribute to filling this research gap. Firstly, by providing an updated account of the literature on how aging influences the time-based prospective memory performance and time monitoring, as well as its effects on cognition, by means of a meta-analysis. Secondly, by providing new insights and data to the field by means of two experimental studies tackling the internal time processes and motivational mechanisms. Thirdly, by providing an updated theoretical model to account for the effects of time perception on different time monitoring strategies. Although this thesis does not have the presumption to elucidate all the theoretical and empirical implications of time perception in time-based prospective memory, it provided a first comprehensive work that hopefully will help the field to better understand the cognitive processes behind strategic time monitoring and time-based prospective memory, as well as to elucidate the state of the art concerning age effects and related cognitive processes, providing a novel conceptual and methodological framework for future research.

2. State of the art

2.1. Remembering future intentions

In daily lives, people have often very busy agendas filled with tasks that need to be executed at an appropriate future moment, such as remembering to meet a friend at a certain time, to pick up our son on the way back home, or to buy the coffee before going to the office. All these daily tasks involve the same cognitive ability, which is referred to as Prospective Memory (PM). PM is defined as the ability to fulfill delayed intentions at the appropriate future moment while doing a background activity (Einstein & McDaniel, 1990). Often, PM is also referred to as the ability of "remembering to remember" (e.g., Rendell & Thomson, 1993); in this sense, it is distinct from retrospective memory because PM involves remembering to perform actions in the future, while retrospective memory is about remembering past events (Roediger, 1996). Both prospective and retrospective memory are related among each other (A. L. Cohen et al., 2001), but they still depend upon dissociable brain areas and cognitive processes (for a meta-analysis see Cona et al., 2015; Moscovitch et al., 2005; West & Krompinger, 2005). PM requires several phases, namely: (1) *encoding* (or *planning*), in which people establish the intention to be executed; (2) *retention* (or *maintenance*), in which the intention is held in memory while other activities are performed (called ongoing tasks); (3) *retrieval*, in which, at the appropriate moment, the intended action is retrieved from memory; (4) *execution* of the action accordingly to the plan (Ellis, 1996; Kliegel et al., 2000, 2011).

PM does not only impose memory demands but also requires attentional resources (Cona, Scarpazza, et al., 2015; Ihle et al., 2019; Laera et al., 2021; Roediger, 1996), which is one reason why failures in PM are often reported to be the main cause for memory failures in daily life (Crovitz & Daniel, 1984; Haas et al., 2020); this highlights also how PM tasks are ubiquitous in our daily life, as many activities require to fulfill future intentions such as preparing meals or paying bills on time (Rendell & Thomson, 1999); furthermore, PM is highly involved in complex working environments, such as air traffic control, health care, and piloting (Boag et al., 2019; Wilson et al., 2020), whereby forgetting PM tasks can have serious and dangerous consequences (Dismukes, 2012; Loft et al., 2021). For these reasons, it is important to understand the psychological processes underlying PM, and how individual differences, as well as task's characteristics, affect those processes, in order to promote PM interventions in healthy aging (Hering et al., 2014; Woods et al., 2015) as well as in clinical populations (Au et al., 2017; Dermody et al., 2016; Kamminga et al., 2014) with the aim to improve autonomy and quality of life (Hering et al., 2014; Woods et al., 2015).

PM is currently studied in several fields of psychology, such as clinical, lifespan, and applied psychology, as well as neuroscience and neuropsychology (Boag et al., 2019; Kant et al., 2014; Loft et al., 2021; Mioni et al., 2017; Okuda et al., 2007; Suchy et al., 2020; Zuber & Kliegel, 2020). Yet, despite the impact of PM in everyday life, it is only in the last 30 years that the scientific interest toward PM has grown more consistently (see **Figure 1A**). The term "prospective memory" was mentioned for the first time in an unpublished work by Wilkins (1976). Since then, few other authors start investigate "prospective remembering" (R. G. Cook et al., 1985; Harris & Wilkins, 1982; Meacham & Singer, 1977), but it is only from the 1990s – with the seminal works by Einstein and McDaniel – that remembering future intentions was investigated systematically, and referred to as "prospective memory", in a consistent way across studies (Einstein et al., 1995; Einstein & McDaniel, 1990; McDaniel & Einstein, 2000). From 2000 to 2023, there were new 2652 studies in the topic of "Prospective Memory" within the Web of Science database.

2.1.1. Time- and Event-based Prospective Memory

Traditionally, two types of PM task have been distinguished in the literature: (1) time-based prospective memory (TBPM), which refers to remembering to perform an intended action at a specific future time, and (2) event-based prospective memory (EBPM), which refers to remembering an intended action when a particular event or cue occurs in the environment (Einstein et al., 1995; McDaniel & Einstein, 2000). An example of TBPM is remembering to meet a friend at the park at ten o'clock, whereas an example of EBPM is remembering to buy the milk as one approaches the supermarket on the way home. EBPM and TBPM are commonly assessed in laboratory tasks (Einstein et al., 1995; D. C. Park et al., 1997), which require people to engage in a background activity (e.g., a lexical decision task), referred to as ongoing task (OT)[1], while remembering to perform an intention. In EBPM tasks, people are asked to remember to perform a specific action in response to a particular external cue (e.g., pressing ENTER each time the word "book" is displayed within the lexical decision task), while in TBPM tasks, people are asked to remember to perform a specific action at a given future time (e.g., pressing ENTER each two minutes); in TBPM tasks, people are usually free to check a clock on the computer screen by pressing another key (e.g.: the SPACEBAR) in order to track the elapsing time (Einstein & McDaniel, 1990; D. C. Park et al., 1997).

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[1] The OT is critical in the PM paradigm, because it provides useful information concerning the allocation of attentional resources between the OT and PM task (Scullin et al., 2010; Smith, 2003); moreover, the inclusion of the OT makes the PM task a more ecologically valid representation of real-life situations, where people have to remember to do something while also being engaged in other activities (Kvavilashvili & Fisher, 2007; McBride et al., 2011).

At a first glance, the main differences between the two PM tasks lies in the nature of the PM cue; specifically, the PM cue in EBPM tasks is a cue in the environment, while the PM cue in TBPM is a specific duration or future time-point. Although this distinction might appear as true, it might not be as scientifically rigorous as it aims to be. On the one hand, some TBPM tasks (e.g., meet a friend at 10:00 p.m.) could sometimes become – or been executed as – an EBPM task (e.g., meet a friend after dinner). On the other hand, concepts of events such as “after dinner” or “at sunset” require simultaneity and temporal order judgments (Duncan, 1980; Zivi et al., 2022), which are timing abilities essential for the cognitive elaboration of any external time measurement system, from the most rudimental (i.e., based on natural or social events) to the most complex, such as modern clocks (van de Grind, 2006). Therefore, the concepts of *time* and *event* seem to be inevitably related, because physical time (e.g., a given duration measured with the clock) is defined upon physical events (e.g., the digits on the clock). In other words, physical time is the measure of change – and measured by change – of events (for an overview see Coope, 2005; for implications in time perception, see Gibson, 1975; Jones, 1976; Jones & Boltz, 1989)[2]. This definition implies that both TBPM and EBPM are

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[2] The relationship between time and event, as well as the relative implications for time perception, have been debated throughout the entire history of philosophy, physics, and scientific psychology (Coope, 2005; Gibson, 1975; James, 1890; Jones & Boltz, 1989). For instance, earlier authors initially argued that people do not perceive time but only events, since we do not have a sense organ delegated to the elaboration of the temporal dimension of reality; for this reason, the perception of time is inevitably linked to the perception of events, which happens in space and, as such, can be perceived directly with the senses (Gibson, 1975). In fact, our experience is always filled with non-temporal external stimuli (e.g.: clock ticks, sunlight cycle) or, at the very least, with the rhythm of the individual's body (e.g.: hearth beat), through which the cognitive system is able to track the elapsing time more or less explicitly (Fraser & Lawrence, 1975; James, 1890). More recently, other authors have departed from this initial position demonstrating the possible existence of distinctive internal rhythmic structures, usually referred as pace-makers, internal clocks, or oscillators, that extract and compute pure temporal information from environmental events to guide behavior (Bolger et al., 2014; Jones & Boltz, 1989; Matell & Meck, 2004; Meck et al., 2012; Simen et al., 2013; Teki et al., 2017; Treisman et al., 1990; Walsh, 2003, 2015; Zakay, 1992; Zakay & Block, 2004). Overall, the concept of subjective time is still an unsolved issue for contemporary psychology (Mondok & Wiener, 2023; Thönes & Stocker, 2019); however, it is clear that animals and humans developed the capacity to use the temporal relationships between events that fill the

performed in response to an environmental cue (either a specific time on the clock, or a cue within the OT stimuli). Therefore, any PM task can be formalized as a goal-directed behavior based on association between a given cue "C" in the environment and the intended action "A". Such relationship can be described as a sensorimotor program: "*if C, then A*" (van de Grind, 2006). This program is common between TBPM and EBPM and it seems to be related mainly to metabolic and hemodynamic changes in fronto-polar cortex – the Brodmann Area 10 (Debarnot et al., 2015; Gilbert et al., 2006; Gonneaud et al., 2014; Okuda et al., 2007). In fact, although the anatomy and function of the fronto-polar cortex is still a matter of debate (Costa et al., 2013; Hogeveen et al., 2022), the activity of the fronto-polar cortex has been consistently related to the implementation of delayed intentions and not to other cognitive processes (e.g., working memory) implicated in the execution of PM tasks (Reynolds et al., 2009), regardless of the material adopted (e.g., shapes, words, figures) and the attentional demands of the task (Burgess et al., 2001, 2011; Okuda et al., 2007).

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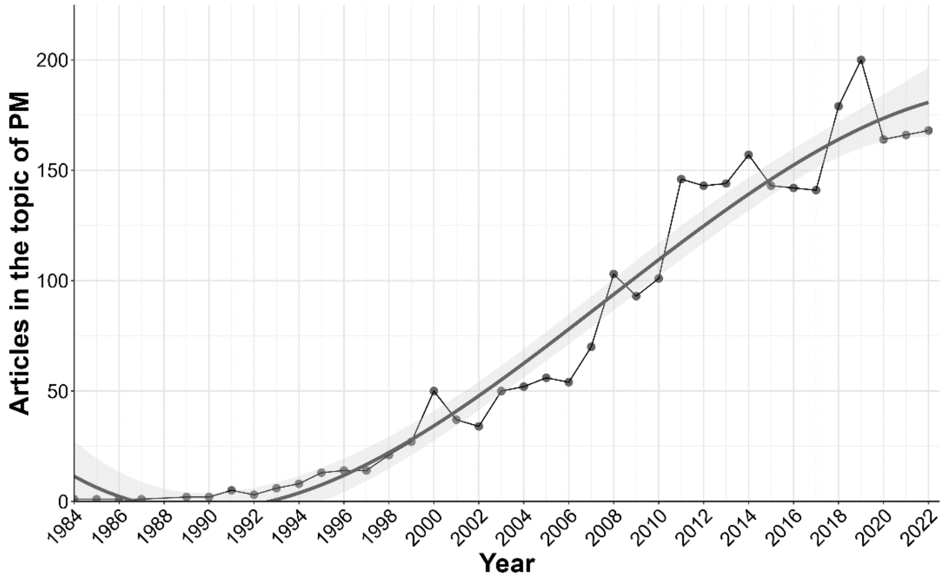
world in order to attend or anticipate such events, especially if these have an adaptive value (Coull et al., 2011; Matell & Meck, 2004; Meck et al., 2012; Nobre et al., 2007; Teki et al., 2017).

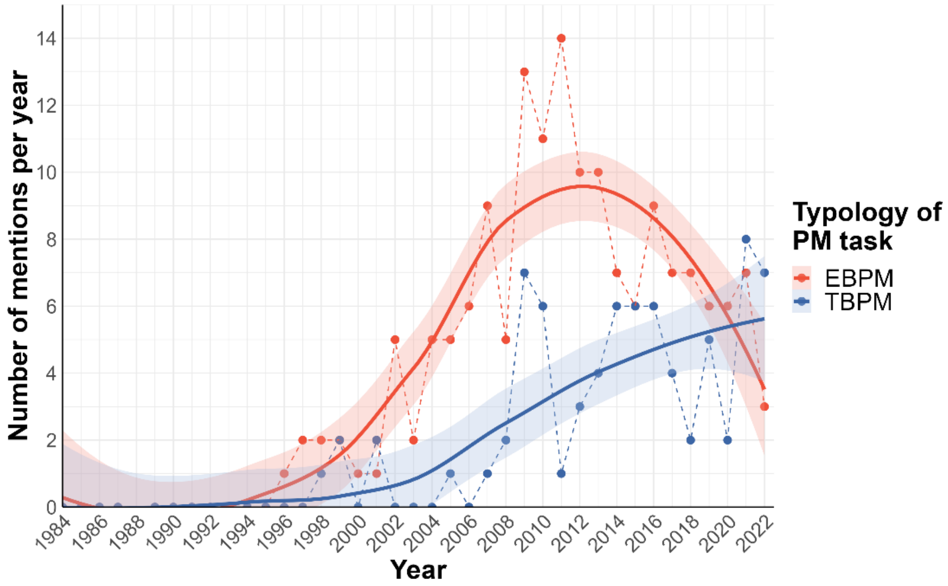
Figure 1

Mentions over time in scientific articles within the Web of science database

A) “Prospective memory”



B) “Event-based“ and “time-based prospective memory”



Note. Scatterplot showing the number of PM studies in the Web of Science database that were included in the topic of “Prospective Memory” in the last 48 years (1984-2022); shaded areas represent the standard errors. (A) Scatterplot showing the number of studies over time included in the topic of "prospective memory" (query: ("prospective memory"[Topic])). (B) Scatterplot showing the number of studies over time that included in the topic of only event- or time-based prospective memory, using the two queries: one for event-based prospective memory: (("event-based prospective memory"[Topic]) NOT ("time-based prospective memory"[Topic])) NOT ("time-based"[Topic]) NOT ("time- "[Topic]); and one for time-based prospective memory: (("time-based prospective memory"[Topic]) NOT ("event-based prospective memory"[Topic])) NOT ("event-based"[Topic]) NOT ("event- "[Topic]). The dashed line is the rate of mentions for event- (in blue) and time-based prospective memory (in red).

2.2. Monitoring future intentions

The main difference between EBPM and TBPM does not lie in the nature of the PM cue triggering the intended action (which is always a cue in the environment), but rather in the way the PM cue is monitored. *Monitoring* refers to a series of cognitive and executive processes by which an individual evaluates the progress of an initiated plan, anticipates obstacles, and temporally integrates action sequences with environmental cues (Fuster, 1993; Luria, 1966; Norman & Shallice, 1986). In EBPM tasks, the PM cue is monitored in response to some features in the environment which are presented along the OT that people perform while remembering the delayed intention. Indeed, monitoring in EBPM is often measured indirectly using OT accuracy or reaction times, comparing a baseline block in which participants perform only the OT, with a PM block in which they perform the OT in the presence of a PM task; this measure is usually referred as *PM cost* (Anderson et al., 2019; Peper & Ball, 2022; Smith, 2003). There is converging evidence that it is driven by task-switching attentional processes based on proactive cognitive control (Braver, 2012); yet, it is still unknown how individuals set their decision to monitor (Anderson et al., 2019), and the cognitive mechanisms behind PM cost are still not entirely understood (Einstein et al., 2005; Heathcote et al., 2015;

Smith, 2003). In TBPM tasks, the PM cue, or the *PM target time* (i.e., the duration at which a given PM task need to performed) is monitored via clock-checking, which requires more self-initiated monitoring processes (Conte & McBride, 2018). For this reason, TBPM tasks is considered to be more difficult than EBPM tasks (Craik, 1986; Einstein et al., 1995) and should rely more on executive functions and cognitive control processes and/or internal time processes (Cruz et al., 2017; Labelle et al., 2009; Zuber & Kliegel, 2020).

Controlling the clock (i.e., time monitoring behavior) is extremely important for TBPM accuracy as it guarantees people to perform TBPM tasks on time (Waldum & Sahakyan, 2013). It has been replicated consistently in the literature that PM accuracy increases when people used the clock strategically, meaning that they checked the clock few times as the task starts, and then increase the number of clock checks as the PM target time approaches, forming a “J-shaped” curve (Labelle et al., 2009; Mäntylä et al., 2006; Mioni et al., 2017; Mioni, Grondin, et al., 2020; Vanneste et al., 2016). However, despite this well-known replicated finding, the cognitive processes underlying time monitoring and TBPM are still not fully understood (Graf & Grondin, 2006; Munaretto et al., 2022). This might be due to the fact that the research interest in TBPM has been lower compared to EBPM in the past years (**Figure 1B**); for this reason, EBPM is supported by a more substantial amount of empirical evidence compared to TBPM, and several theoretical models have been proposed to explain the neurocognitive processes involved in EBPM tasks (Einstein et al., 2005; Guynn, 2003; Heathcote et al., 2015; Smith & Bayen, 2004). The same cannot be said for TBPM: the scarcer amount of empirical evidence did not allow the development of valid theoretical models explaining cognition behind TBPM (Block & Zakay, 2006; Harris & Wilkins, 1982). Overall, the present thesis aimed to fill this gap with a series of empirical evidence and theoretical arguments on the cognitive processes underlying strategic time monitoring in TBPM.

2.2.1. Theoretical models of time monitoring

The first model that described internal time processes in time monitoring and TBPM was the *Test-Wait-Test-Exit* model (TWTE). According to this model (Harris & Wilkins, 1982; Mioni & Stablum, 2014), as the TBPM task starts, participants first estimate a duration as close as possible to the PM target time; such temporal representation is periodically updated by checking the external clock in a series of test-wait cycles. As soon as the PM target time approaches (i.e., the “critical” period), people switch the reliance from the internal time to the external clock by significantly increasing time monitoring (i.e., the frequency of test-wait cycles) until the ongoing time matches with the PM target time. A conceptually important assumption of the TWTE model is that time estimation abilities are essential to strategically monitor for the occurrence of the PM target time (Block & Zakay, 1996; Harris & Wilkins, 1982)[3]. However, the TWTE model does not explain the mechanisms through people compute internal representations of time and use them to strategically monitor for the PM target time. Therefore, other authors have tried to theoretically address the precise timing

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[3] Time estimation refers to the ability to estimate how long a given interval lasts; it is based on time perception, which refers to the ability to perceive, judge, and represent time intervals (Liu et al., 2021; Thönes & Stocker, 2019). It is assessed using several methods (van Wassenhove et al., 2019); the most common are time production and reproduction (for an overview, see Mioni, 2018). Time production refers to tasks which requires to produce or generate specific durations, while time reproduction refers to the ability to reproduce specific durations presented by the experimenter. Both time estimation tasks can be administered alone as well as along with a secondary non-temporal task; in this case, they are referred as dual-task time estimation paradigms (van Wassenhove et al., 2019; Zakay & Block, 2004). Interestingly, Block and colleagues (2018) argued that TBPM tasks are similar to the dual-task time production paradigm: in both paradigms, participant have to prospectively attend a given duration while engaged in a secondary – non-temporal – task (i.e., the OT in TBPM); however, in the time production task, this is achieved without the aid of an external clock, which is present in TBPM tasks instead (Block et al., 2018, p. 45).

mechanism involved in TBPM by adapting a former theoretical model of time estimation – namely the *Attentional-Gate model* (AGM) – to the TBPM paradigm (Block & Zakay, 2006).

According to the traditional AGM (Block, 1990; Zakay, 1992; Zakay & Block, 1997), any prospective time-based response is driven by a pacemaker that constantly produces rhythmic pulses; as the task starts, the attentional gate allows these pulses to be stored in memory, so that the number of the stored pulses determines the perceived temporal duration of the elapsing time (many pulses stored in memory lead to an overestimation of a given interval, whereas few pulses stored in memory lead to an underestimation). In the TBPM context (Block & Zakay, 2006), the modified AGM (referred to as IR-AGM in the text) integrates an *intention-retrieval* component, so that any PM response is the result of the match between the ongoing count of signals (i.e.: clock checks) and the representation of the number of pulses in memory, which is constantly updated at each clock check (Block, 1990; Zakay, 1992; Zakay & Block, 1997). As soon as the PM target time approaches, people are thought to increase the frequency of clock checks to have a most precise representation of the elapsing time (i.e.: number of pulses in memory) in the specific time-windows within which people perform the TBPM response. Both the TWTE and the AGM state that the dynamic reliance between external and internal clock allows to use internal time representation to keep track of the elapsing time in the first minutes of the TBPM task, minimizing the cost of time monitoring (Block & Zakay, 2006).

Recently, Munaretto and colleagues (2022) proposed a further integrative framework on monitoring in TBPM. Following Atkin & Cohen (1996), the authors distinguished two types of external monitoring patterns: periodic monitoring (at fixed time intervals) and interval reduction (decreasing the time interval between successive monitoring events, with the time window between pairs of contiguous clock checks becoming smaller and smaller). According to Atkin & Cohen, when the occurrence of the deadline can be predicted via external monitoring (e.g., via a time distance measure as in TBPM tasks with the availability of an external clock), the monitoring strategy is interval reduction opposed to periodic monitoring (Atkin & Cohen, 1996). Munaretto and colleagues found empirical support for interval reduction in their TBPM study, with a tighter compliance to this pattern in the “critical” time window closer to the deadline. This increase in frequency near to the deadline is usually captured by an exponential growth function of clock checks (i.e., the “J-shaped” pattern in TBPM; see also Einstein et al., 1995; Harris & Wilkins, 1982; Mäntylä & Carelli, 2006). However, the authors also pointed out that, in specific circumstances (e.g., when monitoring is not informative about the proximity of the deadline), the pattern of monitoring may follow a more uniform trend (Huang et al., 2014; Mioni & Stablum, 2014). In other words, the interval reduction approach allows people to progressively reduce the distance between pairs of monitoring events and it is very effective in predictable contexts when coupled with an increase of monitoring frequency closer to the PM target time, whereas a periodic monitoring approach allows participants to distribute clock checks uniformly over time but it should not be used when the distance to the deadline is reliably predictable (see Munaretto et al., 2022). Although this framework represented the first attempt to offer an integrative account of time monitoring in TBPM, it is not a cognitive model; to date, only the TWTE and the IR-AMG are the sole cognitive models in the field.

Although both the TWTE and the IR-AGM assume the engagement of internal time processes in time monitoring, only in the IR-AGM these are formally theorized (i.e., the AGM and IR-AGM are *processing* models), while the TWTE assume them without any formal theorization (i.e., the TWTE is a *descriptive* model); therefore, the IR-AGM overcomes the limitations of the TWTE model by describing the cognitive processes underlying time monitoring in TBPM. Nonetheless, the empirical support for the IR-AGM is virtually inexistent, with most prospective remembering researchers that seem to be not aware of the IR-AGM (e.g., none of the papers in the field of TBPM cites the IR-AGM or tries to test it empirically)[4]. Moreover, internal time processes are extremely complex and influenced by various factors, both internal (e.g., attention, arousal, memory, and emotional state) and external (e.g., task importance and complexity), and involve the coordination of multiple brain regions and neural networks that are still a matter of debate (Block & Gruber, 2014; Jones, 2019; Matell & Meck, 2004; Mondok & Wiener, 2023; Walsh, 2015); this makes particularly difficult to isolate and study specific time-related processes in TBPM. Therefore, the TWTE model is still considered as the a state-of-the-art model in many TBPM researches (Huang et al., 2014; Mioni & Stablum, 2014; Vanneste et al., 2016; Varley et al., 2021) despite the lack of an exhaustive explanation of the cognitive processing underlying strategic time monitoring. However, it is important to further improve the TWTE model to answer to questions that are currently still open: What happens while a person is waiting? How does the person decide that another test is needed? What is being tested? What are the cognitive processes guiding strategic time monitoring? How are they modulated over the time course of the TBPM task? Overall, the present thesis aimed to contribute in this regard too, with a series of empirical

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[4] The AGM has been challenged even in the time perception literature because several studies did not supported it behaviourally (e.g., Bangert et al., 2019), and did not successfully dissociate the neural basis of some model's components, such as the attentional gate or the pace-maker (Coull et al., 2011; Merchant et al., 2013); indeed, other neurocognitive models of time perception have been proposed more recently, which included updated conceptions of the internal clock (Gu et al., 2015; Matell & Meck, 2004), time-based decision-making mechanisms (Meck et al., 2012; Rhodes, 2018), and memory processes for duration (Jones, 2019; Jones & Boltz, 1989) as well other theoretical assumptions related to a higher-level counting system (Walsh, 2003, 2015), and enteroception (Mondok & Wiener, 2023; Naghibi et al., 2023).

evidence and new theoretical arguments by integrating the TWTE model with cognitive processes underlying strategic time monitoring (see chapter 7).

2.2.2. Empirical framework

The relationship between time perception and strategic time monitoring in TBPM has been tested empirically in several studies aiming to test whether internal time processes drive strategic time monitoring, which is a core theoretical assumption of the TWTE model. In general, most part of the studies reported correlational evidence, showing that time estimation abilities were related to time monitoring, especially over the last interval before the PM target time (Mioni et al., 2012; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016). However, correlational findings on TBPM performance per se indicated a less consistent pattern, as some of them showed that better temporal abilities (i.e., time production and reproduction) were positively correlated to higher TBPM accuracy (Mioni et al., 2017; Vanneste et al., 2016), but others did not report such effects (Lecouvey et al., 2017; Mackinlay et al., 2009; Mioni et al., 2012; Mioni, Grondin, et al., 2020).

Beside correlational evidence, few studies investigated experimentally the involvement of internal time processing in TBPM. For instance, Huang and colleagues (2014) carried out a study examining how individuals control time in TBPM. In the control condition, participants performed a lexical decision task only, whereas in the TBPM conditions, people were additionally required to make a TBPM response after 11 minutes. The authors manipulated if participants received a reminder, and if clock checking was discouraged (people were asked to check the clock the least possible). The results showed that reminders prompted participants to check the clock, and improved TBPM accuracy; moreover, participants decreased the frequency of clock checks when they were discouraged from clock-checking, but this decrement did not impair TBPM performance. The authors concluded that time monitoring in TBPM tasks can be either external and/or internal, driven respectively by the presence of external reminder, and by the possibility/accessibility to clock checks; the external control reflects the cost for maintaining the intention in mind, whereas the internal control allows to track internally the current passage of time (Huang et al., 2014). Another study by Gan and Guo (2019) investigated experimentally whether both the TBPM accuracy and time estimation ability significantly improved after training. In two experiments, people were trained to the 1-minute TBPM task and successively tested on a 1-minute time estimation task, and vice-versa; the control condition was a training on the OT only (n-back task). The authors found that both time estimation and TBPM abilities improved after the trainings compared to the control group, indicating that TBPM was related to individuals' time estimation abilities (Gan & Guo, 2019). Therefore, the temporal processes involved in both time estimation and TBPM could be shared, at least partially.

2.2.3. Bridging monitoring in event- and time-based prospective memory

Besides the theoretical and empirical evidence that support the involvement of time estimation abilities in strategic time monitoring and TBPM performance (Gan & Guo, 2019; Huang et al., 2014; Labelle et al., 2009), it is important to consider other theoretical models from the EBPM literature that may also apply to TBPM. As mentioned above, the principal difference between EBPM and TBPM lies in the way the PM cue is monitored: while the PM cue (i.e., the *PM target time*) is monitored via clock-checking in TBPM tasks, in EBPM tasks, the PM cue is monitored in response to some features in the environment which are presented along the OT. However, it has been also highlighted that the theoretical models of monitoring in TBPM are not as advanced as in EBPM, for which several theoretical models have been proposed (Einstein et al., 2005; Guynn, 2003; Heathcote et al., 2015; Smith & Bayen, 2004). Interestingly, some authors recently argued that such models can be helpful to explain time monitoring in TBPM too (Bugg & Ball, 2017; Peper & Ball, 2022; Shelton & Scullin, 2017).

The most popular model in the field of EBPM is the *multi-process model*, which assumes two distinct processes, namely spontaneous retrieval and strategic monitoring (Einstein et al., 2005; McDaniel & Einstein, 2000). Spontaneous retrieval refers to bottom-up memory recognition processes or orienting responses that can occur without executive resources allocated to the PM intention (Einstein et al., 2005); strategic monitoring refers to top-down resource-demanding attentional processes that allow people to monitor the environment for the PM cue's occurrence (Einstein et al., 2005; McDaniel & Einstein, 2000; Smith & Bayen, 2004). According to the multi-process model, people rely to different degrees on strategic monitoring or spontaneous retrieval depending on PM cue features, OT demands, and individual differences (Einstein et al., 2005; Einstein & McDaniel, 2005; McDaniel & Einstein, 2000). The *dynamic multi-process model* (Shelton & Scullin, 2017) takes the multi-process model to a further step, assuming that spontaneous and strategic processes can dynamically switch during task performance. For example, suppose someone needs to buy the coffee for the office before going to work. As the person is on the tram, s/he comes across someone else that is drinking coffee or something similar, which spontaneously reminds him/her of the intention to buy it before going to work. The presence of this and other environmental cues enhance the probability that, as the person gets closer to the coffee shop, s/he engages in strategic monitoring, paying attention to the intention to buy the coffee, until it is eventually fulfilled (and the person is no longer out of coffee at the office). In summary, while the multi-process model assumes that people can exert spontaneous retrieval processes *or* strategic monitoring, the dynamic multi-process model assumes that, based on the contextual information available in the environment, people can exert spontaneous retrieval *and* strategic monitoring dynamically over time, because it is assumed that environmental cues can elicit spontaneous retrieval of a previously encoded intention, but then people can engage strategic monitoring if the intention can be performed soon (Scullin et al., 2013; Shelton & Scullin, 2017).

A recent meta-analysis highlighted that the dynamic multi-process model, originally conceived for EBPM, can be helpful to understand monitoring processes in TBPM too. Specifically, the authors showed that the presence of context information about the next PM cue occurrence (e.g., by telling participants that the PM cues occurred at specific OT trial numbers) improved PM performance in EBPM tasks; the authors showed that, for context to be beneficial to PM performance, context identification demands must be minimized by making context predictable (Peper & Ball, 2022). Given that clock time is a predictable stream of environmental information, the authors highlighted that strategic time monitoring in TBPM may be like strategic "event" monitoring in EBPM, where participants use contextual information (e.g., trial counters) to improve PM accuracy. However, as mentioned above, there is one important difference between the TBPM and EBPM laboratory paradigms, so that contextual information in the EBPM are externally cued, whereas in a TBPM, the temporal information (driven via clock-checking) is maintained internally (Block & Zakay, 2006; Labelle et al., 2009; Vanneste et al., 2016); for this reason, at its current formulation, the dynamic multi-process model do not explain how spontaneous retrieval and strategic monitoring potentially occur during time monitoring, because these cognitive processes are thought to be elicited rather externally from the environment (Scullin et al., 2013; Shelton & Scullin, 2017). Moreover, the dynamic multi-process model does not allow to disentangle whether all clock checks are supported by the same cognitive processes over time, or whether the checks made in the initial moments of the TBPM task are supported by different cognitive processes compared to those supporting the checks made right before the PM target time occurrence.

To overcome these limits, other models specific for TBPM only have been proposed (Block & Zakay, 2006; Harris & Wilkins, 1982), which assume that the main difference between TBPM and EBPM is that TBPM presumably involves internal time processing (see section 2.2.1). Yet, despite the conceptually important role of time processing in TBPM, it is not established yet whether internal time plays a crucial role in TBPM or not (Gan & Guo, 2019; Graf & Grondin, 2006; Labelle et al., 2009; Mioni & Stablum, 2014). One of the aims of the thesis was to experimentally test this assumption. As mentioned above, almost all the findings in the literature are correlational, and they involved measurements of different time estimations tasks as indirect measure of the contribution of time estimation in time monitoring and TBPM (Gan & Guo, 2019; Labelle et al., 2009; Lecouvey et al., 2017; Mackinlay et al., 2009; Mioni et al., 2012, 2017; Mioni, Grondin, et al., 2020; Vanneste et al., 2016; Waldum & McDaniel, 2016; Waldum & Sahakyan, 2013). Therefore, in Study 1, we proposed an experimental approach to examine the effect of internal time processes on time monitoring and TBPM performance using a novel manipulation of the external clock-speed, and to measure how it affects time monitoring and TBPM performance.

2.3. Individual differences

One way to possibly disentangle the cognitive processes supporting TBPM and time monitoring is to look at individual differences, and how these potentially modulate strategic monitoring behavior and, in turn, TBPM performance. Individuals are inherently different in various aspects, exhibiting differences not only in physical attributes, such as height, weight, and strength, but also in psychological characteristics, including skills, interests, attitudes, learning habits, cognitive and motor abilities (A. J. Fisher et al., 2018). Several sources of individual differences have been investigated in EBPM, such as age, motivation, psychopathology, and cognition (Ball et al., 2019; Bhat et al., 2018; Dermody et al., 2016; Guo, 2023; Kant et al., 2014; Platt et al., 2016). For instance, individual differences influence PM performance causing potential negative consequences for health, such as forgetting to take medication or accidentally taking an excessive dose (Ball et al., 2019), and this is particularly evident in clinically impaired groups, which show significant PM deficits linked to their cognitive dysfunction (Au et al., 2017; Dermody et al., 2016; Platt et al., 2016); examples include impaired executive functioning in individuals with psychopathologies, like obsessive-compulsive disorder or depression (Bhat et al., 2018; Zhou et al., 2017), or neurological impairments, such as specific memory deficits in patients with stroke or Alzheimer's disease (Dermody et al., 2016; Kant et al., 2014; for a critical review, see Liu et al., 2021). The heterogeneity in impaired memory and attention processes among these clinical populations led most of the times to dissociable profiles of PM deficits (e.g., see Carlesimo et al., 2011). Therefore, studying clinical populations of various nature helped researchers understand PM mechanisms and develop compensation strategies (Ball et al., 2019).

Another aspect investigated in PM literature (especially with event-based tasks) is the role of individual differences in cognition (Ball et al., 2015; Macan et al., 2010; Uttl et al., 2013); overall, these studies showed that individual differences in PM performance were explained – at least partially – by individual differences in executive control and retrospective memory (Ihle et al., 2019; Laera et al., 2021; Zuber et al., 2016), but also working memory (Ball et al., 2022; Cherry & LeCompte, 1999). In TBPM, some studies showed that lower variability at time estimation tasks were associated with a more strategic time monitoring behavior and, in turn, to better TBPM performance (Gan & Guo, 2019; Labelle et al., 2009). Overall, all these findings highlighted the importance to account for individual differences in specific cognitive abilities when examining EBPM and TBPM (Ball et al., 2019). Beside clinical and cognitive functioning, many other sources of individual differences potentially affect behavioral performances, like gender, age, intelligence, interests, prior knowledges, learning style, motivation, locus of control, self-efficacy, and epistemological beliefs (Simsek, 2012). In the context of TBPM, examining individual differences can provide additional and complementary conceptual arguments to refine the understanding of how attentional resources are allocated for time monitoring (Joly-Burra et al., 2022; Mäntylä et al., 2009). In the present work research, the focus was on two sources of individual differences: aging and motivation.

2.3.1. Age effects

Aging is probably the most studied source of individual differences in PM (for meta-analyses see Henry et al., 2004; Kliegel et al., 2008; Uttl, 2008, 2011). In older adults' everyday life, TBPM is very relevant as health-related intentions are often part of daily activities, such as taking medication regularly, or going to appointments with the doctor (Haas et al., 2020; Hering et al., 2018; Woods et al., 2015); nonetheless, while differences in TBPM performance between younger and older adults are well established (Einstein et al., 1995; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; D. C. Park et al., 1997; Vanneste et al., 2016), age differences in time monitoring are still not fully clear. For example, some studies suggested that younger adults check the clock more frequently than older adults (Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014;

Vanneste et al., 2016), while others find the opposite pattern (Mäntylä et al., 2009) or no differences at all (McFarland & Glisky, 2009). The empirical inconsistency is reflected in turn in the debate concerning which cognitive processes underlying age differences in TBPM. Some argue that age differences result from time estimation (Labelle et al., 2009; Mioni & Stablum, 2014; Vanneste et al., 2016), while others suggest attentional processes as the main source (Lecouvey et al., 2017; Varley et al., 2021; Zuber & Kliegel, 2020).

A recent study by Varley and colleagues (2021) disentangled the cognitive processes responsible for age effects in TBPM by investigating the impact of attentional and temporal processes on age-related differences in TBPM performance. They assigned participants to three conditions: (1) "visible", where a timer was constantly present during the TBPM task; (2) "monitored", where the timer appeared after a button press (as in the traditional TBPM paradigm); and (3) "hidden", where access to the timer was not possible at all. The study revealed that age-related impairments in TBPM were only present when participants had access to the timer, suggesting that age differences in TBPM accuracy were due to impairments in attentional processes rather than time estimation abilities (Varley et al., 2021)[5]. Nonetheless, this study used a very brief PM target time (1-minute). Some authors argued that 1-minute PM target times are more

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[5] Although it seems that, in the context of TBPM, age differences in performance are due to impairments in attentional processes rather than time estimation abilities, internal time processing is still affected by aging, as reported by studies in the literature of time perception (Droit-Volet et al., 2019; Lamotte & Droit-Volet, 2017; Mioni, Capizzi, et al., 2020; Turgeon et al., 2016). Specifically, temporal performance per se do not differ between young and older participants, suggesting that the representation of duration do not change with age (Droit-Volet et al., 2019). However, the variability of duration judgments is greater in older than young adults, and directly related to lower attentional capacity of older participants (Lamotte & Droit-Volet, 2017; Mioni, Capizzi, et al., 2020). The most accredited explanation of these findings is that age-related decline in attention and memory would increase the noise within the timing mechanisms in the brain – presumably supported by dopamine-glutamate interactions in cortico-striatal circuits (Matell & Meck, 2004) – thus increasing the age-related variability of the timing responses (Turgeon et al., 2016).

likely to involve sustained attentional processes than longer PM target times (Bastin & Meulemans, 2002), which instead are likely to involve time estimation processes, especially in the initial moments of the TBPM task (Block & Zakay, 2006; Harris & Wilkins, 1982; Mioni & Stablum, 2014). Therefore, short PM tasks as of 1-minute might be ideal to capture age-related impairments in TBPM that are associated to attentional control processes, since it is possible that participants held the intention in mind throughout the whole 1-minute interval via sustained attentional control[6]. However, using only such short delays do not allow to draw a complete picture of all possible cognitive processes engaged by older adults when remembering intentions. In this regard, a systematic examination of age differences in TBPM with longer PM target times might shed light on the possible age-related modulation of the cognitive processes involved in TBPM as a function of the duration of the PM target time (Bastin & Meulemans, 2002; Conte & McBride, 2018), as well as possible compensatory age-related processes (Cabeza et al., 2018; Reuter-Lorenz & Cappell, 2008).

Overall, the empirical evidence suggested that there are age-related differences in TBPM performance, as measured by laboratory tasks, but it is currently unknown how large the age effect is in time monitoring, as well as how cognitive processes are modulated as a function of age and specific task-related features, such as the duration of the PM target time. Hence, a second aim of the present thesis was to quantify meta-analytically age-related differences in TBPM and time monitoring assessed in the laboratory setting; furthermore, we investigated whether there was a relationship between age effects in TBPM performance and time monitoring, and explored how

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[6] Such sustained attentional processes involved in TBPM tasks with 1-minute PM target times are conceptually similar to the processes of strategic monitoring theorized in the multi-process model (see section 2.2.3).

specific task-related features affected age-related differences in TBPM performance and time monitoring.

2.3.2. Motivational aspects

Another source of individual differences in PM is *motivation*, defined as the driving process that initiates, guides, and maintains goal-oriented behaviors (Nevid, 2013). Motivation is a broad complex construct that includes biological, emotional, social, and cognitive forces that altogether activate human behavior (Wasserman & Wasserman, 2020). Intuitively, it is evident that there might be (at least) a theoretical association between motivation (i.e., the driving process governing goal-oriented behaviors) and PM, which is inherently a goal-directed behavior (Penningroth & Scott, 2007). In fact, several studies investigated the role of motivational mechanisms in PM, which were measured mainly through incentives (tokens or monetary reward) or through social relevance (for an overview, see Walter & Meier, 2014). For example, in a pioneering study by Meacham and Singer (1977), people were asked to mail post cards back to the researcher on pre-specified dates over a period of eight weeks. Participants in an incentive group, who received money for returning the cards on time, did so with higher probability and more of them indicated the use of external reminders (e.g., calendars) to support their PM than participants in a no-incentive group. Relatedly, Horn and Freund (2021b, 2021a) compared the effect of monetary gain incentives (for accurate responses on PM target events) and loss incentives (deductions from a monetary endowment for missed PM responses) in EBPM across adulthood. Results indicated that both gain- and loss-incentives (compared to a control condition without performance-contingent incentives), improved PM accuracy, even though age-related individual differences (Freund & Ebner, 2005) appear to play an important role. These and other studies suggested that monetary consequences may increase the perceived importance of a PM task and induce the use of mnemonic strategies, improving PM performance (Horn & Freund, 2021b, 2021a; Kliegel et al., 2001, 2004; Meacham & Singer, 1977; Walter & Meier, 2014).

The studies on PM that manipulated motivation focused mainly on laboratory computer-based EBPM tasks (e.g., Brandimonte et al., 2010; Cook et al., 2015; Horn & Freund, 2021). Only two studies investigated the effect of motivational incentives in TBPM (Altgassen et al., 2010; Kliegel et al., 2001). Kliegel and colleagues (2001) showed that the perceived importance of an intended action increased the use of monitoring strategies as well as performance in TBPM tasks, but not in EBPM; the authors argued such improvement is related to increased strategic allocation of attentional resources towards the PM task (Kliegel et al., 2001). Altgassen and colleagues (2010) investigated how age effects in TBPM interacted with incentives, manipulated as social importance: half of the participants received the standard prospective memory task instruction (i.e., control group) whereas the other half received the social importance instruction, in which they were instructed that they were doing the experimenter a favor when they would remember to press the key after the 2 minutes. Results showed that younger adults generally outperformed older adults in TBPM accuracy; nonetheless, there was an interaction between age and social importance, showing that younger adults were not influenced by social importance; in contrast, older adults improved TBPM accuracy in the social importance condition compared to the control condition, and such improvement was supported by a more strategic time monitoring behavior (Altgassen et al., 2010).

In summary, although monetary incentives have been given in several studies using laboratory, computer-based PM tasks, the effect of losses avoidance has been barely explored experimentally in TBPM so far; furthermore, the impact of incentives on time monitoring has never been investigated, thus it is still unknown how motivational processes affect strategic monitoring and, in turn, TBPM performance (M. A. Brandimonte et al., 2010; Schnitzspahn, Ihle, et al., 2011)[7]. Yet, a better understanding of the role of motivation also in time monitoring is particularly relevant in TBPM tasks, as many daily scenarios come with secondary costs on clock-checking. For example, in certain contexts such as during a medical procedure, when driving on the motorway, or while operating machinery, time monitoring can have particularly detrimental consequences, as it imposes an additional cognitive task (i.e., checking the clock) which demands attentional resources; time monitoring may have social costs too (e.g., colleagues may perceive someone as impolite if they look at their wristwatch frequently during a meeting). Therefore, the relation between the benefits of successful TBPM and the cost of time monitoring in real life is complex, and it is influenced by our personal goals as well as the consequences of time monitoring behavior (Suchy, 2020; Wilson et

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[7] One possible way to further explore the effect of motivational processes on strategic time monitoring in TBPM could be to explore the role of motivation in time perception, since the latter is (presumably) involved in strategic time monitoring. However, the literature in this field is in its infancy (for a recent overview, see Gable et al., 2022). The few studies that investigated the role of motivation in time perception focused on opposite action tendencies: *approaching*, which encourage the individuals to move toward the desired goal, and *withdrawing*, which encourages the individuals to move away from an aversive stimulus (Gable & Dreisbach, 2021). Overall, the few empirical evidences highlighted that individuals perceive time passing quickly while experiencing approach-motivated states, which may provide significant advantages related to goal pursuit because, when the passage of time is experienced as passing faster, the readiness for action is more rapid, thus decreasing the likelihood of delaying – or hindering –the pursuit of the goal (Droit-Volet & Meck, 2007). In contrast, perceiving time passing slowly while experiencing withdrawal-motivated states may promote action avoidance by engaging attentional processes (i.e., when the passage of time is experienced as passing slower, the action readiness is lower). Interestingly, both motivational processes and time perception have been associated with dopaminergic activity, especially in the dorsal striatum (Martel & Apicella, 2021; Matell & Meck, 2004), and in the mesial prefrontal cortex (Cheng et al., 2016; Gu et al., 2015). Besides these findings, it is still unknown what is the complex relationship between motivation and time perception (Gable et al., 2022), and how it affects strategic time monitoring in TBPM.

al., 2020). Therefore, it seems crucial to carefully consider the trade-off between the costs associated with time monitoring and the advantages of effective intention execution. So far, however, very little is known about the relation between time monitoring, its consequences (in terms of cost), and TBPM, as well as whether and how individuals modulate their time monitoring strategy based on the presence of motivational incentives. Hence, the third aim of the present thesis was to address this gap by investigating for the first time how the monetary cost on time monitoring affected TBPM.

3. Research questions and hypotheses

The general aims of the thesis were (1) to better understand the cognitive processes behind strategic time monitoring and TBPM (Study 1); (2) to elucidate the state of the art concerning age effects and related cognitive processes in time monitoring and TBPM by means of a meta-analysis of the literature (Study 2); (3) to investigate the potential modulation of the cognitive processes involved in time monitoring and TBPM driven by motivational incentives (Study 3). The next sub-sections present three research questions in further detail and articulates the related research hypotheses. Two experimental studies (Study 1 and 3) were designed to answer both research question 1 and 3; a meta-analysis (Study 2) was carried out to answer research question 2.

3.1. Research question 1: How do participants monitor the target time in TBPM tasks? Do participants actively use internal timing processes?

Despite the conceptually important role of time processing in the core TBPM models (Block & Zakay, 2006; Harris & Wilkins, 1982), it is not fully established yet whether internal time plays a crucial role in TBPM or not (Gan & Guo, 2019; Graf & Grondin, 2006; Labelle et al., 2009; Mioni & Stablum, 2014); the present study set out to experimentally test this assumption. Specifically, the effect of internal time processes on time monitoring and TBPM performance as examined using a novel manipulation of the external clock-speed, and to measure how it affects time monitoring and TBPM performance. Participants performed two identical TBPM blocks: the first TBPM block with no clock-speed manipulation, followed by a second TBPM block, where the clock-speed was manipulated, and people were randomly assigned either to faster, slower, or control condition.

3.1.1. Research question 1: hypotheses

We predicted that the clock-speed would affect time monitoring and the response's deviation from the PM target time, as both rely directly on the internal elaboration of temporal information from the environment. In contrast, the rate of TBPM tasks' completion should not be affected because it does not directly involve the internal computation of temporal information; rather, it should reflect retrospective memory and attentional processes involved in PM retrieval, for both EBPM and TBPM tasks (Bastin & Meulemans, 2002; Lecouvey et al., 2017; Okuda et al., 2007). In other words, manipulating the clock-speed should not affect whether people remembered to perform the PM task, but rather on how they monitor time and, in turn, the temporal precision of the PM responses.

The hypotheses for the Study 1 are based on the distinction between temporal and numerical proximity (see section 4.2.1). If people rely on tracking the *temporal* proximity between ongoing and the PM target time, manipulating the clock-speed should lead to differences in performance which are mediated by the subjective passage of time and internal estimations of duration. Given that the TBPM blocks appeared to be to have the same duration regardless of the clock-speed manipulation, behavioral differences related to clock-speed can be interpreted as discrepancies between internal representations of time and external elapsed time, indicating that time monitoring was based on time estimation strategies (i.e., participants checked the clock to estimate the remaining duration to the PM target time). For example, individuals in the faster clock condition may check the clock less frequently, increasing the likelihood of "too late"

TBPM responses, while those in the slower clock condition may check the clock more frequently, increasing the likelihood of “too early” TBPM responses. On the contrary, if people rely solely on counting and matching *numerical* proximity between ongoing external time and the PM target time, clock-checking and, in turn, TBPM performance should not be affected by clock-speed manipulation, indicating that participants counted and matched the digits displayed on the clock with the representation of the PM target time at each clock check, rather than estimating remaining duration to the PM target time. These results can be explained assuming that, regardless of clock-speed, the attentional resources devoted to detecting the PM cue during TBPM would remain constant, allowing the same amount of temporal information to be computed and stored. Hence, external clock manipulation could support the idea that people "wait" for the PM target time based on numerical metrical events rather than estimating remaining duration to the PM target time at each clock check (see chapter 4 for a deeper theoretical discussion).

3.2. Research question 2: What are the age-related differences in time monitoring assessed in the laboratory setting? How do specific task-related factors affect age-related differences in TBPM?

Aging research is abundant in the PM field, suggesting that there are important age-related differences in TBPM performance. However, there is a lack of knowledge regarding the magnitude of the age-related impact on time monitoring. Additionally, the cognitive processes responsible for the age effects in time monitoring and TBPM performance may be affected by other task-related factors, which could potentially moderate the magnitude of the age-related effect associated with TBPM (see chapter 5 for a more detailed overview about these features). Therefore, the main aim of study 2 was to quantify age effects on TBPM performance and time monitoring meta-analytically, and to investigate how task-related features modulate such age effects. To do so, all studies involving laboratory based TBPM tasks in age groups of younger and older adults were reviewed and analyzed.

The specific research goals of the meta-analysis were:

a) To quantify age-related differences in TBPM and time monitoring assessed in the laboratory setting.
b) To determine if there's a relationship between age effects in TBPM performance and time monitoring.
c) To measure how specific task-related factors (i.e., the duration of the PM target time, the frequency of the PM task, and the interval criterion for correct PM responses) affect age-related differences in TBPM performance and time monitoring.

3.3. Research question 3: How do monetary costs affect time monitoring and TBPM, as well as their relationship? Do people change time monitoring strategy?

Several studies suggested that monetary consequences affect PM accuracy (Horn & Freund, 2021b, 2021a; Kliegel et al., 2001; Meacham & Singer, 1977). So far, however, the impact of incentives on time monitoring has not been investigated. As argued above, a better understanding of the cost of time monitoring is particularly relevant in TBPM tasks, as many scenarios come with secondary monitoring costs which can have serious consequences. To fill this gap, Study 3 investigated experimentally the effect of monetary costs on time monitoring and TBPM. Motivation was manipulated in three conditions: in the single-cost condition, missed PM responses were penalized with a monetary deduction from an initial endowment; in the double-cost condition, not only missed PM responses, but also time monitoring resulted in deductions from the endowment. Lastly, in a control group, participants received no information regarding an additional incentive prior to the experiment.

3.3.1. Research question 3: hypotheses

Based on research on motivated cognition (e.g., Horn & Freund, 2021a; Kruglanski et al., 2002; Penningroth & Scott, 2007; Shah et al., 2002), we considered three different scenarios for the different conditions. In the control condition, the TBPM task was only linked to a very general and abstract "higher-level" goal (i.e., get remuneration for participation in the study); by contrast, in the single-cost condition, TBPM accuracy was charged with an additional monetary cost, and might have been linked with a more concrete "mid-level" goal (i.e., "avoid monetary losses in this task") which, in turn, was linked to a more generic "higher-level" goal of getting money for participation. Finally, in the double-cost condition, both TBPM accuracy and time monitoring might have been linked with a more concrete "mid-level goal" (see chapter 6 for a more detailed theoretical framing on goal-hierarchy). Based on these ideas, we expected that participants in the double-cost condition used the clock less frequently, but more strategically, than participants in the single-cost or control condition, as only in the double-cost condition, time monitoring would be linked with a "mid-level" goal of avoiding cost. We also expected that strategicness in time monitoring correlates positively with TBPM accuracy, especially in the double-cost condition (Joly-Burra et al., 2022; Labelle et al., 2009; Mäntylä et al., 2009; Mioni, Grondin, et al., 2020; Vanneste et al., 2016). We further expected that TBPM accuracy is highest in the single-cost condition because there was a motivational incentive to avoid losses (following PM misses) while having the opportunity to engage in time monitoring "free of charge". In contrast, participants in the double-cost condition were expected to check the clock more parsimoniously to avoid further costs, which might decrease TBPM accuracy compared to the other conditions.

4. Study 1[8]:

Keeping the time: the impact of external clock-speed manipulation on time-based prospective memory

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[8] Article currently in preparation for submission in *Journal of Memory and Language*.

4.1. Abstract

Several studies have suggested that time monitoring is important for appropriate TBPM performance. However, it is still unknown whether people actively use internal timing processes to monitor the approaching target time, and whether they do so by tracking the duration between clock digits, or by counting and matching the numerical progression of clock ticks' digits with the target time. Therefore, in the present study, we investigated whether a manipulation of the external time affected time monitoring and TBPM performance. In two experiments, participants performed two identical TBPM tasks: a first TBPM block with no clock-speed manipulation followed by a second TBPM block, where the clock-speed was manipulated as faster or slower (experimental conditions) or normal (control condition). The results showed that only participants in the slower clock condition increased time monitoring in the second compared to the first TBPM block; however, both faster and slower clock condition did not differ from the control condition. No effect was found for TBPM performance. Overall, results suggested that people tracked the target time by counting and matching the numerical progression of clock ticks' digits with the target time. The findings are discussed considering the most recent theoretical advancements about the relationship between time perception and TBPM.

4.2. Introduction

There is converging evidence that time monitoring behavior is key for TBPM accuracy and several studies have revealed time monitoring being highly correlated to TBPM accuracy (Ceci & Bronfenbrenner, 1985; Gan & Guo, 2019; Harris & Wilkins, 1982; Huang et al., 2014; Mäntylä et al., 2006; Mioni & Stablum, 2014; Vanneste et al., 2016). Moreover, zooming in on the patterns of time monitoring, it has been revealed that beyond the overall frequency of time checks, time monitoring is truly efficient only when deployed strategically (Labelle et al., 2009; Mäntylä et al., 2006; Mioni et al., 2017; Mioni, Grondin, et al., 2020; Vanneste et al., 2016). This has led to the research question as to which cognitive processes drive time monitoring strategically in a TBPM task (Joly-Burra et al., 2022; Labelle et al., 2009; Lecouvey et al., 2017; Mackinlay et al., 2009; Mioni et al., 2012, 2017; Mioni, Grondin, et al., 2020; Vanneste et al., 2016; Waldum & McDaniel, 2016; Waldum & Sahakyan, 2013), and few theoretical hypotheses have been proposed too (see section 2.2 for an overview on theoretical models on intention monitoring).

It is still unclear if TBPM involves timing processes and how internal time processes eventually affect time monitoring and TBPM performance (Block & Zakay, 2006; Gan & Guo, 2019; Labelle et al., 2009). Interestingly, almost all the empirical findings in the literature measured the performance at different time estimations tasks (e.g., time production; i.e., the ability to produce given durations) as indirect measure of the contribution of time estimation in time monitoring and TBPM (Gan & Guo, 2019; Labelle et al., 2009; Lecouvey et al., 2017; Mackinlay et al., 2009; Mioni et al., 2012, 2017; Mioni, Grondin, et al., 2020; Ogden et al., 2011; Vanneste et al., 2016; Waldum &

McDaniel, 2016; Waldum & Sahakyan, 2013). On the one hand, this was motivated by the methodological similarities between a TBPM and time production tasks: a TBPM task without a clock is essentially a time production task under a dual task condition, in which people are asked to estimate a given duration while engaged in another non-temporal task (Block et al., 2018; Varley et al., 2021). On the other hand, in time estimation tasks like time production, judgements of durations (i.e.: subjective time estimations) are treated as dependent variable (Jones, 2006; Mioni, 2018; Mioni et al., 2014; Zakay et al., 1983; Zakay & Block, 2004) because these judgments are the measures of interest. Diversely, estimating time is not the main task in TBPM, but it might serve to accomplish on time PM tasks, which are fundamentally "non-temporal" (e.g.: pressing a button; sending a letter; going to an appointment; see also section 2.1.1).

4.2.1. Temporal and numerical proximity

Considering all this, two main hypotheses have been advanced in the literature. The first hypothesis argued that, if time estimation is involved time monitoring (Mioni et al., 2012; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016), it is necessarily mediated by the presence of the external clock (Fetzer & Cristian, 1997), which is used in a goal-directed way (Gan & Guo, 2019; Labelle et al., 2009; Zakay & Block, 2004); however, this hypothesis implies that individuals check the clock to estimate the remaining duration to the PM target time, which is therefore based necessarily on the constant duration between hierarchically-organized clock digits (e.g., the seconds embodied in minutes, embodied in hours, etc.). In other words, individuals attend and execute TBPM tasks based on the *temporal* proximity between the ongoing clock time and the PM target time, updated at each clock check. The second – alternative

– hypothesis has been initially proposed by Graf and Grondin in 2006, and then developed by the researchers in EBPM (see also section 2.2.3), which argued that monitoring processes might be shared between TBPM and EBPM (Bugg & Ball, 2017; Cona, Arcara, et al., 2015; Graf & Grondin, 2006; Peper & Ball, 2022). For example, a study by Bowden and colleagues (2017) showed that, when people are told that the EBPM cue will occur at specific OT trial number intervals, this contextual information led to higher PM accuracy compared to the "standard" condition, in which participants did not received any instruction about the PM cue occurrence. The results indicated that, only in the "context" condition, participants strategically directed the attentional focus away from the OT towards the trial number in order to detect the PM cue (Bowden et al., 2017; Bugg & Ball, 2017; Cona, Arcara, et al., 2015). This attentional mechanism could be supported by accumulation of evidence and by setting higher response thresholds for switching between the OT task and "event" monitoring (Heathcote et al., 2015; Strickland et al., 2017): the more the trial number goes forward, the greater is the probability that the incoming PM cue will occur soon, the higher is the likelihood that people check the clock – and perform accurate PM responses (Marsh et al., 2006; Smith, 2003)[9]. Since clock time is a predictable stream of environmental information , time monitoring in TBPM may be similar to strategic "event" monitoring in EBPM, where

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[9] According to this hypothesis, formalized as "delay theory of prospective memory" (Heathcote et al., 2015; Strickland et al., 2017), before individuals decide to initiate a PM task, they subconsciously accumulate evidence about the appropriateness of initiating the task at a constant rate over time. As time progresses, individuals continuously monitor the accumulated evidence, checking whether the evidence has reached the threshold required to initiate the PM task. When the accumulated evidence surpasses the threshold, a decision point is reached, and individuals initiate and execute the PM task. These processes are associated with the activity of distributed neural circuitry (Braver, 2012), encompassing the lateral pre-frontal cortex, involved in sustained attention (Badre, 2008; De Pisapia et al., 2007), the anterior cingulate cortex, involved in conflict detection (Cruz et al., 2017; De Pisapia & Braver, 2006), as well as parietal regions, involved in associative retrieval mechanisms (Speer et al., 2003).

participants use contextual information to improve PM accuracy (Bugg & Ball, 2017; Cona, Arcara, et al., 2015; Peper & Ball, 2022). This hypothesis implies that individuals check the clock to count and match the ongoing external time on the clock with PM target time, match that is based necessarily on the numerically ascending progression of hierarchically organized clock digits. In other words, individuals attend and execute TBPM tasks based on the *numerical* proximity between the ongoing clock time and the PM target time, updated at each clock check.

4.2.2. The present study

Within this conceptual framework, there is still a fundamental open question that is still not addressed: is the prediction of the PM target time's occurrence driven by the *numerical* or by the *temporal* proximity between the external clock time and the PM target time? In other words, is strategic time monitoring supported by the temporal interval between clock digits (i.e., the *temporal* proximity between ongoing and target time), or simply by the fact that clock includes a progressive numerical set of expected events (i.e., the *numerical* proximity between ongoing and target time)? A possible unexplored way to answer to such question is to directly manipulate the duration between clock ticks (i.e.: clock-speed) and to measure how it affects monitoring behavior and TBPM accuracy.

Clock-speed manipulation approach has been proposed in the literature to study the effect of external (and internal) time on other physiological and cognitive parameters; these studies showed that faster/slower clock-speed induced an accelerated/decelerated passage of time that corresponds to over-/underestimations of durations (Christandl et al., 2018; C. Park et al., 2016; Thönes et al., 2021; for a review, see Thönes et al., 2018). In order to induce a disruption of the internal time, researchers used an experimental procedure that starts with a task block with a regular clock (one second is 1000 ms), followed by another identical task block with an altered clock that is faster and/or slower (for instance, one second is 800 or 1200 ms, respectively; e.g., Thönes et al., 2021). If internal time processes are important for strategic monitoring in TBPM (Gan & Guo, 2019; Huang et al., 2014; Labelle et al., 2009; Mioni et al., 2012; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016), and external time manipulation can change the subjective passage of time and/or the internal estimations of duration (Christandl et al., 2018; Fetzer & Cristian, 1997; Thönes et al., 2018, 2021), then any behavioral differences in time monitoring (and, in turn, in the TBPM accuracy) related to the clock-speed manipulation might be interpreted as the mediated effect of the internal time – either as subjective time passage or internal estimation of duration (Thönes & Stocker, 2019) – originated from the manipulation of external elapsing time (Block & Zakay, 2006; Fetzer & Cristian, 1997; Harris & Wilkins, 1982; Jones, 2006; Thönes et al., 2018).

The present study was the first that introduced clock-speed manipulation in TBPM. In two experiments (one laboratory-based, and one administered online), participants performed two identical TBPM blocks: the first TBPM block with no clock-speed manipulation, followed by a second TBPM block, where the clock-speed was manipulated, and people were randomly assigned either to faster, slower, or control condition. Importantly, although the two blocks differed in their *real* duration, they still appeared to last the same amount of time (i.e., in both blocks, participants always performed a 4-minute PM task; hence, the blocks were virtually identical for them). The differences across clock-speed conditions during TBPM blocks allowed to measure the effect of the clock-speed on internal time representation behind TBPM performance, which should be found only in the second TBPM block and not in the first TBPM block. We measured three behavioral outcomes: (1) the *rate of TBPM tasks' completion*, which was calculated as standardized mean proportion of the number of PM tasks accomplished, regardless of the timing of the PM responses; it was used as indication of whether people remembered (or not) to perform the PM task (Bastin & Meulemans, 2002; Yang et al., 2013). (2) *Response deviation from the PM target time*, which was calculated as the difference (in seconds) between the time-point when people performed the TBPM task and the time-point required by the TBPM task (positive values indicated later PM responses; negative values indicated earlier PM responses); this measure was used as indicator of temporal accuracy (Guo & Huang, 2019; Varley et al., 2021). (3) *Time monitoring*, which was measured as mean clock check frequency per minute (Labelle et al., 2009; Mioni & Stablum, 2014; Vanneste et al., 2016).

4.3. Experiment 1

Experiment 1 was conducted in the laboratory. Participants performed two identical TBPM blocks: the first TBPM block with no clock-speed manipulation (1 second = 1000 ms) followed by a second TBPM block, where the clock-speed was manipulated in two experimental conditions to which participants were randomly assigned: faster clock (1 second = 800 ms) vs. slower clock (1 second = 1200 ms)[10]. Regardless of the

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[10] There was also another condition (present in both Experiment 1 and 2) in which clock-speed was not manipulated, but people were not allowed to check the time whenever they wished; instead, the clock appeared on the screen automatically at specific pre-set time points. This further condition, called *external-control* condition, is out of the scope of this article, and it was introduced to measure the effect of self-retrieved aspect of time monitoring, because the clock appeared on the screen automatically at specific pre-set time points, so participants did not have the possibility to check the time whenever they wished. Further information are reported in the Supplementary materials (section 11.1.1.1).

clock-speed condition, the displayed digits of the external clock did not change in both TBPM blocks (i.e., the blocks appeared to have the same duration); instead, they only differed in terms of actual (real) duration.

If people rely on tracking the *temporal* proximity between the ongoing and the PM target time, then we should expect differences between clock speed conditions in the second TBPM block (even though the actual digits displayed on the clock did not change among TBPM blocks). For instance, people in the faster clock might check the clock averagely less compared to the people assigned to the slower clock conditions, but only at the level of the TBPM experimental block. This might be due to "longer" internal time estimation formed previously during the baseline TBPM block: following the IR-AGM (see section 2.2.1), in the first TBPM block (i.e., without clock-speed manipulation), people use a representation of seconds and minutes that is dynamically updated and consolidated throughout the task via time monitoring. When people are exposed again to the same TBPM task, but with a faster clock, such representation would be no longer adequate (e.g.: it would contain more "pulses", so it would be "too long"); hence, people might wait "too much time" to reach the critical temporal window around the PM target time in which it is ideal to increase time monitoring, decreasing in turn the mean clock check frequency, and consequently impairing the TBPM performance. On the contrary, people in the slower clock condition would form a representation of the PM target time containing more "pulses" (so it would be "too long"); hence, the likelihood of missing the critical temporal window around the PM target time (in which it is ideal to increase time monitoring) should be lower, and behaviorally evident in higher mean clock check frequency which, consequently, improved TBPM performance. If this hypothesis is true, then it can be argued that people try to "wait" for the PM target time – as argued by the

TWTE model (Harris & Wilkins, 1982) – and that such waiting period is necessarily supported by the actual temporal feature of the clock (i.e.: the constant duration between clock digits), and not only by predictable triggering events (i.e.: the clock's digits). The computation of actual temporal information might then confirm the idea that there are internal time processes involved in time monitoring and TBPM, supporting the IR-AGM (Block & Zakay, 2006).

Diversely, if people rely exclusively on counting and matching the *numerical* proximity between the ongoing and the PM target time, then we should expect no differences between baseline and experimental TBPM block because people would use the actual digits displayed on the clock, which did not change among the TBPM blocks. Regardless the clock speed manipulation, participants would not change the amount of attentional resources deployed to detect the PM cue during the TBPM with the altered clock, allowing them to compute and store the same amount of temporal information – via clock checking – as they did during the TBPM with regular clock (Heathcote et al., 2015; Loft & Remington, 2013); thus, clock speed manipulation would not change neither the amount of evidence accumulated concerning the incoming PM cue, nor the response thresholds for switching between OT and time monitoring (Strickland et al., 2017). If this hypothesis is true, then it can be argued that, during TBPM tasks, people try to "wait" for the PM target time, but such waiting is not necessarily supported by internal estimation of the PM target time (based on the constant interval between clock ticks), but rather by numerical metrical events (i.e.: the progression of clock digits) that, regardless their temporal properties, strategically prompt the necessity (or not) to increase time monitoring (Graf & Grondin, 2006). In this scenario, time monitoring and TBPM can be explained without considering the involvement of internal time processes computing the temporal relationships between external clock events, but only accounting for attentionally-driven processes based on predictable cues (Peper & Ball, 2022).

4.3.1. Methods

4.3.1.1. Participants

This study was powered to detect moderate-to-large differences in behavioral performances between clock-speed conditions (faster vs. slower) over one repeated measure variable (TBPM block: first vs. second); power analysis was carried out using the R-package *WebPower* (Zhang & Yuan, 2018). In the power analysis, we used an effect size of f = .33[11] for a mixed ANOVA model (within-between interaction); the power analysis indicated that detecting an effect size f of .33, at 80% power (two-tailed α at .05), would require a minimum sample size of 74 participants. Data were collected from 80 participants (age-range: 18-36 years; M_{age} = 23; SD_{age} = 4.05; 56 females); all of them were recruited using flyers. Nine participants (6.7% of the sample size) reported to have a history of neurological or major psychiatric disease within the last 5 weeks (e.g.: epilepsy, depression, anxiety), or to take psychotropic drugs or others affecting the central nervous system. These participants were excluded; moreover, one participant was further excluded because of problems in understanding the TBPM task instructions. Eight participants detected that clock-speed was manipulated (10% of the sample size); 7 belonged to the faster clock condition and 1 to the slower clock condition; we further excluded these participants. All the analyses were carried out on a sample of 64

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[11] The effect size of f = .33 was chosen as it corresponds to the median point between a medium effect size (f = .25) and a large effect size (f = .40), according to Cohen's rules of thumb (J. Cohen, 1988, pp. 284–288).

participants (age-range: 18-36 years; M_{age} = 23.2; SD_{age} = 4.26; 47 females); the number and age of participants in each clock-speed condition are depicted in

Table 1.

All participants gave their written informed consent before participating in the study that was conducted in accordance with the Declaration of Helsinki, and the protocol had been approved by the ethics commission of the Faculty of Psychology and Social Sciences of the University of Geneva (PSE.20191004.05); moreover, all of them received monetary compensation of 20 CHF as reimbursement for taking part to the experiment.

Table 1

Number of participants and mean age

	Experiment 1 (lab.)			**Experiment 2 (online)**		
	Age		***N***	**Age**		***N***
Experimental condition	***M***	***SD***		***M***	***SD***	
faster	23.4	4.28	27	26.4	3.79	39
slower	23.0	4.30	37	28.7	4.92	36
control				26.4	4.94	39

Note. Number of participants assigned to different clock-speed condition (faster, slower, control) for both Experiment 1 and 2; descriptive data on age are reported for each group and experiment.

4.3.1.2. Materials

Time-based prospective memory task. Participants performed two identical TBPM blocks on the computer. For both blocks, the TBPM task was to remember to press the ENTER key on the keyboard every 4 minutes; in total, five PM responses were collected for each block; during the first TBPM block, clock-speed was not manipulated (1 second = 1000 ms), whereas in the second TBPM block, clock-speed was manipulated, and participant were assigned randomly to the faster or slower clock condition (between-subject manipulation). For the faster clock, each minute lasted 48 seconds (1 second = 800 ms), whilst for the slower clock, each minute lasted 72 seconds (1 second = 1200 ms). These specific durations of clock's seconds were chosen because previous studies showed that, using these clock-speeds, a negligible portion of the sample should recognized the manipulation of the external time as such (Thönes et al., 2021). In both the first and the second TBPM blocks, participants were free to check the clock as often as they wanted by pressing the SPACEBAR; if they did so, a digital clock (format: "00:00") appeared on the screen for 3 seconds (the duration of each second lasted accordingly to the speed of the clock: 2400 ms in the faster clock condition; 3600 ms in the slower clock condition).

Ongoing task. While carrying out the TBPM tasks, participants performed a lexical decision task as OT (Meyer & Schvaneveldt, 1971), which asked them to indicate if a string of letters presented on the screen forms a word or not; the procedure was administered in French. We included two OT tasks blocks without additional delayed intention performed before and after the two TBPM blocks, respectively. These tasks were identical to the OT performed during the TBPM blocks; the first OT served as baseline for the PM cost (Guo et al., 2019; McBride & Flaherty, 2020), whereas the second OT served as control for any collateral fatigue effect related to the clock-speed manipulation. Each OT trial started with a fixation cross (1000 ms) followed by the stimulus (2000 ms) and a subsequent black period screen that lasted randomly between

300 and 1000 ms. All the stimuli (words and non-words) had between 5 – 8 letters; 1136 stimuli (568 words) were selected based on their highest scores in terms of accuracy and lowest reaction times (i.e.: the easiest to detect) following the rules of Ferrand (Ferrand et al., 2010). The choice to use easily detectable stimuli was made to ensure that the cognitive load related to the OT was the lowest as possible, so the effect of the clock-speed was free from confound effects related to the difficulty of the OT task, preventing also learning effects; at the same time, the random blank period avoided any temporal regularity related to the OT trials, which has been demonstrated to potentially work as temporal cue supporting time monitoring (Guo & Huang, 2019; Heathcote et al., 2015). All OT stimuli were presented in fully randomized order across all the blocks. The total duration of each TBPM block varied between ~16 and ~25 minutes accordingly to the correspondent clock-speed manipulation. Consequently, the OT trials' number varied across the blocks (~290 trials in blocks with regular clock; ~235 in blocks with faster clock; ~340 in blocks with slower clock). Regardless of the clock condition, all the TBPM task's blocks had apparently the same duration (21 minutes), meaning that the displayed clock's digits did not change among the blocks, while the real task duration did.

Follow-up questionnaire. We administered a short follow-up questionnaire related to the time manipulation's awareness ("During this experiment, you did two blocks where we asked you to press the ENTER key every 4 minutes. Did you notice a difference between the first and second blocks? What did you notice?"). Participants were asked to give binary responses ("yes" or "no") to this question (and to each of the follow-up questions too); in the case of a "yes", the subjects were asked to provide a short statement of clarification. We explored the subjective reports at the question in a descriptive fashion to detect participants that noticed the manipulation of clock-speed beyond a mere feeling of time moving faster or slower. This procedure was adopted because the clock-speed manipulation should remain undetected, and its eventual effect should be taken into account in the analyses (Thönes et al., 2018, 2021).

4.3.1.3. Procedure

All the computerized tasks were administered using *E-Prime 3* (Psychology Software Tools, Pittsburgh, PA, USA), whereas the questionnaires were administered using *LimeSurvey* (LimeSurvey Project Team / Carsten Schmitz, 2012). In total, a testing session lasted approximately 2 hours. In order to control for temporal cues that could affect time monitoring, clocks from the testing room were removed; moreover, windows were closed to eliminate all the temporal influence provided by the day-night cycle, keeping only artificial lights in the room during the experiment (Barner et al., 2019; Esposito et al., 2015; Rothen & Meier, 2017). As the participants arrived in the laboratory, the experimenter explained the aim of the study, providing an information sheet and the consent form. Once participants accepted to take part at the study, they filled the sociodemographic questionnaire, and then performed the lexical decision task without additional intention, which was identical to the OT administered subsequently in the TBPM blocks. Before passing to the first TBPM block (without clock-speed manipulation), participants performed a practice block lasting approximately 4 minutes, which allowed them to familiarize with the TBPM task. After the experimenter has ascertained that the participant understood the task, the first block of the TBPM block was administered; when the participants completed it, the second TBPM block was administered (faster, slower, or regular/external clock condition). Following on this, participants performed another lexical decision task. Once people completed this last task, the follow-up questionnaire was administered. At this point, the experiment ended, and participants received the monetary remuneration and were debriefed about the aims and background of the study before they left the laboratory.

4.3.2. Results

We applied mixed-design ANOVAs with post-hoc *t*-tests corrected using Bonferroni's method for the *p*-values of the comparisons (indicated in the text as p_{adj}). We focused on two effects of interests:

1. The interaction effect Block * Clock-speed (present in all ANOVAs), as a measure of the effect of clock-speed on the dependent variables.
2. The interaction effect Time * Block * Clock-speed, as a measure of the effect of clock-speed on the strategicness of time monitoring (this effect was present only in the analysis on time monitoring).

For all the analyses, Greenhouse-Geisser correction was used when assumptions of sphericity were not met; moreover, we calculated the effect sizes using partial eta squared values (η^2_p). The rejection level for inferring statistical significance was set at $p < .05$. Data pre-processing and figures were carried out in R – version 4.2.1 (R Core Team, 2022) – with the support of ChatGPT for building the R-script (OpenAI, 2023). In addition to the frequentist analyses, we also ran Bayesian ANOVAs, which was used to quantify how much model for the null hypothesis is more likely than the model for the alternative hypothesis. Specifically, in the present study, the alternative hypothesis is that there was a difference in the dependent variable as a function of the clock-speed condition over the second TBPM block. We tested the two interaction effects of interest (i.e., Block * Clock-speed, and Time * Block * Clock-speed) against a Bayesian null model containing all other effects that were not of interest (as well as the effect of Participants); this strategy allowed to test the effects of interest against all others. The analyses were carried out in *Jamovi*, version 2.3.21.0 (The Jamovi Project, 2021); Bayesian analyses were carried out using the Jamovi module *jsq* with default settings (Rouder et al., 2012). Descriptive statistics are reported in

Table 2. Retrospective power analyses were later obtained for each ANOVA using the R- package *WebPower* (Zhang & Yuan, 2018), and they are reported in the Supplementary material (section 11.1.1.2).

Table 2

Descriptive statistics (Experiment 1)

		Rate of TBPM task completion (%)		**Timing error of PM responses (seconds)**		**Monitoring over time**							
						First TBPM block				**Second TBPM block**			
	Experimental condition	**First TBPM block**	**Second TBPM block**	**First TBPM block**	**Second TBPM block**	**t1**	**t2**	**t3**	**t4**	**t1**	**t2**	**t3**	**t4**
M	faster	95.60	90.40	6.82	9.73	0.45	0.66	0.83	2.24	0.30	0.62	0.83	2.01
	slower	85.80	90.50	2.83	-3.60	0.66	0.97	1.20	2.34	0.76	1.23	1.48	2.92
SD	faster	8.47	12.90	15.50	14.60	0.48	0.64	0.54	1.39	0.27	0.75	0.58	1.28
	slower	18.00	12.90	14.30	15.90	0.80	1.48	1.52	1.74	1.77	1.88	1.80	2.22

Note. Mean and standard deviation of both the prospective memory task performance and time monitoring for Experiment 1 as a function of clock-speed condition (faster vs. slower) and task's block (First vs. Second). Time-based prospective memory performance is reported as rate of prospective memory tasks completed (in percentage) and as timing error (i.e., as mean response deviation of the prospective response from the target time, in seconds; maximum accuracy = 0; positive values indicate later prospective memory responses; negative values indicate earlier prospective memory responses). Time monitoring is represented as mean clock check frequency in both time-based prospective memory blocks over time (minute 1 vs. minute 2 v. minute 3 vs. minute 4). TBPM: time-based prospective memory; t1: minute 1; t2: minute 2; t3: minute 3; t4: minute 4.

4.3.2.1. Time-based prospective memory

Two mixed-design ANOVA were carried out separately for (1) the rate of TBPM task completion – as standardized mean proportion of the number of PM tasks accomplished, regardless of the timing of the PM responses – and (2) the timing error of the PM responses (as difference in seconds between the actual time point when people performed the TBPM task, and the objective time point required by the TBPM task; positive values indicated later PM responses; negative values indicated earlier PM responses). For both analyses, the between-subjects independent variable was Clock-speed (faster vs. slower), whereas the within-subjects independent variable was Block (first TBPM block vs. second TBPM block). The TBPM performance is represented graphically in **Figure 2A**.

The analysis on the rate of TBPM task completion revealed no significant main effect of Block ($p = .922$) and Clock-speed ($p = .074$), but a significant interaction Block * Clock-speed, $F(1, 63) = 4.70$, $p = .034$, $\eta^2_p = .07$. Post-hoc comparisons revealed that such effect was driven mainly by individual differences in the first TBPM block, although still comparison was not statistically significant ($p_{adj} = .066$); all other comparisons were not statistically significant ($ps_{adj} > .05$). Bayesian analysis was carried out testing the alternative model comprising the interaction effect of interest Block * Clock-speed against a null model containing the main effects of Clock-speed, Block and Participants; the Bayes Factor was 2.30, indicating only anecdotal evidence for the alternative hypothesis (Wetzels et al., 2015). The analysis on the timing error of the PM responses did not reveal any significant main effect of Block ($p = .483$) as well as interaction effect Block * Clock-speed ($p = .065$); however, a main effect of Clock-speed was found, $F(1, 63) = 9.09$, $p = .004$, $\eta^2_p = .13$. Post-hoc tests revealed that people in the faster clock condition carried out later PM responses ($M = 8.28$, $SD = 15.80$) than people in the slower clock condition ($M = -.38$, $SD = 17.10$), $t(63) = 3.01$, $p_{adj} = .004$. The difference in the response's deviations between the faster and slower clock conditions was not found in the first TBPM block, where the mean response's deviation from the PM target time between faster ($M = 6.82$, $SD = 15.50$) and slower clock condition ($M = 2.83$, $SD = 14.30$) did not differ significantly among each other ($p_{adj} = 1$); instead, the mean response's deviation from the PM target time significantly differed between faster ($M = 9.73$, $SD = 14.60$) and slower clock condition ($M = -3.60$, $SD = 15.90$) only during the second TBPM block, $t(63) = 3.44$, $p_{adj} = .006$; specifically, people exposed to the faster clock performed later PM responses than people exposed to the slower clock. Bayesian analysis was carried out testing the alternative model comprising the interaction effect of interest Block * Clock-speed against a null model containing the main effects of Clock-speed, Block and Participants; the Bayes Factor was 1.38, indicating anecdotal evidence for the alternative hypothesis (Wetzels et al., 2015).

4.3.2.2. Time monitoring

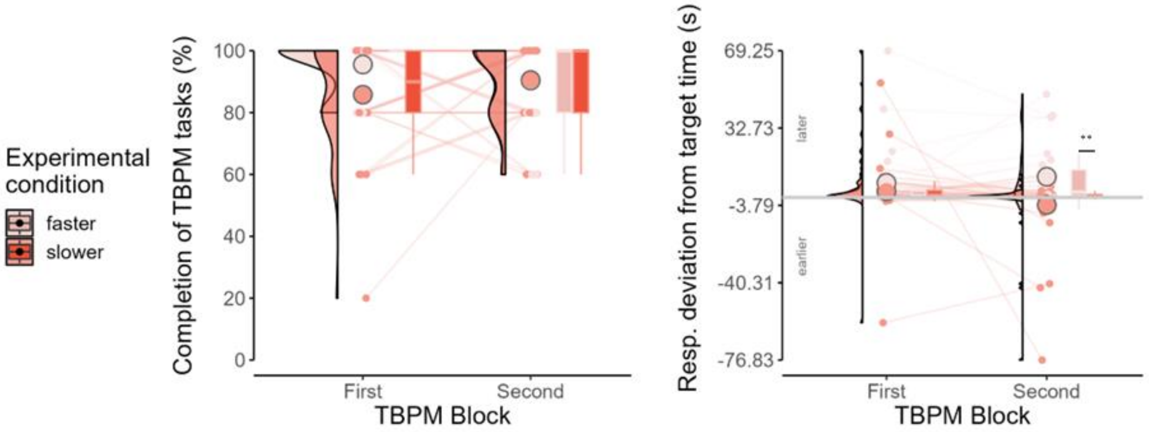
A mixed-design ANOVA was carried out to measure the effect of Clock-speed (faster vs. slower clock) as between-subject variable, and Block (first TBPM block vs. second TBPM block) and Time (minute 1 vs. minute 2 vs. minute 3 vs. minute 4) as within-subject variables, on time monitoring (measured as mean clock check frequency per minute). Time monitoring is represented graphically in **Figure 2B**. The statistical analysis showed a main effect of the Time, $F(1.45, 91.29) = 124.15$, $p < .001$, $\eta^2_p = .66$, as well as interaction effects of Block * Clock-speed, $F(1, 63) = 7.86$, $p = .007$, $\eta^2_p = .11$, and Time * Block * Clock-speed, $F(2.41, 152.02) = 4.15$, $p = .012$, $\eta^2_p = .06$. Post-hoc analyses for the main effect of Time revealed that people checked the clock strategically overall; specifically, the results showed that participants checked the clock less frequently in minute 1 ($M = .55$, $SD = 1.03$) compared to minute 2 ($M = .87$, $SD = 1.37$), $t(63) = -4.90$, $p_{adj} < .001$, minute 3 ($M = 1.09$, $SD = 1.34$), $t(63) = -8.54$, $p_{adj} < .001$, and minute 4 ($M = 2.38$, $SD = 1.76$), $t(63) = -12.25$, $p_{adj} < .001$. Similarly, participants checked the clock less in minute 2 compared to minute 3, $t(63) = -5.03$, $p_{adj} < .001$, and minute 4, $t(63) = -11.83$, $p_{adj} < .001$. Clock check frequency was significantly lower in minute 3 than minute 4 too, $t(63) = -11.11$, $p_{adj} < .001$.

Post-hoc comparisons for the interaction effect Block * Clock-speed showed that people exposed to the slower clock increased significantly clock checks frequency from the first TBPM block ($M = 1.29$, $SD = .03$) to the second TBPM block ($M = 1.60$, $SD = .04$), $t(63) = -3.23$, $p_{adj} = .011$. The same comparisons for participants in the faster clock condition did not show significant results ($p_{adj} > .05$). Post-hoc comparisons for the interaction effect Time * Block * Clock-speed furtherly showed that the interaction effect Block * Clock-speed occurred only during the third and fourth minute before the PM target time; specifically, people exposed to the slower clock increased significantly clock check frequency from the first TBPM block to the second TBPM block, but only on minute 3 ($M_{first\ TBPM\ block} = 1.20$, $SD_{first\ TBPM\ block} = 1.52$; $M_{second\ TBPM\ block} = 1.48$, $SD_{second\ TBPM\ block} = 1.80$), $t(63) = -3.88$, $p_{adj} = .020$, and on minute 4 ($M_{first\ TBPM\ block} = 2.34$, $SD_{first\ TBPM\ block} = 1.74$; $M_{second\ TBPM\ block} = 2.92$, $SD_{second\ TBPM\ block} = 2.22$), $t(63) = -3.63$, $p_{adj} = .041$. The same comparisons for minute 1 and 2, as well as the comparison with the faster clock condition, did not show significant results ($p_{adj} > .05$). Bayesian analysis was carried out testing the alternative model comprising the interaction effects of interest (i.e., Block * Clock-speed, and Time * Block * Clock-speed) against a null model containing the main effects of Clock-speed, Block and Participants, as well as the interaction effects of Block * Time, and Time * Clock-speed; the Bayes Factor was 45.84 for the effect Block * Clock-speed, indicating very strong evidence for the alternative hypothesis, and 8.01 for the effect Time * Block * Clock-speed, indicating moderate evidence for the alternative hypothesis (Wetzels et al., 2015).

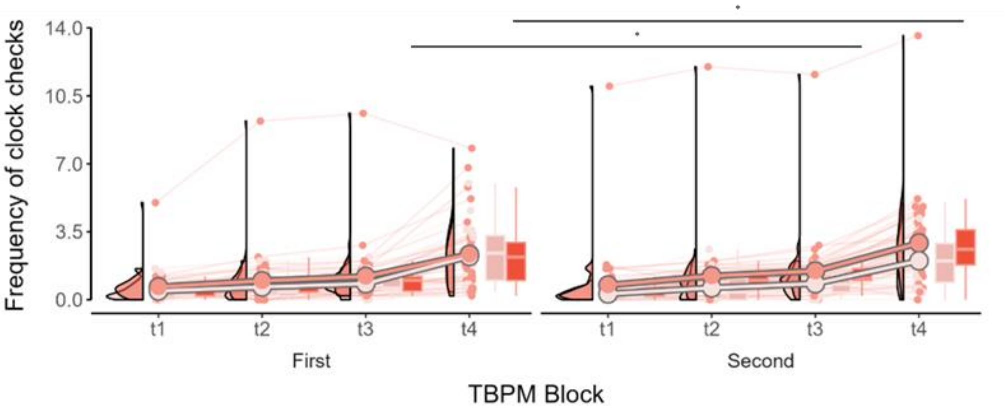
Figure 2

Prospective memory performance and time monitoring (Experiment 1)

A) Time-based prospective memory



B) Frequency of monitoring over time



Note. Graphical representations of time-based prospective memory performance and time monitoring from Experiment 1. (A) The left panel depicts the prospective memory performance as percentage of completed tasks, regardless of the response's timing. The right panel depicts the timing error of the prospective memory responses, as deviation from the target time (in seconds; maximum accuracy = 0; positive values indicate later prospective memory responses; negative values indicate earlier prospective memory responses). (B) Time monitoring as mean frequency of clock checks over time per time-based prospective memory blocks. TBPM: time-based prospective memory; First TBPM block: prospective memory task without clock-speed manipulation; Second TBPM block: prospective memory task with clock-speed manipulation; t1 = minute 1; t2 = minute 2; t3 = minute 3; t4 = minute 4. * $p < .05$; ** $p < .01$.

4.3.3. Discussion

In Experiment 1, we tested experimentally the effect of internal time processes on time monitoring and TBPM by manipulating the external clock-speed. Our results showed that TBPM performance was not affected by the clock-speed (**Figure 2A**). Diversely, findings on time monitoring showed that people monitored more often when they were exposed to a slower clock, especially over the last two minutes before the PM target time; however, there was no difference compared to the faster clock condition (**Figure 2B**). Because both faster and slower clock condition did not differ in terms of both TBPM performance and time monitoring, the results then supported the hypothesis that people “waited” for the PM target time following the numerical metrical events, rather than the temporal relationship between them (i.e., the constant interval between clock ticks); hence, it is likely that participants used the clock not to estimate internally the temporal occurrence of the PM target time, but to detect the *numerical* proximity between the ongoing clock time with the PM target time, regardless of the duration between clock digits.

Nonetheless, we still found that participants checked the clock more often in the second compared to the first TBPM block, but only when exposed to the slower clock condition, and especially during the last two minutes before the PM target time. This finding might underlie a possible benefit of slowing down time, meaning that people exposed to the slower clock had objectively more time to elaborate the temporal information. However, compared to the faster clock condition, such advantage is not translated neither into a statistically significant increase of the temporal precision of the TBPM response, nor into a better remembering of the intention itself. Thus, it is likely that these changes reflected merely the fact that participants had more time to complete the task and, and perhaps were expecting the PM target time earlier than the moment of its actual occurrence. However, even though such anticipatory processes were engaged – especially before the PM target time occurrence – it cannot be excluded that internal time processes are involved in TBPM: in this sense, slower clock might have facilitated such anticipatory processes, so people might have used the clock to estimate the temporal occurrence of the PM cue based on the constant duration between hierarchically-organized clock digits (i.e., the *temporal* proximity between the ongoing and the PM target time). To further clarify this pattern of results, we replicated and extended the experimental procedure in Experiment 2.

4.4. Experiment 2

In Experiment 2, we aimed to replicate the results obtained from Experiment 1 adding one more between-subjects control condition in which clock-speed was not manipulated (1 second = 1000 ms); such control condition was included to compare both faster and slower clock conditions with a group of participants that were not exposed to any clock-speed manipulation. Experiment 2 was administered online, as previous studies demonstrated that, although people seemed generally more distracted when tested remotely, online assessment yielded to similar results as the laboratory assessment (Germine et al., 2012; Greene & Naveh-Benjamin, 2022; Uittenhove et al., 2023), also when PM is assessed (Finley & Penningroth, 2015; Laera et al., under review;

Zuber et al., 2022). Overall, the experimental procedure was almost identical between the two experiments, with few minor changes that we made to better adapt the experiment for online testing (see Methods section below).

4.4.1. Methods

4.4.1.1. Participants

This study was powered to detect moderate-to-large differences in behavioral performances between clock-speed conditions (faster vs. slower vs. control) over one repeated measure variable (TBPM block: first vs. second). In the power analysis, we used an effect size of $f = .33$ for a mixed ANOVA model (within-between interaction); the power analysis indicated that detecting an effect size f of .33, at 80% power (two-tailed α at .05), would require a minimum sample size of 93 participants. We collected data from 120 participants (age-range: 18-35 years; $M_{\text{age}} = 27.10$; $SD_{\text{age}} = 4.65$; 64 females); all of them were recruited using *Prolific* (www.prolific.co), an online platform in which participants receive payment for completion of web-based experiments. We pre-selected healthy participants using the Prolific pre-screening system with the following criteria: age between 18 and 35 years old; being fluent in English; no current alcohol therapy or medication intake, no head injury, long-term health condition/disability, and chronic condition/illness; no mild cognitive impairment/dementia/mental illness. Three participants were excluded because they detected that clock-speed was manipulated (2.6% of the sample size); all of them belonged to the faster clock condition. One participant was excluded because s/he performed the TBPM task each 2 minutes (instead each 4 minutes; presumably s/he did not fully understand the task's instruction). Two participants (1.8% of the sample size) were furtherly excluded because they pressed the ENTER key at almost every OT trial. All the analyses were carried out on a sample of 114 people (age-range: 18-35 years; M_{age} = 27.1; SD_{age} = 4.66; 62 females); the number and age of participants in each clock-speed condition are depicted in

Table 1. All participants gave their consent before participating in the study that was conducted in accordance with the Declaration of Helsinki, and the protocol had been approved by the ethics commission of the Faculty of Psychology and Social Sciences of the University of Geneva (CUREG-2022.02.20). Remuneration for the participation was carried out using the Prolific's system, and it was set at 8 £ per hour. The remuneration was delivered according to the duration taken by each participant to finish the experiment; as the experimental procedure took on average 45 minutes (minimum = 32 minutes, maximum = 102 minutes), people were paid on average 6 £.

4.4.1.2. Materials

Time-based prospective memory task. Participants performed almost identical TBPM tasks administered in the laboratory: as in Experiment 1, participants performed two TBPM tasks asking them to press the ENTER key on the keyboard every 4 minutes (i.e., within-subject manipulation); during the first TBPM block, clock-speed was not manipulated (1 second = 1000 ms), whereas in the second TBPM block, clock-speed was manipulated, and participants were assigned randomly to three clock-speed conditions (faster vs. slower vs. control condition; between-subject manipulation). As in Experiment 1, for the faster clock, each minute lasted 48 seconds (1 second = 800 ms), whilst for the slower clock, each minute lasted 72 seconds (1 second = 1200 ms). In the control condition, in clock-speed was not manipulated (1 second = 1000 ms); in other words, the first and second TBPM blocks were temporally identical for participants assigned to the control condition.

Although the TBPM paradigm was almost identical between experiments, we reduced the number of PM tasks per TBPM block: in Experiment 1, five PM responses were collected each block, whereas in Experiment 2, two PM responses for the first TBPM block (i.e., the block *without* clock-speed manipulation), and four PM responses for the second TBPM block (i.e., the block *with* clock-speed manipulation) were collected. This was made to limit the overall duration of the procedure and to avoid that participants withdraw due to a long experimental procedure (Finley & Penningroth, 2015; Logie & Maylor, 2009).

Ongoing task. While carrying out the TBPM tasks, volunteers performed a lexical decision task as OT (Meyer & Schvaneveldt, 1971)[12]. The OT was in English (diversely from the OT in Experiment 1, which was in French). We chose to switch the language because very few people in Prolific are fluent French-speakers, which in turn decreases the number of potential eligible participants; instead, many participants on Prolific are fluent in English. The OT trial structure was identical to the OT administered in Experiment 1. The OT stimuli were taken from the English Lexicon Project (Balota et al., 2007; Goh et al., 2020), and they were selected following the same criteria used in Experiment 1. We selected in total 596 stimuli (298 words). The total duration of the first TBPM block was ~8 minutes (~135 OT trials), whereas the second TBPM block

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[12] As in Experiment 1, we included a measure for the PM cost which has not been included in the present article (for more information, see Supplementary materials, section 11.1.2.1). However, in Experiment 2 we did not include the second OT after the TBPM tasks, because we wanted to limit the overall duration of the experimental procedure, decreasing the rate of online withdrawn by the participants, as shown by previous studies (Finley & Penningroth, 2015; Logie & Maylor, 2009).

varied between ~13 and ~19 minutes accordingly to the correspondent clock-speed manipulation. Consequently, the OT trials' number varied across the blocks (~268 OT trials in blocks with regular clock; ~215 in blocks with faster clock; ~321 in blocks with slower clock).

To prevent participants online from performing the tasks poorly, we included an additional check during the tasks that was not present in Experiment 1: if people did not respond to more than three OT trials in a row, the OT stopped, showing the following message: "It looks like you have stopped to give answers to the requested task. Please resume the task by pressing the 'p' key on your keyboard. Thanks for your collaboration."; once the participants pressed "p", the OT continued. If people pressed the "p" key more than three times during the tasks, s/he was subsequently excluded from the analysis. This procedure has proved to be effective in eliminating the presence of missing data (0% overall), as only 5 participants reported having pressed the "p" key, but no more than once during the whole experimental procedure.

Follow-up questionnaire. The same follow-up questionnaire used in Experiment 1 was administered online in Experiment 1.

4.4.1.3. Procedure

The entire experimental procedure has been programmed using *Psychopy*, version 2021.2.3 (Peirce et al., 2019), and hosted online on *Pavlovia* (https://pavlovia.org/; Bridges et al., 2020), which was integrated into Prolific for the experiment's execution. In total, a testing session lasted approximately 45 minutes. Prior to participation, all relevant information concerning the experimental procedure and data access were provided in written form on the screen; participants provided informed consent to anonymous data usage before participation in the study. If participants accepted to take part in the study, they were introduced to the OT baseline; however, before passing to the practice block, they went through an instruction quiz (i.e., participants had to answer correctly to questions on the task's instructions before proceeding; Finley & Penningroth, 2015). If participants responded correctly to all the questions of the instruction quiz, they performed a short practice session of the OT baseline, which comprised 8 trials (4 words and 4 non-words). Once participants reached an OT accuracy of at least 80%, the OT baseline was administered. When they completed the OT baseline, participants were introduced to the TBPM task; they performed a new instruction quiz including the instructions of the TBPM task. As for the OT baseline, if participants responded correctly to all the questions of the instruction quiz, the practice block was administered, which lasted approximately 4 minutes, allowing participants to familiarize with the TBPM task. Only when participants correctly performed the PM response, and reached an OT accuracy of at least 80%, the first TBPM block started. When participants completed it, the second TBPM block was administered (faster, slower, or control condition). Once participants completed this last task, the follow-up questionnaire was administered. At this point, the experiment ended, and participants were debriefed about the aims and background of the study; then, they had to provide an a-posteriori consent for the data usage after the experiment's debriefing, before receiving the remuneration.

4.4.2. Results

Overall, we applied mixed-design ANOVAs with post-hoc *t*-tests corrected using Bonferroni's method for the *p*-values of the comparisons (indicated in the text as p_{adj}). As in Experiment 1, we focused on two effects of interests:

1. The interaction effect Block * Clock-speed (present in all ANOVAs), as a measure of the effect of clock-speed on the dependent variables.
2. The interaction effect Time * Block * Clock-speed, as a measure of the effect of clock-speed on the strategicness of time monitoring (this effect was present only in the analysis on time monitoring).

Greenhouse-Geisser correction was used when assumptions of sphericity were not met; moreover, we calculated the effect sizes using partial eta squared values (η^2_p). The rejection level for inferring statistical significance was set at $p < .05$. Descriptive statistics are reported in **Table 3**. As in Experiment 1, Bayesian ANOVAs were carried out in addition to the frequentist analyses to quantify how much model for the null hypothesis is more likely than the model for the alternative hypothesis (Wetzels et al., 2015). Retrospective power analyses were later obtained for each ANOVA, and they are reported in the Supplementary materials (section 11.1.2.2).

Table 3

Descriptive statistics (Experiment 2)

		Rate of TBPM task completion (%)		**Timing error of PM responses (seconds)**		**Monitoring over time**							
						First TBPM block				**Second TBPM block**			
	Experimental condition	**First TBPM block**	**Second TBPM block**	**First TBPM block**	**Second TBPM block**	**t1**	**t2**	**t3**	**t4**	**t1**	**t2**	**t3**	**t4**
M	faster	95.80	96.50	1.38	4.99	1.08	1.38	1.78	4.07	0.94	1.45	1.84	3.55
	slower	98.70	98.70	2.50	1.60	1.67	2.22	2.12	5.13	1.58	1.99	2.79	6.35
	control	96.20	98.10	2.22	2.60	1.46	1.54	1.92	4.71	1.38	1.80	2.39	5.14
SD	faster	14.00	8.77	5.45	11.60	0.80	0.96	1.04	2.19	0.83	0.90	1.12	1.50
	slower	8.01	5.59	3.39	3.50	1.41	2.30	1.19	2.50	1.18	1.29	1.68	2.29
	control	13.50	6.75	1.90	1.83	1.23	1.35	1.35	2.32	1.57	2.01	1.98	2.14

Note. Mean and standard deviation of both the prospective memory task performance and time monitoring for Experiment 2 as a function of clock-speed condition (faster vs. slower vs. control) and task's block (First vs. Second). Time-based prospective memory performance is reported as rate of prospective memory tasks completed (in percentage) and as timing error (i.e., as mean response deviation of the prospective response from the target time, in seconds; maximum accuracy = 0; positive values indicate later prospective memory responses; negative values indicate earlier prospective memory responses). Time monitoring is represented as mean clock check frequency in both time-based prospective memory blocks over time (minute 1 vs. minute 2 v. minute 3 vs. minute 4). TBPM: time-based prospective memory; t1: minute 1; t2: minute 2; t3: minute 3; t4: minute 4.

4.4.2.1. Time-based prospective memory

We carried out the same analyses described in Experiment 1. The only difference was the between-subjects independent variable Clock-speed, which in Experiment 2 comprised the additional control condition (faster vs. slower vs. control). TBPM performance is represented graphically in **Figure 3A**. The analysis on the rate of TBPM task completion revealed no significant main effect of Block ($p = .473$) and Clock-speed ($p = .337$) as well as no significant interaction Block * Clock-speed ($p = .802$). Bayesian analysis was carried out testing the alternative model comprising the interaction effect of interest Block * Clock-speed against a null model containing the main effects of Clock-speed, Block and Participants; the Bayes Factor was 0.10, indicating no evidence for the alternative hypothesis. The analysis on the timing error of the PM responses revealed no significant main effect of Block ($p = .415$) and Clock-speed ($p = .406$), but a significant interaction Block * Clock-speed $F(2, 111) = 3.25$, $p = .042$, $\eta^2_p = .06$; however, post-hoc test for such effect did not reveal any significant comparison ($ps_{adj} > .05$). Bayesian analysis was carried out testing the alternative model comprising the interaction effect of interest Block * Clock-speed against a null model containing the main effects of Clock-speed, Block and Participants; the Bayes Factor was 1.80, indicating only anecdotal evidence for the alternative hypothesis (Wetzels et al., 2015).

4.4.2.2. Time monitoring

We carried out the same analyses described in Experiment 1. The only difference was the between-subjects independent variable Clock-speed, which in Experiment 2 comprised the additional control condition (faster vs. slower vs. control). Time monitoring is represented graphically in **Figure 3B**. The statistical analysis showed a main effect of the Time, $F(1.70, 188.51) = 429.66$, $p < .001$, $\eta^2_p = .80$, and no significant interaction Block * Clock-speed ($p = .076$). Instead, the triple interaction Time * Block * Clock-speed was statistically significant, $F(2.72, 302.30) = 7.10$, $p < .001$, $\eta^2_p = .11$. Post-hoc analyses for the main effect of Time revealed that people checked the clock strategically, indicating that people checked the clock less frequently in minute 1 (M =

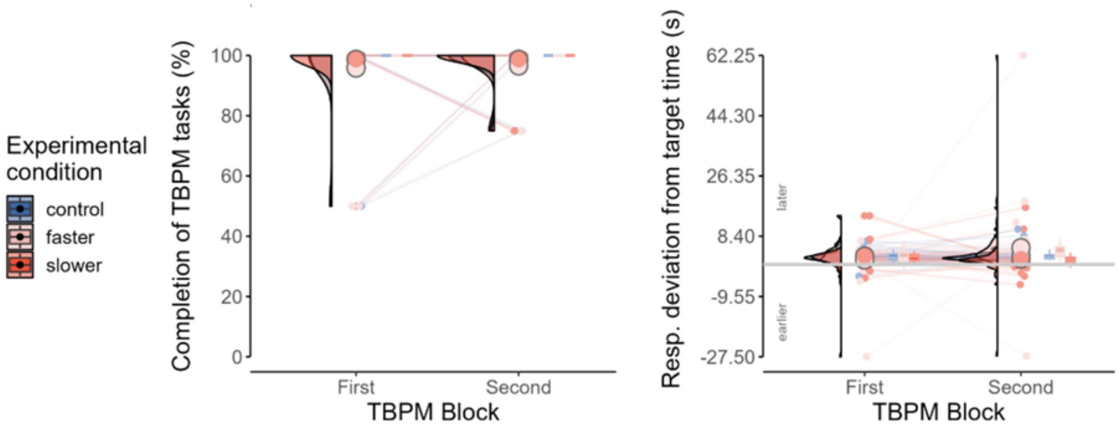
1.34, *SD* = 1.10) compared to minute 2 (*M* = 1.77, *SD* = 1.45), *t*(111) = -5.32, $p_{adj} < .001$, minute 3 (*M* = 2.12, *SD* = 1.27), *t*(114) = -12.93, $p_{adj} < .001$, and minute 4 (*M* = 4.85, *SD* = 2.02), *t*(111) = 23.79, $p_{adj} < .001$. Similarly, participants checked the clock less in minute 2 compared to minute 3, *t*(111) = -5.48, $p_{adj} < .001$, and minute 4, *t*(111) = 22.79, $p_{adj} < .001$. Clock check frequency was significantly lower in minute 3 than minute 4 too, *t*(111) = -21.78, $p_{adj} < .001$.

Post-hoc analysis for the interaction Time * Block * Clock-speed showed that people exposed to the slower clock significantly increased clock check frequency from the first TBPM block to the second TBPM block, but only on minute 4 ($M_{first\ TBPM\ block}$ = 5.13, $SD_{first\ TBPM\ block}$ = 2.50; $M_{second\ TBPM\ block}$ = 6.35, $SD_{second\ TBPM\ block}$ = 2.29), *t*(111) = -4.82, $p_{adj} = .001$. Moreover, only during the second TBPM block, people in the faster clock condition checked the clock less (*M* = 3.55, *SD* = 2.50) than people in the slower clock condition, but only on minute 4, *t*(111) = -5.99, $p_{adj} < .001$. All other comparisons were not significant ($p_{adj} > .05$). Bayesian analysis was carried out testing the alternative model comprising the interaction effects of interest (i.e., Block * Clock-speed, and Time * Block * Clock-speed) against a null model containing the main effects of Clock-speed, Block and Participants, as well as the interaction effects of Block * Time, and Time * Clock-speed; the Bayes Factor was 2.93 for the effect Block * Clock-speed, indicating anecdotal evidence for the alternative hypothesis, and 27.54 for the effect Time * Block * Clock-speed, indicating very strong evidence for the alternative hypothesis (Wetzels et al., 2015).

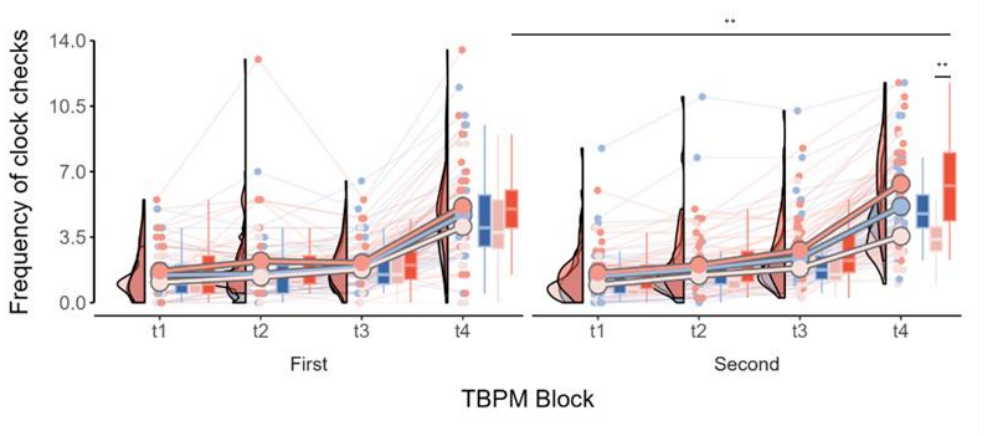
Figure 3

Prospective memory performance and time monitoring (Experiment 2)

A) Time-based prospective memory



B) Frequency of monitoring over time



Note. Graphical representations of time-based prospective memory performance and time monitoring from Experiment 2. (A) The left panel depicts the prospective memory performance as percentage of completed tasks, regardless of the response's timing; the right panel depicts the timing error of the prospective memory responses, as deviation from the target time (in seconds; maximum accuracy = 0; positive values indicate later prospective memory responses; negative values indicate earlier prospective memory responses). (B) Time monitoring as mean frequency of clock checks over time per time-based prospective memory blocks. TBPM: time-based prospective memory; First TBPM block: prospective memory task without clock-speed manipulation; Second TBPM block: prospective memory task with clock-speed manipulation; t1 = minute 1; t2 = minute 2; t3 = minute 3; t4 = minute 4. * $p < .05$; ** $p < .01$; *** $p < .001$.

4.4.3. Discussion

In Experiment 2, we replicated Experiment 1 adding one more control condition, in which clock-speed was not manipulated. The results from Experiment 1 have been partially replicated in Experiment 2: we found that TBPM performance (as both rate of TBPM task completion and timing error of the PM responses) was not affected by the clock-speed in Experiment 2, indicating that clock-speed did not change whether people remembered to perform the PM task nor the temporal precision of their responses (**Figure 3A**). This result was in line with findings from Experiment 1 (**Figure 2A**). Results on time monitoring were significant only for the last minute before the PM target time, showing that people monitored more often when they were exposed to a slower clock across TBPM blocks, as well as when compared to the participants assigned to the faster clock condition. Diversely from Experiment 1, where the difference between faster and slower clock in time monitoring was present only on a descriptive level (**Figure 2B**), in Experiment 2 such difference was statistically significant (**Figure 3B**). Moreover, the difference across TBPM blocks in the slower clock condition was present over both the 3rd and the 4th minute in Experiment 1, whereas the difference across TBPM blocks in the slower clock condition was significant only during the 4th minute in Experiment 2.

These results then furtherly supported the hypothesis that people “waited” for the PM target time following the numerical metrical events, rather than the temporal relationship between them (i.e., the constant interval between clock ticks); hence, it is likely that participants used the clock not to estimate internally the temporal occurrence of the PM target time, but to detected the *numerical* proximity between the ongoing clock time with the PM target time, regardless of the duration between clock digits. Nonetheless, similarly with Experiment 1, we still found that participants in the slower clock condition checked the clock more frequently during the second TBPM block, particularly in the last minute before the PM target time. Yet, this advantage did not lead to a significant increase in the precision of the TBPM response or better recall of the intention, compared to both faster clock and control conditions. Hence, these results confirmed that, because participants had more time to complete the task, they might have anticipated the PM target time more easily compared to participants exposed to the faster clock.

4.5. General discussion

Despite the conceptually important role of internal time processing in the core TBPM models, it is not established yet whether internal time plays a crucial role in TBPM or not (Gan & Guo, 2019; Graf & Grondin, 2006; Labelle et al., 2009; Mioni & Stablum, 2014). Therefore, in the present study, we investigated how a manipulation of the external clock-speed in the TBPM paradigm affected strategic time monitoring and TBPM performance through the mediating role of internal time processing. If people relied on tracking the *temporal* proximity between the ongoing and the PM target time, then differences between clock-speed conditions during the second TBPM block were expected; the internal computation of pure temporal information might then confirm experimentally the assumption that there are internal time processes involved in time monitoring and TBPM performance (Block & Zakay, 2006; Labelle et al., 2009). In contrast, if people used the digits displayed on the external clock – rather than the temporal interval between them – no differences between clock-speed conditions during the second TBPM block were expected. Hence, it can be argued that TBPM with external clocks could involve only attentional and executive – but not internal timing – processes, which are based on the *numerical* proximity between the ongoing clock time and the PM target time (Bowden et al., 2017; Graf & Grondin, 2006).

4.5.1. External clock-speed's effect and internal time processing

Overall, our results from both experiments showed that TBPM performance (as both the rate of TBPM task completion and the timing of the PM responses) was not affected by the clock-speed, indicating that clock-speed did not change whether people remembered to perform the PM task. Results on time monitoring showed that, especially over the last minute before PM target time, people monitored the external clock more often across TBPM blocks when they were exposed to a slower clock; moreover, people checked the clock more often in the slower compared to the faster clock condition, although such difference was statistically significant just in Experiment 2, and only over the last minute before the PM target time. In summary, these results supported the hypothesis that people "waited" for the PM target time following the numerical metrical events, rather than the temporal relationship between them (i.e., the constant interval between clock ticks); hence, it is likely that participants used the clock not to estimate internally the temporal occurrence of the PM target time, but to detected the *numerical* proximity between the ongoing clock time with the PM target time, regardless of the duration between clock digits.

Interestingly, results from both experiments consistently suggested that participants checked the clock more often in the second compared to the first TBPM block, but only when exposed to the slower clock, and especially during the last minute before the PM target time. However, compared to both control and faster clock conditions, such advantage was not associated neither with a statistically significant increase of the temporal precision of the TBPM response, nor with a better remembering of the intention itself. Thus, it is likely that these changes reflected merely the fact that participants had more time to complete the task and, and perhaps were expecting the PM target time earlier than the moment of its actual occurrence. However, if such anticipatory processes were engaged – especially before the PM target time occurrence – it cannot be excluded that internal time processes are involved in TBPM. Following the IR-AGM, in the slower clock condition participants might have formed a representation of the PM target time containing more "pulses" (so it would have been "too long"); hence, the likelihood of missing the critical temporal window around the PM target time (in which it is ideal to increase time monitoring) should have been lower, and behaviorally evident in higher mean clock check frequency. In this sense, slower clock might have facilitated such anticipatory processes, so people might have used the clock to estimate the temporal occurrence of the PM cue based on the constant duration between hierarchically-organized clock digits (i.e., the *temporal* proximity between the ongoing and the PM target time).

One possible explanation for the lack of difference between clock-speed conditions in both experiments could be related to the capacity of people to dynamically update internal time representations: participants might have adapted their temporal representation to the new clock-speed rather quickly and flexibly (Vanneste et al., 2016) in an implicit manner (Mento et al., 2013). Such possible adaptation of the internal time processing with the altered clock-speed could have cancelled out behavioral differences mediated by the internal time because of the low demand of the TBPM task used in this study. Thus, future studies could replicate our findings manipulating the task demand by increasing the OT difficulty, or the complexity of the TBPM task, to see whether the differences between altered and regular clock-speed emerge (Cicogna et al., 2005; Del Missier et al., 2021; Occhionero et al., 2010). Furthermore, it is possible that the involvement of internal time estimation and/or attentional control processes is modulated by task-related constraints, as well as by psychological processes (for an overview, see Zuber & Kliegel, 2020). In this regard, few studies imposed some constraints on time monitoring: Harris and Wilkins (1982) placed the clock behind participants' backs, requiring an overt turning around (see also Niedźwieńska & Barzykowski, 2012). Huang and colleagues (2014) instructed participants to use the timer as infrequently as possible in one of their experimental conditions, whereas Mioni and Stablum (2014) permitted participants in one experimental condition to check the clock only up to six times over the course of five minutes. All these studies consistently showed that, when restrictions were imposed on time monitoring, the frequency of clock-checks decreased, but strategicness increased (Harris & Wilkins, 1982; Huang et al., 2014; Mioni & Stablum, 2014); therefore, in those specific circumstances, it is possible that people might engage more internal time processes to optimize the strategic use of the clock when time monitoring is somehow constrained, whereas in the present study this was not case as no constraints were imposed on time monitoring. Future studies could test this assumption by manipulating clock-speed and imposing constraints on time monitoring. One first attempt in this regard has been made in the present thesis, within the framework of motivated cognition (see chapter 6).

4.5.2. Attentional and executive processes in time-based prospective memory

As mentioned above, the lack of significant differences between experimental (faster and slower clock conditions) and control condition for both time monitoring and TBPM performance challenged the conceptual explanation that involves internal time processing in TBPM (Bowden et al., 2017; Graf & Grondin, 2006). In this perspective, time monitoring in TBPM may be explained exclusively by attentional and executive processes that allow to count and match the *numerical* proximity between the ongoing and the PM target time: the more the time advances, the higher the probability that the incoming PM cue is occurring soon, the higher the likelihood that people check the target number (and performed accurate PM responses).

However, another aspect to be considered is the involvement of executive functions in internal time processing. Several evidence showed that executive functions as attentional control and working memory are essential to estimate durations (Block & Gruber, 2014; Block & Zakay, 2006; Coull & Nobre, 1998; Jones, 2006); at the brain level, such functions are supported by several distributed neural areas related to attentional control, involving especially the anterior cingulate cortex (Zakay & Block, 2004), a brain area dedicated to the strategic decision-making and action monitoring (Akam et al., 2021; Gehring & Knight, 2000; van Veen et al., 2004). Some authors have shown that, when a person decides to estimate a duration, contextual information associated with the previous acts of time estimation are learned and retrieved to guide the temporal estimation (Üstün et al., 2017; Zakay & Block, 2004). Interestingly, Cruz and colleagues

(2017) found that the anterior cingulate cortex was highly involved in time monitoring and TBPM performance. The authors argued that the retrieval of the time-based intention, related to time monitoring behavior, underlies the evaluation of the current time with respect to the PM target time; thus, there is an intrinsic decision-making mechanism guiding the intention execution (Cruz et al., 2017); according to the present study, such decisional mechanism is based on the *numerical* proximity of the current time displayed on the clock and the PM target time. The involved of the anterior cingulate cortex in PM retrieval is also postulated in the model by Cona and colleagues (2015), the Attention to Delayed Intentions model (Cona, Scarpazza, et al., 2015). Interestingly, this model was conceived mainly for EBPM; yet, it could work also for TBPM because such PM processes may interact with executive functions related to attentional control (e.g., task-switching) and decision-making too, with the latter two both involved in EBPM as well as TBPM tasks (Bugg & Ball, 2017; Cona, Arcara, et al., 2015).

Another aspect involving attentional and executive processes concerns the awareness of the clock-speed manipulation. In our study, participants were not aware of the clock-speed manipulation, and the few who detected the manipulation were excluded. We chose to use this approach to follow the literature, as all the few studies that used clock-speed manipulation kept people unaware of such manipulation (Christandl et al., 2018; Thönes et al., 2018, 2021; Yamane & Matsumura, 2015); indeed, there is no study that investigated whether the awareness of clock-speed manipulation affect people's behavior. In the TBPM context, people might adapt to the new clock-speed if they expect that the clock-speed will change. Thus, knowing that the clock is altered can affect the way people monitor time and eventually the representation of the external elapsing time, which in turn could affect their TBPM performance. For example, if people are aware that clock are slower, they might choose to allocate more attentional resources to the OT than the PM task, because they expect the PM target time later on; thus, it would not be strategic to monitor as the clock-speed was regular because, with slower clock, the PM target time would occur objectively later compared to the TBPM block in which the clock-speed is not manipulated. On the contrary, people aware of faster clock might decide to focus more on the PM task rather than the OT, because the PM target time is expected to come earlier than the PM target time within the TBPM block without clock-speed manipulation. Temporal expectancy is driven by attentional allocation over time (Bolger et al., 2014; Coull et al., 2011; Coull & Nobre, 1998; Nobre et al., 2007), so the need to check the clock could emerge from the attentional resources dedicated to the PM and to the OT which, in turn, affect the internal representation of the elapsing time, as well as how such representation is used strategically to monitor the external time. In this regard, including a further condition of awareness of the manipulation (e.g.: aware vs. unaware), can help to identify to which degree the effect of clock-speed – and the relative temporal expectancies – affect time monitoring and TBPM.

4.6. Conclusions

In two experiments, we found that people exposed to the slower clock showed increased individual mean frequency of clock checks across TBPM blocks. However, we did not find significant differences between experimental (faster and slower clock) and control condition for both time monitoring and TBPM performance. Thus, although results cannot allow to disentangle whether attentional and/or internal time processes were involved in TBPM, at least using the traditional paradigm, it was demonstrated that participants based their clock-checking strategy on counting and matching the ongoing time with the PM target time (i.e., the *numerical* proximity). This was the first study that introduced a clock-speed manipulation in TBPM; therefore, future studies are needed to replicate the results, and to further understand the role of internal time processing in TBPM.

5. Study 2[13]:

Aging and time-based prospective memory in the laboratory: a meta-analysis on age-related differences and possible explanatory factors

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5.1. Abstract

In older adults' everyday life, TBPM is relevant as health-related intentions are often part of daily activities. Nonetheless, it is still unclear which task-related factors can potentially moderate the magnitude of age-related differences, such as duration of the PM target time (the time-window within which an individual must complete a given TBPM task), the frequency of the TBPM tasks, and the criterion chosen to compute PM accuracy. The present meta-analysis aimed to quantify age-related differences in laboratory TBPM tasks, and to investigate how specific task-related factors potentially moderate the magnitude of age effects. The results showed that age effects consistently emerged among the studies, with older adults showing lower TBPM performance and checking the clock less often than younger adults, especially for shorter intervals (e.g., ≤ 4 minutes). Furthermore, the results indicated that the duration of the PM target time interacted with the frequency of the PM task, suggesting that learning effects may attenuate the magnitude of age differences in TBPM performance. The results are discussed in terms of potential implications about the possible cognitive processes involved in TBPM and aging, as well as in terms of robustness of the TBPM laboratory paradigm in aging research.

5.2. Introduction

In older adults' everyday life, TBPM is very relevant as health-related intentions are often part of daily activities, such as taking medication regularly, or going to appointments with the doctor (Haas et al., 2020; Hering et al., 2018; Woods et al., 2015); nonetheless, it is not clear how TBPM is affected by aging. Indeed, although most of the studies examining the age-related differences in TBPM showed that younger adults outperform older adults in laboratory TBPM tasks (Einstein et al., 1995; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; D. C. Park et al., 1997; Vanneste et al., 2016), there is an ongoing debate on how large this difference between younger and older adults indeed is (Varley et al., 2021). In fact, meta-analytic evidence on TBPM and aging has been provided by Henry and colleagues (2004), which showed that, in laboratory settings, younger participants outperformed older participants at TBPM tasks; however, this meta-analysis included only six studies that assessed TBPM in the laboratory (Henry et al., 2004). In the last 15 years, there have been an increasing number of studies on TBPM, but so far, a systematic quantification of the age-related differences in the laboratory TBPM paradigm is still missing.

Moreover, it is unclear whether time monitoring differs between age groups: although most of the studies found that younger adults checked the clock more often than older adults (e.g., Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016), other authors found the opposite pattern (Mäntylä et al., 2009), or even no differences between age groups (McFarland & Glisky, 2009). The cognitive processes underlying age differences in TBPM are also not well understood, with some authors arguing that age differences are due mainly in time estimation (Labelle et al., 2009;

Mioni & Stablum, 2014; Vanneste et al., 2016) and others suggesting rather that attentional processes is the main source of age differences in TBPM (Lecouvey et al., 2017; Varley et al., 2021; Zuber & Kliegel, 2020). Only a recent study by Varley and colleagues (2021) examined experimentally the impact of attentional and temporal processes on TBPM in younger and older adults, suggesting that age differences in TBPM accuracy were due to impairments in attentional processes, rather than time estimation abilities (Varley et al., 2021).

5.2.1. The role of specific task-related factors

The cognitive processes responsible for the age effects in time monitoring and TBPM performance could be affected by other task-related factors, which could potentially moderate the magnitude of the age-related effect associated with TBPM (Bastin & Meulemans, 2002; D'Ydewalle et al., 2001; Einstein et al., 1992; McBride et al., 2011; Meier et al., 2006). For example, some authors highlighted the importance of the duration of the PM target time (i.e.: the time-point indicating that a given action needs to be performed) and the task frequency (i.e.: how many PM task in a TBPM task block). In the literature, many studies used different durations of the PM target time, ranging from 30 seconds to 10 minutes (Bastin & Meulemans, 2002; Gonneaud et al., 2017; Mioni & Stablum, 2014; Vanneste et al., 2016; Waldum & McDaniel, 2016), as well as different paradigms in which the PM task needed to be carried out once (Waldum & McDaniel, 2016) or multiple times (Mioni, Grondin, et al., 2020; Vanneste et al., 2016); however, only few studies investigated the impact of the PM task's duration and frequency on the age-related differences in TBPM (Bastin & Meulemans, 2002; Einstein et al., 1995; McBride et al., 2011; Meier et al., 2006). Yet, it can be very informative to investigate the effect of these task's parameters as they can have direct implications for internal time mechanisms as well as executive and memory processes (Bastin & Meulemans, 2002; Block & Zakay, 2006; Conte & McBride, 2018; Gan & Guo, 2019; Guo & Huang, 2019; Lecouvey et al., 2017; McBride et al., 2011; Varley et al., 2021).

For example, Einstein and colleagues (1995) found that younger adults consistently outperformed older adults on PM tasks, regardless of the duration of the PM target time (Einstein et al., 1995); other studies have also found similar age-related differences in performance with different PM target times, ranging from 1 to 6 minutes (Bastin & Meulemans, 2002; Conte & McBride, 2018; D. C. Park et al., 1997), although one study reported that both younger and older adults had lower accuracy when the PM target time was 1 minute compared to when it was 2 minutes (Bastin & Meulemans, 2002). Interestingly, the authors of this study suggested that a PM target time of 1 minute required more attentional control processes than a target time of 2 minutes, leading to lower accuracy for both younger and older adults. The effects of PM task frequency on age-related differences in TBPM are less clear. The first study that systematically investigated the effect of PM task frequency on aging in TBPM found no significant differences in accuracy and time monitoring between 6- and 12-event PM tasks (D. C. Park et al., 1997). However, a recent study has shown that repeating the same PM task with the same target time can lead to learning effects in younger adults (Gan & Guo, 2019); nonetheless, it is still unclear which processes are responsible for such learning effect, as it could be due either to better distribution of the attentional resources between OT and PM task, or to an improvement of time estimation abilities involved in the monitoring of the PM target time. Moreover, it is currently unknown whether and how the frequency of the TBPM task has similar effects on older adults' performance too.

Another methodological aspect that can affect age-related TBPM differences is the criterion chosen to compute PM accuracy. Typically, PM accuracy is measured as a binary score based on whether participants completed the task within a specified interval around the PM target time. Some studies have used lenient criteria with larger intervals, such as 15% of the whole PM target time interval (e.g.: Mioni & Stablum, 2014), while others used stricter criterion with smaller interval, such as 10% of the whole PM target time (e.g.: Vanneste et al., 2016). There have been a few studies that have explored the impact of different criterion on age-related differences in TBPM. One study found that older adults had more difficulty with TBPM regardless of whether a larger or smaller interval was used for accuracy (D. C. Park et al., 1997). A more recent study contrasted these findings, showing that a larger interval improved TBPM performance for older adults but not for younger adults (Yang et al., 2013). Apart from these few findings, there is currently no systematic investigation on the effect of the criterion of the PM accuracy on age-related differences in TBPM; yet this aspect can have methodological and analytical implications on how PM accuracy is scored and on the magnitude of the age effects.

5.2.2. The present meta-analysis

Overall, the empirical evidence suggested that there are age-related differences in TBPM performance and time monitoring, as measured by laboratory tasks, but it is currently unknown how large the age effect is in time monitoring. Time monitoring has only been assessed in laboratory settings so far, whereas studies measuring time monitoring in naturalistic settings are still missing; although it would be extremely interesting to investigate older adults' clock-checking in naturalistic settings – also considering the age PM paradox[14] – as of today, it is not possible to meta-analyze time monitoring across settings. Hence, this meta-analysis aimed to: (1) quantify age-related differences in TBPM and time monitoring assessed in the laboratory setting, (2) determine if there's a relationship between age effects in TBPM performance and time monitoring, and (3) measure how specific task-related factors (i.e., the duration of the PM target time, the frequency of the PM task, and the interval criterion for correct PM responses) affect age-related differences in TBPM performance and time monitoring. This meta-analysis was the first to quantify the relationship between time monitoring and TBPM performance and explore meta-analytically the potential role of PM task-related factors. It provided a conceptual understanding of the cognitive processes behind the age effect in time monitoring and TBPM performance and offered a methodological framework for future aging research.

5.3. Methods

5.3.1. Search strategy

This systematic review follows the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, Moher et al., 2015). The articles were searched using PsycInfo, PubMed, and Web of Science databases, from the earliest

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[14] Many studies have shown that, in both TBPM and EBPM, younger adults generally perform better than older adults in laboratory tasks, but older adults tend to outperform younger adults in tasks carried out in everyday life (Faytell et al., 2017; Kvavilashvili & Fisher, 2007; Rendell & Thomson, 1999). This age-related difference in performance is known as the *age PM paradox* and presents a significant challenge for aging research in PM (Aberle et al., 2010). There is currently a debate on the nature of such paradox (Bailey et al., 2010; Cauvin et al., 2019; Schnitzspahn et al., 2020), which is out of the scope of this thesis.

available date to the end of October 2022. The following descriptive verbal expressions were used: “prospective memory”, “time-based”, combined with “aging” or “ageing”, and “monitoring”. the meta-analysis has been registered before data coding (Open Science Framework pre-registration DOI: https://doi.org/10.17605/OSF.IO/9JW6X).

5.3.2. Eligibility criteria

For an outline of the search and screening steps, see the PRISMA flow chart (**Figure 4**). Included studies were required to meet the following criteria: (1) had experiments involving young and older adults[15]; (2) used laboratory TBPM tasks, (3) tested PM performance (as sum or proportional accuracy) or time monitoring (as total clock checks), or both, as dependent variable(s), (4) were published in a peer-reviewed, English language journals. The following exclusion criteria were also applied: (a) studies, or single experiments within studies, which included any experimental manipulation of the OT and/or TBPM task, as they could affect OT and PM performance. From these studies, we kept only the data from the TBPM tasks that were not subjected to any experimental manipulation; this choice had been made to ensure that the studies were comparable without the risk of confounding effects related to different experimental manipulations (van Rhee et al., 2015), (b) studies that included clinical samples (Costa et al., 2015; Mioni et al., 2017; Smith-Spark et al., 2017), (c) studies that involved drug interventions and/or ingestion of substances (Behrendt et al., 2015; Costa et al., 2008; Platt et al., 2016), or that manipulated other factors including sleep (Bezdicek et al., 2018; Esposito et al., 2015), (d) experiments that included children,

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[15] Age groups were not defined a-priori because there is no agreement on how to define age groups; indeed, all studies used different age ranges for younger and older adults: hence, we extracted the age groups as they were reported within each study, regardless of the differences in age ranges across studies.

adolescents, and middle-age adults (Nigro et al., 2002; Zöllig et al., 2010), although we kept some studies still eligible, but only when it was possible to extract the data of both younger and older adults leaving out the middle-age group (Bozdemir & Cinan, 2021; Einstein et al., 1995: Experiment 3; Gonneaud et al., 2014; Mäntylä et al., 2009; Zuber et al., 2022). Finally, two studies from the same research group reported different neural measures on the same behavioral results (Morand et al., 2021, 2022), which are therefore redundant; thus, we decided to keep one of them (Morand et al., 2021).

5.3.3. Study selection

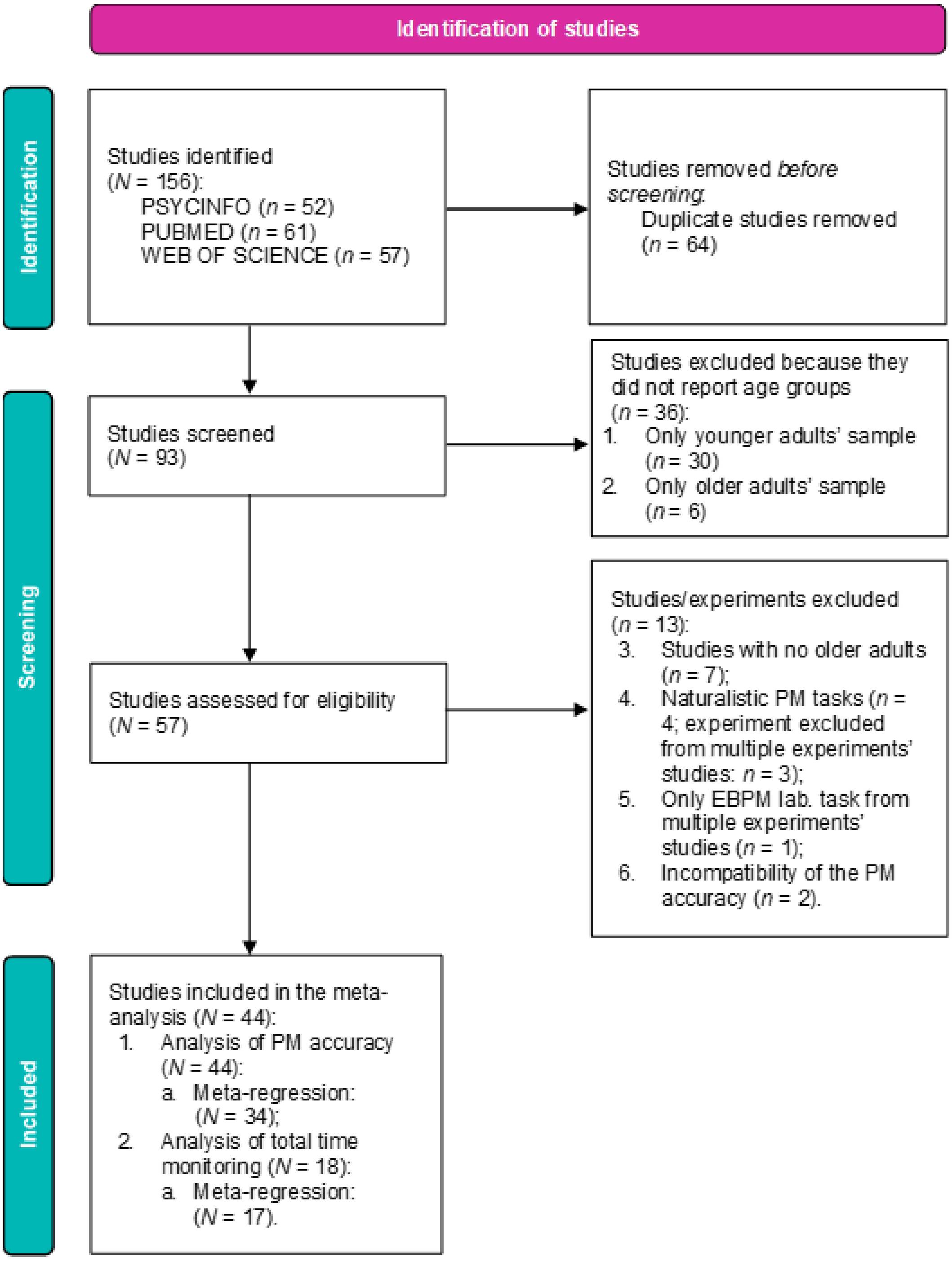
In total, 93 studies were screened; 36 were excluded because they did report only samples of younger (Huang et al., 2014; Khan et al., 2008) or older adults (e.g., Schnitzspahn & Kliegel, 2009; Sullivan et al., 2018), with no age comparisons, so it was not possible to calculate the (age) effect size for these studies. Hence, 56 studies were assessed; seven were excluded because they reported only samples of younger adults (Cona et al., 2012; Cruz et al., 2017; Gonneaud et al., 2014; Haines et al., 2020; Oksanen et al., 2014; Okuda et al., 2007; Tracy et al., 2000). We excluded four studies as they reported only naturalistic assessment of TBPM (Kvavilashvili & Fisher, 2007; Maylor, 1990; McBride et al., 2013; Rendell & Thomson, 1993), as well as single experiments (within 3 studies) that included only naturalistic assessment of TBPM (Aberle et al., 2010: Experiment 2; Niedźwieńska & Barzykowski, 2012: Experiment 2; Rendell & Thomson, 1999: Experiment 1 and 2). One further experiment was excluded as it reported only EBPM task (Einstein et al., 1995: Experiment 2). Concerning the studies with Virtual Week (e.g., Henry et al., 2012; Mioni, Grondin, et al., 2020; Rendell & Craik, 2000), we kept only the stop-clock sub-task, as it comprised comparable TBPM tasks (e.g.: "check lung capacity at 2 and 4 minutes on the clock"), whereas the other subtasks, often referred as "regular" and "irregular", are based on a fictious time-week tasks (e.g.: "remember to call your partner at 4 p.m. to collect photocopies") and, as such, cannot be compared with the outcomes provided by the traditional TBPM paradigm (Einstein et al., 1995).

Many studies did not report the measures necessary for the meta-analysis (for more information on the outcome measures, see the following section); for example, some studies reported a task in which monitoring was (or could have been) measured, but the behavioral data on monitoring were not reported (Lecouvey et al., 2017; Varley et al., 2021). Therefore, we used two alternative sources of information: figure digitalization and author's contact. The figure digitalization has been applied to 16 articles that reported data in the figures, but not in the tables (Altgassen et al., 2010; Bastin & Meulemans, 2002; D'Ydewalle et al., 2001; Einstein et al., 1995; Gonneaud et al., 2011; Henry et al., 2012; Lecouvey et al., 2017; Mäntylä et al., 2009; Martin & Schumann-Hengsteler, 2001; Mioni et al., 2015; Mioni & Stablum, 2014; Rendell et al., 2011; Rendell & Thomson, 1999; Schnitzspahn, Ihle, et al., 2011; Schnitzspahn et al., 2014; Vanneste et al., 2016); therefore, we extracted the data from the figure by digitalization using the software *DigitizeIt* (version 2.5); such software has been proved to be reliable for meta-analytical studies in psychology as well as in other disciplines, showing that the values obtained using the software do not differ from the real data (Rakap et al., 2016; Schild & Voracek, 2013; Wojtyniak et al., 2020).

Seven papers did not report data of TBPM accuracy and/or time monitoring neither in table nor depicted in figures (Aberle et al., 2010; Haines et al., 2020; Rendell et al., 2011; Rendell & Craik, 2000; Rendell & Thomson, 1999; Varley et al., 2021; Zuber et al., 2022). Thus, we contacted the corresponding authors of these articles; all authors replied to the email. However, only in three cases data were available or compatible with the goals of the present meta-analysis (Aberle et al., 2010; Varley et al., 2021; Zuber et al., 2022). Finally, we excluded two studies because they reported incompatible PM accuracy measures, such as time completion of the TBPM task (Waldum & McDaniel, 2016) or deviation of the subjective PM response from objective PM target time (Patton & Meit, 1993). Such choice was made because, in a meta-analysis, it is important to use a consistent measure of the construct of interest across studies to calculate effect sizes (Harrer et al., 2021; Hedges, 1981). The time of task completion and the PM response's deviation are purely temporal measures that (1) do not have a maximum score (as the PM accuracy score), and (2) it is not standardized across different PM target time durations (e.g., the minutes of completion can be problematic as they depend from the duration of the PM target time). The consistent use of a single measure of the construct across studies is essential in meta-analysis to calculate effect sizes; therefore, given that PM accuracy was way more common across studies than the other measures, it was better to use only studies that have standardized PM accuracy to ensure consistency in effect size computation, and to facilitate interpretation of the results. For the analysis on age effects in TBPM performance, 52 unique effect sizes were included, nested in 44 studies; for the analysis on age effects in time monitoring, 20 unique effect sizes were included, nested in 18 studies. The selection from the search results has been executed by the first and the second author in advance; nonetheless, if a full-text review of an article did not result in a clear verdict, the decision on in- or exclusion was made by mutual agreement of all the authors.

Figure 4

PRISMA flow diagram



Note. PRISMA flow diagram of the literature review process for the meta-analysis (up to October 2022); PM: prospective memory.

5.3.4. Statistical analyses

All analyses were carried out in R (version 4.2.1) (R Core Team, 2022) using the packages *metafor* (Viechtbauer, 2010), *meta* (Balduzzi et al., 2019), and *metaSEM* (Cheung, 2015). Data, metadata, and R-code are available in the Open Science Framework (https://doi.org/10.17605/OSF.IO/EPBNK). All analyses were carried out using the standardized mean difference (Hedge's *g*) of TBPM performance (i.e.: proportional accuracy, sum scores, z-values) and total time monitoring (i.e., number of clock checks) as outcome measures (formulas are reported in the Supplementary materials, section 11.2.1). Among the studies included in the meta-analysis, few of them reported multiple effect sizes as a function of PM duration (Bastin & Meulemans, 2002), PM task frequency (D. C. Park et al., 1997), or criterion chosen for the PM accuracy (Yang et al., 2013). Even though these are not the majority of the studies, it is reasonable to assume that some kind of dependency is introduced within the reported data; such dependency was taken into account by integrating a third layer into the structure of the meta-analytic model, resulting in a three-level meta-analysis (Assink & Wibbelink, 2016; Cheung, 2014; Van den Noortgate et al., 2015) with participants (level 1) nested in the individual effect sizes (level 2), which were, in turn, part of a number of larger units, the studies (level 3). Wald-type tests was used to calculate the confidence interval around the pooled effects; the amount of heterogeneity (i.e., τ^2), was estimated using the restricted maximum-likelihood estimator (Viechtbauer, 2005) and it was de-composed into two partitions to account for within- and between-studies sources of heterogeneity simultaneously (Cheung, 2014). In addition to the estimate of τ^2, the Q-test for heterogeneity (Cochran, 1954) and the I^2 statistic (Higgins & Thompson, 2002) are reported. In case any amount of heterogeneity is detected (i.e., $\tau^2>0$, regardless of the results of the Q-test), a prediction interval for the true outcomes is also provided (Riley et al., 2011).

The meta-analysis was carried out in three steps. In the first step, two random-effect models on age effect were carried out separately on time monitoring (18 studies) and TBPM performance (44 studies); the aim of this first analytic step was to pool effect sizes and to quantify age effects and studies heterogeneity; at this level, publication bias analyses using Egger regression (Borenstein et al., 2009, Chapter 30), and outliers and sensitivity analyses were performed too (Viechtbauer & Cheung, 2010). In the second step, a multi-variate model was carried out jointly on time monitoring and TBPM performance; the aim of this model was to investigate the relationship between the age effect in time monitoring and TBPM performance. In the third and final step, we carried out the same multi-variate model as in step 2, but this time we included task-related features as predictors (i.e., duration and frequency of the PM target time, and standardized interval criterion for correct PM responses); the aim of this model was to investigate the relationship between the age effect time in monitoring and TBPM performance, as well as the effect of task-related features on age effects and studies heterogeneity. The duration of the PM target time was stored in a variable that comprised the duration of the PM target time in minutes; the frequency of the TBPM task was the number of times the TBPM task was performed within each task block. Interval for correct PM responses was standardized as ratio between the whole interval and the PM target time in seconds (e.g.: if a study reported as correct answer any response falling within ± 6 seconds for a 2-minute TBPM task, we have computed the value as follows: 6 * 2 / 120 = .10).

5.4. Results

In Tables 4 and 5 are reported the sample characteristics of the eligible studies included in the meta-analysis, predictors (i.e.: duration of the PM target time, frequency of the PM tasks, and criterion for accuracy), as well as effects of age for TBPM accuracy (**Table 4**) and time monitoring (**Table 5**). Overall, the mean age for the samples of younger adults was 23 years (18 – 41), whereas the mean age for the samples of older adults was 69 (51 – 97).

Table 4

Prospective memory performance, sample, and predictors' characteristics of the eligible studies

	Participants								**Predictors**			**Age effect in TBPM accuracy**			
	Younger adults				**Older adults**								***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ** *M* (range)**	***S.D.***	***N***	**Women**	***M* (range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Criterion used for TBPM accuracy**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
Aberle et al. (2010)	20	16	26.25	8.27	40	32	63.26	5.09		10		0.34	-0.28	0.97	1.45%
Altgassen et al. (2010)	40	21	24.73	3.5	40	19	68.7	4.5	2	4	0.05	1.70	1.19	2.21	1.61%
Bastin & Meulemans, (2002)	48	24	23.17 (20 - 30)	2.55	48	24	64.44 (60 - 70)	3.17	2	6	0.05	1.05	0.62	1.47	3.03%
	48	24	23.17 (20 - 30)	2.55	48	24	64.44 (60 - 70)	3.17	1	12	0.1	1.69	1.22	2.15	3.13%
Bozdemir & Cinan (2021)	41	26	22.29 (19 - 30)	2.45	20	10	65.69 (57 - 75)	4.37				1.35	0.86	1.83	1.65%
Cona et al., (2012)	15	10	23.81 (21 - 28)	2.01	47	30	67.77 (60 - 67)	5.41	3	5	0.1	0.75	0.04	1.46	1.33%
Costermans & Desmette (1999)	20	8	22.35	2.52	20		66.15	3.17	7	6	0.02	0.74	0.09	1.38	1.43%
d'Ydewalle et al. (1999)															
(OT: quiz)	60	36	19.35 (18 - 22)		59	37	62.93 (55 - 84)		4	6	0.09	0.55	0.18	0.92	3.65%
(OT: face recognition)	60	36	19.35 (18 - 22)		48	20	62.93 (55 - 84)		4	6	0.09	0.49	0.12	0.85	3.65%
D'Ydewalle et al. (2001)	48	30	20 (18 - 25)		23	12	69 (60 - 86)		2	5	0.25	0.60	0.18	1.01	1.75%

	Participants								Predictors			Age effect in TBPM accuracy			
	Younger adults				Older adults								*Confidence Intervals*		
Study	*N*	Women	*Age* *M* (range)	*S.D.*	*N*	Women	*M* (range)	*S.D.*	Duration of PM target time	Frequency of TBPM task	Criterion used for TBPM accuracy	Hedges' *g*	Lower	Upper	Weight
Einstein et al. (1995) (Experiment 1)	12		(18 - 21)		12		66 (61 - 78)		10	1	0.1	0.94	0.09	1.78	1.50%
	12		(18 - 21)		12		66 (61 - 78)		10	1	0.05	0.69	-0.16	1.51	1.47%
Einstein et al. (1995) (Experiment 3)	36		20.2 (18 - 22)		26		66.3 (61 - 76)		5	6	0.25	0.84	0.31	1.36	1.59%
Gonneaud et al. (2011)	29	14	24.3 (18 - 35)	4.5	23	13	68.2 (60 - 84)	6.7	3	8	0.06	1.34	0.73	1.94	1.48%
Gonneaud et al. (2017)	20	9	25.15 (18 - 35)	5.14	18	12	62.1 (51 - 76)	2.7	0.5		0.23	1.63	0.91	2.34	1.33%
Guimond et al. (2006)	35	16	22 (15 - 29)	5.2	38	19	68 (60 - 85)	6.4		2		1.69	1.16	2.23	1.58%
Haas et al. (2022)	53	41	23.29 (19 - 32)	2.27	38	25	68.2 (60 - 81)	5.77	5	5	0.1	0.86	0.43	1.30	1.72%
Haines et al. (2020) (Experiment 1)	40	30	24.1 (19 - 30)	3.6	31	21	71.6 (65 - 86)	4.9	2	4	0.08	1.23	0.75	1.70	1.66%
Haines et al. (2020) (Experiment 3)	23	14	22.9 (18 - 34)	4.1	20	13	70.6 (60 - 83)	5.5	2	4	0.08	1.55	0.93	2.16	1.47%
Henry et al. (2020)	125	89	22.9 (18 - 30)	3.45	41	28	73.8 (65 - 85)	5.57		8		1.60	1.31	1.88	1.92%
Henry et al. (2012)	48		20.4 (18 - 27)	2.9	30		73.3 (65 - 84)	5.48		4		2.30	1.78	2.82	1.60%
Hering et al. (2014)	30	6	20.87	4.15	30	12	67.7	4.72	3	2	0.33	0.80	0.27	1.32	1.59%

	Participants								**Predictors**			**Age effect in TBPM accuracy**			
	Younger adults				**Older adults**								***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ***M* (range)**	***S.D.***	***N***	**Women**	***M* (range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Criterion used for TBPM accuracy**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
Ihle et al. (2014)	33		20.8 (18 - 26)	2.1	29		65.2 (54 - 74)	4.9	1	10	0.17	1.51	0.95	2.08	1.54%
Jäger & Kliegel (2008)	30	16	24 (18 - 30)	3	32	18	67.1 (58 - 91)	7.2	2	5	0.04	0.94	0.42	1.47	1.59%
Lecouvey et al. (2017)	35	12	24.8	5.7	40	30	65.28	7.49	4	3		1.69	1.12	2.26	1.53%
Logie et al. (2004)	40	19	21.5 (17 - 27)	2.4	40	24	65.6 (54 - 78)	6.7	3	5		0.62	0.18	1.07	1.71%
Mäntylä et al. (2009)	39	21	23.3 (20 - 30)	2.4	40	23	70.2 (64 - 81)	6.3	5	7	0.07	0.36	-0.09	0.80	1.71%
Martin et al. (2003)	40	21	24.8 (22 - 31)	2	20	8	69.3 (60 - 80)	5.6	2	4	0.08	0.56	0.11	1.00	1.71%
Martin & Schumann-Hengsteler (2001)	90	75	24	3.77	38	25	69	5.49	2	6	1	1.03	0.70	1.35	1.86%
Maylor et al. (2002)	30		25.40	4.96	30		67.27	4.24	3	5	0.02	1.10	0.56	1.65	1.57%
McFarland & Glisky (2009)	32				32		74.88 (65+)	5.2	5	8	0.1	-0.32	-0.82	0.17	1.64%
Mioni et al. (2019)	30	26	22.6	4.23	30	23	74.33	5.54	2	8	0.17	2.68	1.98	3.37	1.35%
Mioni et al. (2015)	19	9	29.95 (22 - 27)	1.22	39	22	73.75 (65 - 84)	5.22	2	10	0.17	1.22	0.53	1.90	1.37%
Mioni & Stablum (2014)	76	45	23.11 (19 - 34)	2.58	76	44	70.05	7.47	5	4	0.07	1.14	0.80	1.49	1.84%
	22	12	25.4	5.19	22	10	62.5	6.05	0.5		0.23	1.19	0.55	1.82	1.44%

	Participants								**Predictors**			**Age effect in TBPM accuracy**			
	Younger adults				**Older adults**								***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ***M*** **(range)**	***S.D.***	***N***	**Women**	***M*** **(range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Criterion used for TBPM accuracy**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
Morand et al. (2021)			(18 - 35)				(51 - 76)								
Niedźwieńska & Barzykowski (2012)	63	42	21.56 (19 - 27)	1.94	29	14	68.4 (64 - 74)	3.16	10	4		0.27	-0.11	0.65	1.80%
D. C. Park et al. (1997)	56	39	19.59	2.07	55	28	69.8	5.84	2	6	0.03	0.79	0.40	1.17	3.95%
	56	39	19.59	2.07	55	28	69.8	5.84	2	6	0.06	1.01	0.62	1.41	4.08%
	56	39	19.59	2.07	55	28	69.8	5.84	2	6	0.16	1.45	1.03	1.87	4.15%
Pupillo et al. (2021)	109		19.94 (18 - 27)		103		70.79 (59 - 85)		1	16	0.08	0.97	0.68	1.25	1.92%
Rendell et al. (2011)	30		21.9	3.28	20	16	75	5.72		12		1.88	1.27	2.48	1.48%
Rendell & Craik (2000)	20	16	21.3 (19 - 24)		47		73.34 (61 - 84)		2.5	14	0.13	1.05	0.48	1.61	1.53%
Rendell & Thomson (1999)	126		(18 - 28)		125	87	(60 - 80)		7	1	0.05	0.93	0.70	1.16	1.97%
Schnitzspahn et al. (2020)	31	19	23.71 (20 - 29)	3.07	67	70	67.09 (60 - 70)	4.66	10	2	0.03	0.62	0.06	1.18	1.55%
Schnitzspahn et al. (2014)	64		19.11 (18 - 25)		57		69.79 (59 - 84)		1	4	0.17	1.00	0.63	1.38	1.80%
(Schnitzspahn, Ihle, et al., 2011)	20	16	21.5 (18 - 25)	2.26	59	37	68.55 (61 - 79)	4.66	2	6	0.1	0.83	0.19	1.48	1.42%
Shum et al. (2013)	79	65	21.44 (18 - 33)	4.53	50	23	68.23 (60 - 75)	4.13	5		0.07	0.28	-0.04	0.61	1.86%
(Vanneste et al., 2016)	40	19	22.7	1.74	38	18	69.15	5.99	1	10	0.1	1.54	1.03	2.04	1.63%
Varley et al. (2021)	53		19.32	2.11	40		71.2	7.5	1	3	1	1.05	0.61	1.49	1.72%

	Participants								**Predictors**			**Age effect in TBPM accuracy**			
	Younger adults				**Older adults**								***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ***M*** **(range)**	***S.D.***	***N***	**Women**	***M*** **(range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Criterion used for TBPM accuracy**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
			(17 - 29)				(60 - 97)								
Yang et al. (2013)	25		21.92	0.95	50	23	71.31	3.82	1	5	0.17	1.83	1.27	2.39	2.44%
			(20 - 24)				(60 - 80)								
	25		21.92	0.95	199		71.31	3.82	1	5	1	1.61	1.07	2.16	2.48%
			(20 - 24)				(60 - 80)								
Zuber et al. (2022)	86	67	28.26	6.06	47	0	67.81	7.08	1	6	0.17	0.78	0.41	1.15	1.81%
			(20 - 40)				(60 - 86)								
Combined effect size												**1.06**	**0.90**	**1.23**	

Note. Sample characteristics of the eligible studies included in the meta-analysis, and predictors variables (i.e.: duration – in minutes – of the PM target time, frequency of the prospective memory tasks, criterion for accuracy), as well as the age effect (Hedges' *g*) on time-based prospective memory accuracy. The list of studies is sorted alphabetically by the name of the first author. Bastin & Meulemans (2002), Einstein et al. (1995, Experiment 1), Park et al. (1997), and Yang et al. (2013) reported distinct accuracy measures on the same sample computed using different intervals for accuracy; d'Ydewalle et al. (1999) reported two measures of time-based prospective memory accuracy: the first one was computed while people performed a quiz as ongoing task, and the second one was computed while people performed a face recognition test as ongoing task. TBPM: time-based prospective memory; OT: ongoing task.

Table 5

Time monitoring, sample, and predictors' characteristics of the eligible studies

	Participants								**Predictors**		**Age effect in time monitoring**			
	Younger adults				**Older adults**							***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ***M*** **(range)**	***S.D.***	***N***	**Women**	***M*** **(range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
Altgassen et al. (2010)	40	21	24.73	3.5	40	19	68.7	4.5	2	4	0.75	0.3	1.21	4.19%
Bastin & Meulemans (2002)	48	24	23.17 (20 - 30)	2.55	48	24	64.44 (60 - 70)	3.17	2	6	0.45	0.04	0.85	14.19%
	48	24	23.17 (20 - 30)	2.55	48	24	64.44 (60 - 70)	3.17	1	12	0.45	0.04	0.85	14.19%
Cona et al., (2012)	15	10	23.81 (21 - 28)	2.01	47	30	67.77 (60 - 67)	5.41	3	5	0.91	0.19	1.63	3.22%
Costermans & Desmette (1999)	20	8	22.35	2.52	20		66.15	3.17	7	6	0.14	-0.48	0.76	3.58%
Einstein et al. (1995) (Experiment 1)	12		(18 - 21)		12		66 (61 - 78)		10	2	0.76	-0.07	1.59	2.85%
Einstein et al. (1995) (Experiment 3)	36		20.2 (18 - 22)		26		66.3 (61 - 76)		5	6	0.49	-0.02	1.01	3.99%
Gonneaud et al. (2011)	29	14	24.3 (18 - 35)	4.5	23	13	68.2 (60 - 84)	6.7	3	8	0.38	-0.17	0.93	3.83%
Hering et al. (2014)	30	6	20.87	4.15	30	12	67.7	4.72	3	2	0.79	0.26	1.32	3.93%
Ihle et al. (2014)	33		20.8 (18 - 26)	2.1	29		65.2 (54 - 74)	4.9	1	10	1.17	0.62	1.71	3.87%

	Participants								**Predictors**		**Age effect in time monitoring**			
	Younger adults				**Older adults**							***Confidence Intervals***		
Study	***N***	**Women**	***Age*** ***M* (range)**	***S.D.***	***N***	**Women**	***M* (range)**	***S.D.***	**Duration of PM target time**	**Frequency of TBPM task**	**Hedges' *g***	**Lower**	**Upper**	**Weight**
Logie et al. (2004)	40	19	21.5 (17 - 27)	2.4	40	24	65.6 (54 - 78)	6.7	3	5	1.04	0.57	1.51	4.14%
Mäntylä et al. (2009)	39	21	23.3 (20 - 30)	2.4	40	23	70.2 (64 - 81)	6.3	5	7	-0.87	-1.33	-0.41	4.18%
Maylor et al. (2002)	30		25.4	4.96	30		67.27	4.24	3	5	0.73	0.21	1.25	3.94%
McFarland & Glisky (2009)	32				32		74.88 (65+)	5.2	5	8	0.26	-0.23	0.75	4.06%
Mioni & Stablum (2014)	76	45	23.11 (19 - 34)	2.58	76	44	70.05	7.47	5	4	0.33	0.01	0.65	4.67%
Mioni et al. (2019)	30	26	22.6	4.23	30	23	74.33	5.54	2	8	1.97	1.36	2.59	3.59%
Schnitzspahn et al. (2014)	64		19.11 (18 - 25)		57		69.79 (59 - 84)		1	4	0.56	0.19	0.92	4.53%
Vanneste et al. (2016)	40	19	22.7	1.74	38	18	69.15	5.99	1	10	0.59	0.14	1.05	4.19%
Varley et al. (2021)	53		19.32 (17 - 29)	2.11	40		71.2 (60 - 97)	7.5	1	3	0.66	0.24	1.08	4.32%
Zuber et al. (2022)	86	67	28.26	6.06	47	0	67.81	7.08	1	6	0.41	0.05	0.77	4.53%
Combined effect size											**0.58**	**0.31**	**0.85**	

Note. Sample characteristics of the eligible studies included in the meta-analysis, and predictors variables (i.e.: duration – in minutes – of the PM target time, and frequency of the prospective memory tasks), as well as age effect (Hedges' *g*) on time monitoring (as total clock checks). The list of studies is sorted alphabetically by the name of the first author. Bastin & Meulemans (2002) reported the same values of monitoring averaged for two different frequency of the prospective memory task (6 vs. 12), and different durations of the target time (1-minute vs. 2-minutes); hence, we decided to duplicate these values and assign each of them for each of the two values of the respective predictors (i.e., duration of the target time, frequency of the prospective memory task, and intervals for accuracy), thus measuring the moderating contribution of the predictors on the age effect in prospective memory performance (see Results for more information); TBPM: time-based prospective memory.

5.4.1. *Age effects & sensitivity analyses*

For the random-effect model of TBPM performance, a total of $k = 52$ unique effect sizes were included in the analysis, which were nested into 44 unique studies. The observed standardized mean differences ranged from –.324 to 2.675; most estimates were positive (96%; i.e.: younger adults performed better than older adults at the TBPM task). The estimated average standardized mean difference based on the random-effects model was $g = 1.064$ (95% CI: .904 to 1.224); the average outcome differed significantly from zero ($z = 13.41$, $p < .001$). The forest plot shows the observed outcomes and the estimate based on the random-effects model (**Figure 5A**). According to the Q-test, the true outcomes appear to be heterogeneous ($Q(50) = 240.531$, $p < .001$); the source was related almost exclusively to the between-studies heterogeneity ($\tau^2_{\text{between-studies}} = .188$, $I^2_{\text{between-studies}} = 66.39\%$) rather than to within-studies heterogeneity ($\tau^2_{\text{within-studies}} = 0.042$, $I^2_{\text{within-studies}} = 14.90\%$). A 95% prediction interval for the true outcomes is given by .08 to 2.04. Hence, even though there may be some heterogeneity, the true outcomes of the studies are generally in the same direction as the estimated average outcome. However, the forest plot suggested that there are some extreme studies' values that contributed substantially to the heterogeneity; thus, a parallel analysis of the outliers was needed.

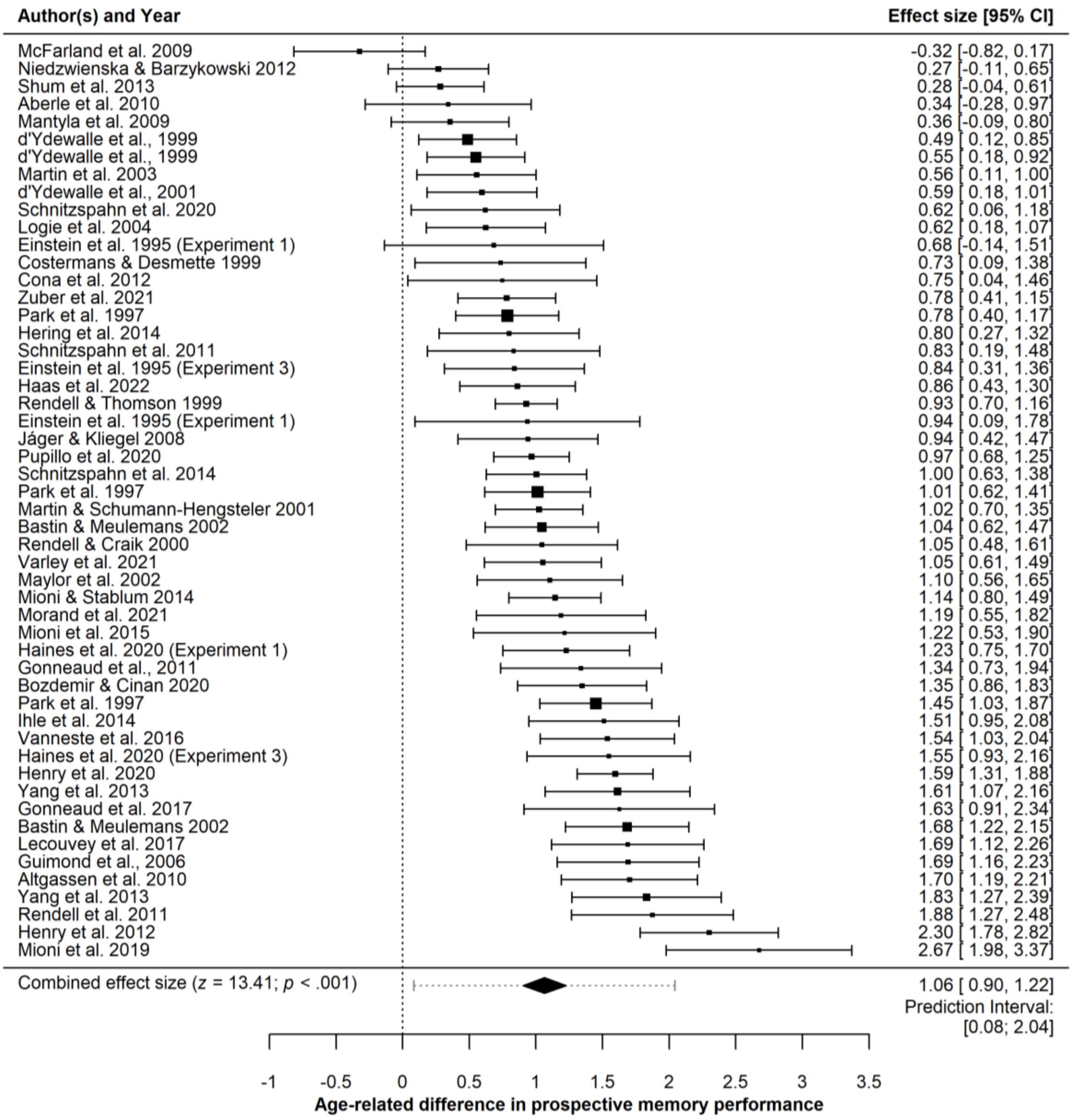
For the random-effect model of time monitoring, a total of $k = 20$ unique effect sizes were included in the analysis, which were nested into 18 unique studies. The observed standardized mean differences ranged from -.869 to 1.974; most estimates were positive (94%; i.e.: younger adults checked the clock more often than older adults). The estimated average standardized mean difference based on the random-effects model was $g = .587$ (95% CI: .333 to .842); the average outcome differed significantly from zero ($z = 4.85$, $p < .001$). The forest plot shows the observed outcomes and the estimate based on the random-effects model (**Figure 5B**). According to the Q-test, the true outcomes appear to be heterogeneous ($Q(19) = 76.068$, $p < .001$); and such heterogeneity was related exclusively to the between-studies differences ($\tau^2_{\text{between-studies}} = .213$, $I^2_{\text{between-studies}} = 78.86\%$) rather than to differences within the studies ($\tau^2_{\text{within-studies}} < .001$, $I^2_{\text{within-studies}} < 1\%$). A 95% prediction interval for the true outcomes is given by −.41 to 1.59. Hence, although the average outcome is estimated to be positive, in some studies the true outcome may in fact be negative.

Egger statistic was not significant for TBPM accuracy ($z = 1.92$, $p = .055$) and time monitoring ($z = 1.43$, $p = .153$), indicating no publication bias. However, 11 studies were identified as outliers for TBPM performance (Bastin & Meulemans, 2002; d'Ydewalle et al., 1999; Henry et al., 2012, 2020; Mäntylä et al., 2009; McFarland & Glisky, 2009; Mioni, Grondin, et al., 2020; Niedźwieńska & Barzykowski, 2012; Rendell et al., 2011; Shum et al., 2013; Yang et al., 2013), while 2 studies were identified as outliers for time monitoring (Mäntylä et al., 2009; Mioni, Grondin, et al., 2020); thus, sensitivity analyses were carried out to investigate the contribution of outliers on either the combined effect size and/or on studies heterogeneity. To achieve this purpose, two separate three-level random-effect models were carried out excluding outliers, one for age effects in TBPM performance, and one for the age effects in time monitoring (Harrer et al., 2021). The model on the TBPM performance without outliers showed that the I^2 heterogeneity shrank considerably when outliers were excluded (from $I^2 = 66.39\%$ to $I^2 = 46.10\%$; $Q(41) = 69.601$, $\tau^2 < .01$, $p = .002$); the pooled age effect ($g = 1.055$) was very close to the age effect in the model with outliers ($g = 1.064$). Concerning the time monitoring, the analysis without outliers showed that the I^2 heterogeneity shrank considerably when the two outliers were excluded (from I^2 = 78.86% to 12.81%; $Q(17) = 19.03$, $\tau^2 < .001$, $p = .329$). The pooled age effect ($g = .573$) was not so different from the model with outliers ($g = .587$). In summary, it is possible to argue that removing outliers did not change the average age effect size of TBPM performance and time monitoring, but it affected the heterogeneity in the data substantially (for detailed information about the publication bias, outliers and sensitivity analyses, see Supplementary material, section 11.2.1.1).

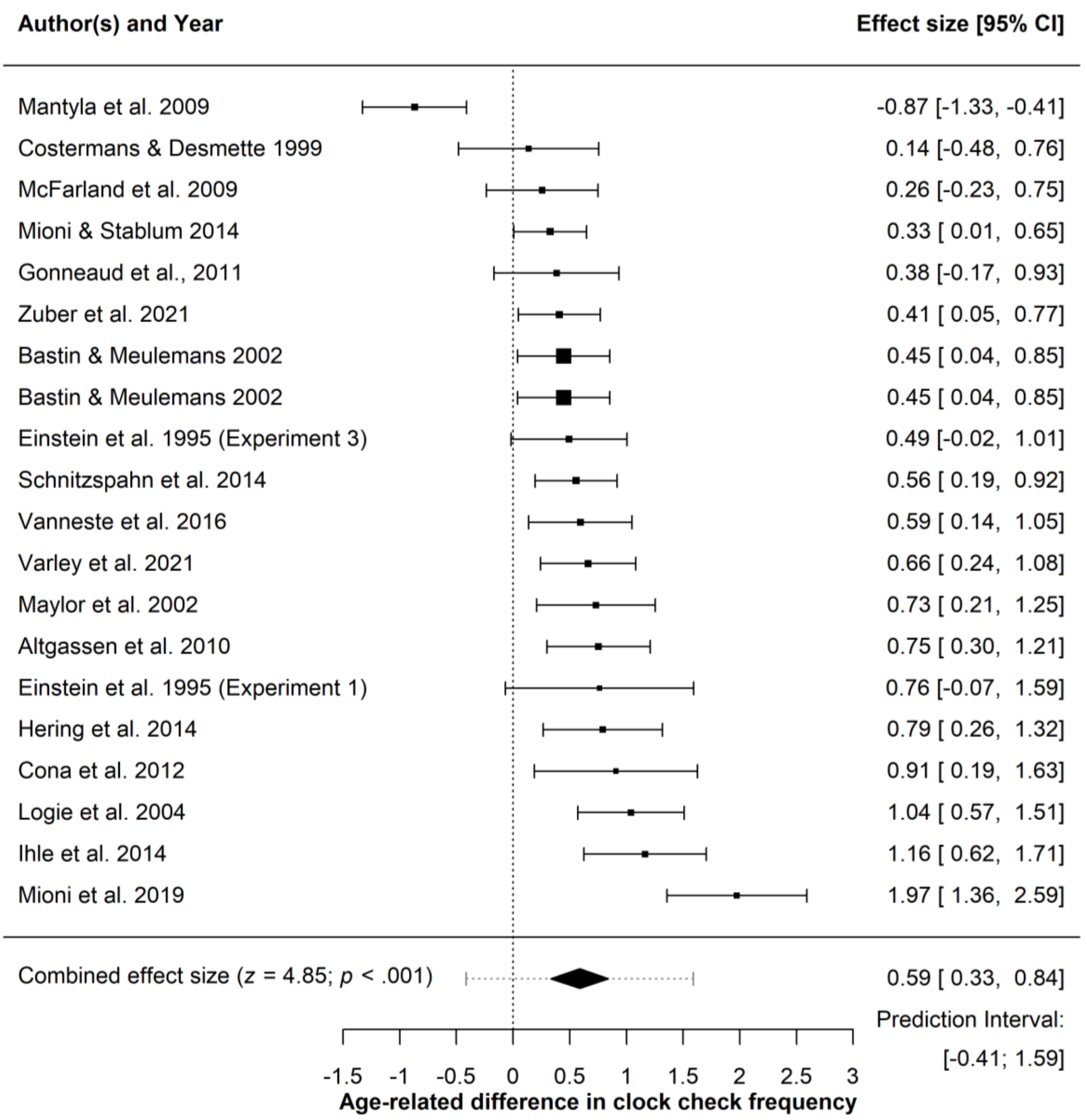
Figure 5

Age effects in time-based prospective memory performance and time monitoring

A) Time-based prospective memory



B) Time monitoring



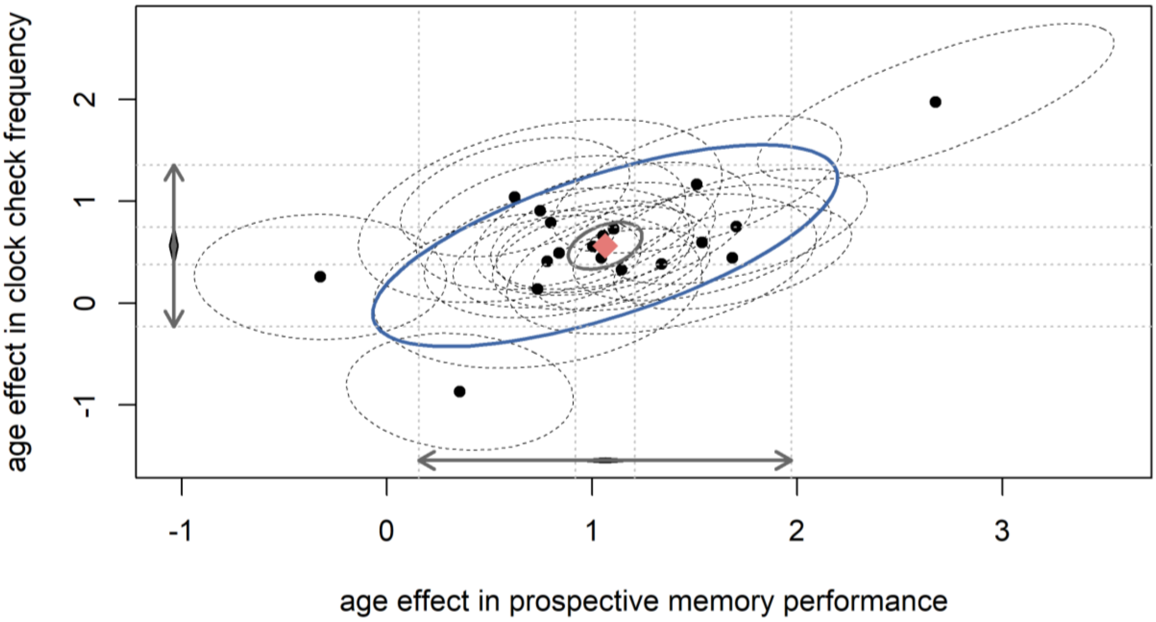
Note. Quantitative summary illustrating the combined effect sizes (Hedges' *g*) of age differences in time-based prospective memory performance and time monitoring. Concerning time-based prospective memory performance (A), points to the right of zero indicated negative effect of age (i.e.: younger adults performing better than the older adults); concerning time monitoring (B), points to the right of zero indicated negative effect of age (i.e.: younger adults checked the clock more frequently than the older adults). In both forest plots, the size of the circles indicates the relative weight assigned to that study in the analysis. Error bars represent the 95% confidence interval of the effect size of each study and, below them, the combined effect size is reported with its confidence interval (the black diamond) and its prediction interval (the dotted line). Studies are sorted in ascending order by effect size.

5.4.2. Association between age effects in time-based prospective memory performance & time monitoring

Multivariate meta-analytic approaches can quantify the relationship between age effects in time monitoring and TBPM performance by estimating the effect sizes for both outcomes jointly in one model; moreover, such approach can be used to determine if studies with a high effect size on one outcome also have higher effect sizes on the other outcome. To achieve this, the multivariate meta-analysis was carried out taking into account the correlation between the age effects (for more detailed information, see Supplementary material, section 11.2.1.2); however, among the studies that were included in this meta-analysis, only 3 reported correlations between time monitoring and TBPM performance, separately for younger (r = .42, .55, and .56) and older adults (r = .51, .69, and .71). Therefore, we have calculated the correlation between age effects in the two outcomes by transforming the effect sizes into Pearson's r coefficients (detailed formulas and procedures are reported in the Supplementary material, section 11.2.1.2). According to the multi-variate analysis, the age effects were $g_{\text{TBPM perf.}} = 1.064$ and $g_{\text{time monit.}} = .565$; both effect sizes were statistically significant ($p > .001$). According to the Q-test, the true outcomes appear to be heterogeneous ($Q(69) = 309.406$, $p < .001$), especially for TBPM performance ($\tau^2 = .214$, $p < .001$), and less for time monitoring ($\tau^2 = .164$, $p = .117$); moreover, the heterogeneity introduced by the relationship between the two outcomes was not significant ($\tau^2 = .126$, $p = .071$). The values of I^2 indicated high between-study heterogeneity in both outcomes ($I^2_{\text{TBPM perf.}} = 80.17\%$; $I^2_{\text{time monit.}} = 74.16\%$). The correlation between age effects on TBPM performance and time monitoring was $r = .67$, suggesting that there was a positive association between the age effect on time monitoring and its effect on TBPM performance (**Figure 6**); in other words, studies that found higher age effects in time monitoring seem to find higher age effects in TBPM performance too.

Figure 6

Association between age effects in time-based prospective memory performance and time monitoring



Note. Effect sizes and confidence ellipses for age differences in time-based prospective memory performance and total time monitoring. The x-axis displays the age effect in time-based prospective memory performance, while the y-axis displays the age effect in time monitoring. Along each respective axis, the pooled age effect and its 95% confidence interval is represented black diamonds; the bi-directional rows along each axis indicate the prediction intervals for each outcome. In the middle of the plot, the pooled effect of both variables is shown as a red diamond; the smaller dark-grey ellipse represents the 95% confidence interval of the pooled age effects, while the larger blue ellipse depicts the 95% prediction interval.

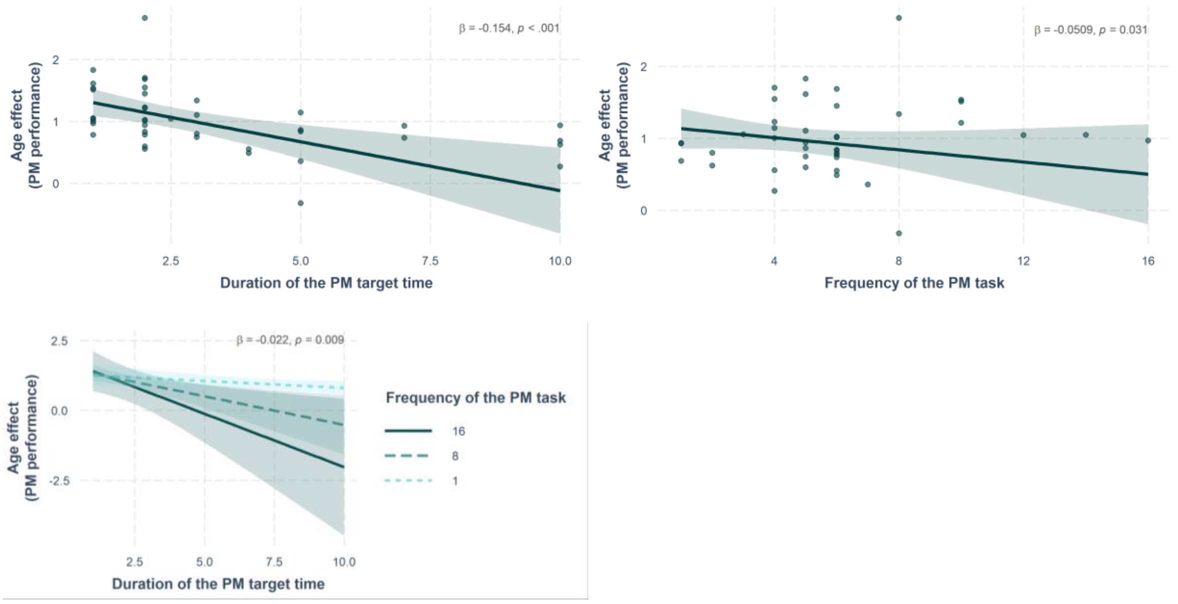
5.4.3. Effect of predictors

The multi-variate meta-regression model was carried out with three task-related features as continuous predictors: (1) the duration of the PM target time (i.e.: the delay of the PM cue in minutes), (2) the PM task frequency (i.e.: how many PM task in a TBPM task block), and (3) arbitrary criterion chosen to compute PM accuracy. The aims of this model were (1) to investigate whether these predictors were linearly associated with the (age) effect size in both TBPM performance and time monitoring, and (2) to establish whether predictors accounted for (some of) the between-studies heterogeneity introduced by the presence of the outliers, which were included in this model. According to the multi-variate analysis, the age effect sizes when predictors were set to their means were $g = .883$ and $g = .396$; both effect sizes were statistically significant ($p >$ .001). According to the Q-test, the true outcomes appear to be heterogeneous ($Q(57) = 202.933$, $p < .001$); however, such heterogeneity was explained by between-studies variance introduced from the variance in the TBPM performance ($\tau^2 = .075$, $p = .03$), but not from the variance in time monitoring ($\tau^2 = .067$, $p = .246$), as well as from the variance in the relationship between the two outcomes ($\tau^2 = .043$, $p = .329$). Indeed, predictors explained the most of the variance of the age effect in TBPM performance ($r^2 = 64.79\%$); specifically, the model indicated that longer durations of target time were associated with a reduction of the age effect in TBPM performance ($\beta = -.15$; $p < .001$; **Figure 7A**, upper left panel); similarly, higher PM task frequency was associated with a reduction of the age effect in TBPM performance ($\beta = -.05$; $p = .031$; **Figure 7A**, upper right panel). Finally, there was a significant negative interaction between duration of the PM target time and PM task frequency ($\beta = -.02$; $p = .009$), meaning that the longer the frequency task duration, the stronger was the effect of the PM target time duration in reducing age differences in TBPM performance (**Figure 7A**, lower panel). Similarly with the results on TBPM performance, predictors explained most of the variance of the age effect in time monitoring too (r^2 = 59.36%). Specifically, the model indicated that longer durations of target time were associated with a reduction of the age effect in time monitoring (β = −.11; *p* = .014; **Figure 7B**, upper left panel); moreover, while the main effect of PM task frequency (β = −.07; *p* = .110; **Figure 7B**, upper right panel) was not significant, there was a significant interaction between duration of the PM target time and PM task frequency (β = −.032; *p* = .026, **Figure 7B**, lower panel). The model indicated that the interval criterion for PM accuracy did not exert any significant effect on both TBPM performance (β = −.009; *p* = .948) and time monitoring (β = .355; *p* = .177). The correlation between age effects on TBPM performance and time monitoring was *r* = .61, suggesting that there was a positive association between the age effect on time monitoring and its effect on TBPM performance.

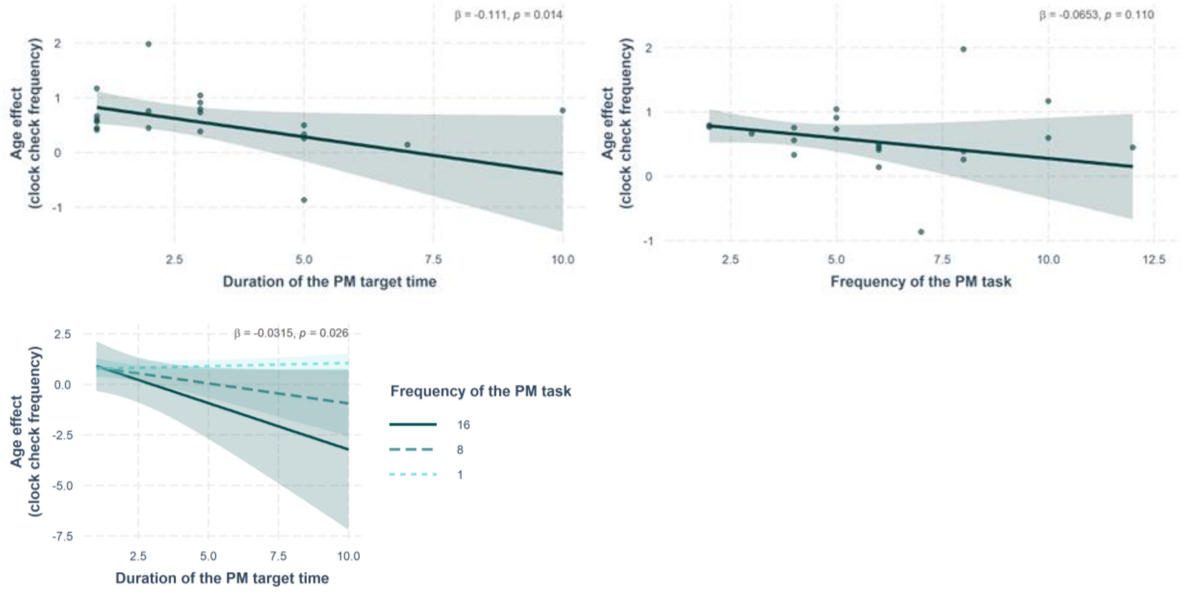
Figure 7

Age effect as function of PM target time's duration and PM task frequency

A) Time-based prospective memory



B) Time monitoring



Note. Graphical representation of age differences in time-based prospective memory performance (A) and time monitoring (B) as function of target time's duration and frequency of the prospective memory task; PM: prospective memory.

5.5. Discussion

The present meta-analysis aimed (1) to quantify age-related differences in TBPM and time monitoring among studies that used laboratory tasks, (2) to estimate the relationship between age effects in both TBPM performance and time monitoring, in order to determine if studies with a high effect size on one outcome also have higher effect sizes on the other outcome, and (3) to measure whether and how specific task-related factors (i.e., the duration of the PM target time, the frequency of the PM task, and the interval criterion for correct PM responses) affect age-related differences in TBPM performance and time monitoring. The meta-analysis comprised 44 studies reporting compatible measures of PM performance (sum or proportional accuracy); 18 of which reported measures of total time monitoring.

5.5.1. Overview of the results

In summary, the meta-analysis found that younger adults performed better than older adults in TBPM tasks (*g*: 1.06; **Figure 5A**). This result is in line with the previous meta-analysis showing a negative effect of age in laboratory TBPM task, with an effect size of .39 (Henry et al., 2004). Our larger effect size might be due to the number of studies: while Henry and colleagues (2004) included 6 studies, we included 44 studies; this huge difference is due to the increasing number of studies in the last 15 years, which in turn affect the magnitude of the age effect (Hak et al., 2016). We also found that younger adults checked the clock more often than older adults (*g*: .59; **Figure 5B**); however, there was substantial unexplained heterogeneity, which dropped considerably when outliers were removed (i.e., from I^2=66.39% to 46.10%, and from I^2=78.86% to 12.81%, for TBPM performance and time monitoring, respectively; see Supplementary material, section 11.2.1.1, for more information). The results from the multi-variate model showed that studies finding significant age effects in TBPM performance seemed to have 67% of probability to find significant age effects in time monitoring too, suggesting that there is a strong relationship between age effects in the two outcomes (**Figure 6**). The meta-regression analysis showed that the duration of the PM target time was negatively related to age effects in both TBPM performance and time monitoring (**Figure 7A** and **Figure 7B**, upper left panels), and PM task frequency was negatively related to the age effect in TBPM performance (**Figure 7A**, upper right panel) but not in time monitoring (**Figure 7B**, upper right panel). For both time monitoring and TPM performance, a significant negative interaction between PM task frequency and duration of the PM target time was found, indicating that the negative relationship between age effects and duration of the PM target time was more pronounced for task blocks with multiple PM cues compared to 1- (single-item) PM task blocks (**Figure 7A** and **Figure 7B**, lower panels). Interestingly, this model seemed to explain the between-studies heterogeneity introduced by the outliers, as shown by the τ^2 which was considerably reduced in this model compared to the one without predictors (i.e., from $\tau^2 = .214$ to $\tau^2 = .075$ for TBPM performance, and from $\tau^2 = .164$ to $\tau^2 = .067$ for time monitoring).

5.5.2. Conceptual and methodological implications

As mentioned above, time monitoring is essential for TBPM accuracy (Ceci & Bronfenbrenner, 1985; Harris & Wilkins, 1982; Mäntylä et al., 2006; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016); yet, the cognitive processes underlying age differences in time monitoring and TBPM are still an open debate. Some authors argued that age-related impairments are related to time estimation ability, especially involved in time monitoring (Labelle et al., 2009; Mioni & Stablum, 2014; Vanneste et al., 2016), whereas others argued that attentional processes, such as task-switching, are responsible for age differences in TBPM (Lecouvey et al., 2017; Varley et al., 2021; Zuber & Kliegel, 2020). Other authors argued that shorter PM target times (≤ 2 minute) involved more attentional control processes (e.g., task switching) than longer PM target times (> 2 minute; Bastin & Meulemans, 2002a; Conte & McBride, 2018). This argument was confirmed by a recent study showing that age differences in a 1-minute TBPM task were due to impairments in attentional processes (Varley et al., 2021). Nonetheless, it is not clear yet whether and how the duration of the PM target time affect attention and/or time estimation processes in aging (Block & Zakay, 2006; Mioni & Stablum, 2014). The average duration of the PM target time in the studies included in the meta-analysis was 4 minutes, ranging from 30 seconds (Gonneaud et al., 2017; Morand et al., 2021) to 10 minutes (Einstein et al., 1995; Niedźwieńska & Barzykowski, 2012). The results showed that younger adults were more accurate and checked the clock more frequently in the TBPM task, especially for shorter intervals (less than 4 minutes). It's possible that the age differences for shorter intervals are due to the involvement of attentional control processes (Conte & McBride, 2018) that are particularly impaired with aging (Craik, 1986; Varley et al., 2021). Diversely, longer PM target times (i.e., ≥ 4 minutes) may either allow more time to better distribute the attentional resources between OT and PM task, as well as engage more time estimation abilities compared to short PM target times, reducing the age differences in time monitoring and TBPM accuracy (Mioni, Capizzi, et al., 2020; Mioni et al., 2021; Varley et al., 2021).

Among the studies included in the present meta-analysis, the frequency of PM target time ranged from 1 (Rendell & Thomson, 1999) to 16 (Pupillo et al., 2021; Shum et al., 2013). The meta-analysis showed that PM task frequency had a selective effect on TBPM performance, but not on time monitoring. Age differences in TBPM performance were influenced by PM task frequency, especially when the PM target time was longer, suggesting that learning from task repetition could counteract or reduce age effects. PM task frequency had no effect on age differences in time monitoring, indicating that these differences are not influenced by task repetition but by PM target time duration; however, this last finding should be taken carefully as there were fewer studies that measures time monitoring (i.e., 18) and thus fewer observations of these effects as for TBPM accuracy, for which there were more studies (i.e., 44); therefore, it is not possible to fully exclude the presence of learning effects in time monitoring too. Indeed, age differences in time monitoring were reduced by PM task frequency, but only when the PM target time was longer, suggesting that learning from task repetition could counteract or attenuate age effects in time monitoring which, in turn, affect age differences in TBPM performance. Future studies are needed to investigate this specific effect experimentally.

The current meta-analysis has several important methodological implications for the design and interpretation of future studies in the field. Firstly, with regards to the design of future tasks, the results of the meta-analysis showed that age effects in TBPM performance and time monitoring were significant when the TBPM task consisted of 6 PM target times, lasting 4 minutes each. As such, future studies that aim to detect age differences in TBPM should replicate these parameters. It is important to note that these parameters can be changed based on the specific research needs; yet researchers should be aware that changing the number of cues and target time duration can impact the magnitude of age effects, and this may be reflective of different cognitive mechanisms, such as task-switching and time estimation, which may interact with learning processes. Another methodological implication concerns the criterion used to determine TBPM accuracy and its impact on age differences in TBPM performance and time monitoring (Yang et al., 2013). The studies included in the meta-analysis used a wide range of interval criteria, ranging from 2% (Costermans & Desmette, 1999) to 100% (Haas et al., 2020; Martin & Schumann-Hengsteler, 2001; Varley et al., 2021; Yang et al., 2013) of the total PM target time. Despite this variability, the results of the meta-analysis showed that age differences were detected regardless of the interval criterion chosen by the researchers, indicating that the TBPM paradigm is robust for studying age effects. As such, the choice of criterion for PM accuracy should not be a concern for researchers, as significant age differences are likely to emerge regardless of the criterion used. Furthermore, the meta-analysis highlights the importance of including measures of time monitoring in any TBPM experiment because it is highly correlated with TBPM and essential for understanding the cognitive processes underlying TBPM performance, as supported by previous research that has demonstrated the close relationship between time monitoring and TBPM (Ceci & Bronfenbrenner, 1985; Harris & Wilkins, 1982; Mäntylä et al., 2006; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016).

Finally, age effects in TBPM performance and time monitoring can be interpreted into the broader context of aging in human memory (Bopp & Verhaeghen, 2005). Specifically, while recollection is disrupted by aging, recognition is usually spared (Yonelinas, 2002). These differences in memory recollection are not solely due to the size of the hippocampus (Van Petten, 2004), but may also be determined by compensatory frontally-mediated executive functions that are engaged in self-initiated processes involved in memory recall (Cabeza et al., 2018; Craik, 1986; West, 1996). In line with such explanation, TBPM has been shown to be particularly difficult for older adults as it requires similar self-initiated processes (Lewis-Peaclock et al., 2016; Martin-Ordas et al., 2010; McDaniel et al., 2015), involving executive functions and cognitive control processes (Cruz et al., 2017; Zuber & Kliegel, 2020) that are particularly impaired in aging (Cabeza et al., 2018; Craik, 1986; West, 1996). However, recent meta-analysis (Fraundorf et al., 2019) challenged the explanation of self-initiated processes being the only source of age-related differences in memory performance (Craik, 1986; West, 1996), as age effects can also be observed in recognition, which presumably should not involve frontally-mediated executive functions (McDaniel et al., 2015; Yonelinas, 2002; Yonelinas et al., 2010). Therefore, it is still unclear whether the age-related deficit reflects a general deficit related to self-initiated processes that affects globally all memory tasks, and further studies are needed to understand this aspect related to aging in human memory.

5.5.3. Limitations & future directions

The present meta-analysis has some limitations. The first limitation concerns the lack of analysis on the strategic aspects of time monitoring, which can be investigated measuring monitoring over time. Several studies have shown that people usually check the clock few times as the task starts, and then increase the number of clock checks as the PM target time approaches, forming a “J-shaped” curve (Labelle et al., 2009; Mäntylä et al., 2006; Mioni, Grondin, et al., 2020; Vanneste et al., 2016); such strategic behavior is associated with better PM accuracy (Ceci & Bronfenbrenner, 1985; Harris & Wilkins, 1982; Mäntylä et al., 2006; Mioni et al., 2012; Mioni, Grondin, et al., 2020; Vanneste et al., 2016; Waldum & McDaniel, 2016). A recent study disentangled the respective contribution of total versus strategic time monitoring to the age differences in TBPM performance. The authors proposed a more fine-grained indicator of strategic behavior (i.e., *relative clock-checking*), which accounts for interindividual differences in the total frequency of clock checks (i.e*., absolute clock-checking*). The results showed that both relative and absolute clock-checking fully mediated the negative age effect on TBPM; yet, relative clock-checking was a stronger predictor of TBPM performance than absolute clock-checking (Joly-Burra et al., 2022). In the present meta-analysis, we could not code monitoring over time given that each study used different PM target times and analyzed monitoring using different intervals, according to the specific research needs. Thus, any inference on strategic time monitoring should be taken carefully considering these current meta-analytic results, and future studies are needed to investigate the strategic aspect of time monitoring. Another limitation is the lack of comparison between laboratory and naturalistic setting (Cauvin et al., 2019; Haas et al., 2020; Kvavilashvili & Fisher, 2007; Maylor, 1990; McBride et al., 2013; Rendell & Thomson, 1993). As mentioned in the introduction, we decided to focus only on laboratory tasks because, as far as known by the authors, there are no studies in the literature that have developed a method for measuring time monitoring in naturalistic settings; hence, considering the relevant role of time monitoring in TBPM, we decided to focus only on laboratory studies. However, with the development of new technologies, such as electronic pads and smartwatches, future studies could develop an experimental protocol to measure time monitoring in naturalistic contexts, allowing future meta-analytic comparisons between laboratory and naturalistic assessments.

Finally, it is also possible that other factors, such as cognitive demands and stimulus material of the OT, may have influenced the results. Indeed, the multivariate analysis with the predictors showed that there was a small but still significant portion of unexplained variance in the age effect in TBPM performance ($\tau^2 = .078$, $p = .04$); it cannot be excluded that such unexplained variance could be due to different OTs. Most of studies in the meta-analysis used traditional cognitive tasks such as working memory (Pupillo et al., 2021; Zuber et al., 2022) or arithmetic tasks (D'Ydewalle et al., 2001; Gonneaud et al., 2011); others used more passive OT such as watching a movie (Logie et al., 2004; Mioni & Stablum, 2014), whereas few studies used alternative OTs such as trivia or jigsaw puzzle (Einstein et al., 1995; Waldum & McDaniel, 2016); some studies used even different OTs across TBPM task blocks (d'Ydewalle et al., 1999; Niedźwieńska & Barzykowski, 2012). Our analysis did not examine the specific nature of the OT, but it cannot be excluded that these factors could also influence age effects in TBPM (D'Ydewalle et al., 2001; Khan et al., 2008; Meier & Zimmermann, 2015). Moreover, it is also possible that PM task frequency and/or the duration of the PM target time were related to the nature of the OT. Future research should consider conducting a more in-depth examination of the role of OT typology in time monitoring and TBPM performance, to provide a clearer understanding of the relationships between this further factor and age-related changes in TBPM.

5.6. Conclusions

Overall, this meta-analysis provided an update on age differences in TBPM accuracy and their potential effect size (Henry et al., 2004), as well as a first meta-analytic quantification of the age difference in time monitoring, investigating the contribution of task-related features, namely the duration of the PM target time, the frequency of the PM task, and the criterion of PM accuracy. Our meta-analytical results have both conceptual and methodological implications. Conceptually, the results of the meta-analysis suggested that the age effect emerged consistently for shorter (e.g., ≤ 4 minutes) rather than longer intervals, probably because of age-related impairment in the attentional processes. Moreover, the effect of the PM target time's duration interacted with the frequency of the PM task, suggesting that there might be some learning effects that can attenuate the magnitude of age effects, especially for longer durations. Concerning the possible methodological implications, it is reasonable to argue that, regardless how researchers code accuracy, TBPM paradigm can detect age-related differences consistently; yet researchers should be aware that changing task-related parameters such as the frequency of the PM task and the duration of the PM target time can affect the magnitude of the age effect in both time monitoring and TBPM performance. In summary, the present meta-analysis can help the conceptual understanding of the cognitive processes underlying age effect in time monitoring and TBPM performance, also providing a methodological framework that can guide future aging research.

6. Study 3[16]:

The cost of monitoring in time-based prospective memory

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[16] Article currently under review in *Scientific Reports*.

6.1. Abstract

TBPM involves remembering to perform actions at a specific future time. Several studies suggested that monetary consequences improved prospective remembering; however, the effect of monetary consequences on strategic time monitoring (i.e., clock-checking behavior) in TBPM is still unknown. The present study investigated how the monetary costs on clock-checking affected TBPM accuracy and strategic time monitoring. Participants performed an ongoing lexical decision task while carrying out a two-minutes TBPM task. Motivational incentives were manipulated across three experimental conditions: a single-cost condition where missed TBPM responses incurred monetary deductions, a double-cost condition where both missed responses and time monitoring resulted in monetary deductions, and a control condition with no monetary deductions. Overall, the findings indicated that monetary costs on clock-checking prompted more parsimonious strategic time monitoring behavior, which negatively impacted TBPM accuracy. These results emphasize the importance of weighing the motivational aspects involved in strategic monitoring, shedding light on the complex relationship between clock-checking behavior, its consequences, and TBPM performance.

6.2. Introduction

In TBPM tasks, time monitoring is essential to determine the correct time point for intention execution (Labelle et al., 2009; Mioni, Grondin, et al., 2020). Yet, time monitoring can be costly: for instance, time monitoring can have detrimental consequences, as it imposes an additional cognitive task and requires attentional resources (e.g., while operating machinery, during conversation, when driving on the motorway, or during a medical procedure). Time monitoring may also have social costs (e.g., colleagues may perceive someone as impolite if they look at their wristwatch frequently during a meeting). The relation between the benefits of successful TBPM and the cost of time monitoring in real life is complex and influenced by personal goals as well as the consequences of time monitoring behavior (Suchy, 2020; Wilson et al., 2020). Therefore, weighing the costs of monitoring (e.g., "Do I look in my calendar again during this meeting?") against the benefits of successful remembering ("Will I catch my train?") appears to be important. So far, however, very little is known about the relation between time monitoring, its consequences (in terms of cost), and TBPM. The present article contributes to addressing this gap by investigating for the first time how a monetary cost of time monitoring affects TBPM.

6.2.1. Importance and incentives effects

Research showed better prospective remembering for tasks that were considered as important (Kliegel et al., 2001, 2004). Perceived importance, in turn, reflects subjective values of desired goals and expectations of anticipated consequences that can be manipulated by task instructions or incentives (e.g., Cook et al., 2015; Horn & Freund, 2021b). Penningroth and Scott (2007) have suggested that intentions that are related to personally relevant goals are perceived as more important and can improve performance in PM tasks through various cognitive processes, such as monitoring. Moreover, the importance of goals is predictive of attention allocation, monitoring, and strategy use (Shah et al., 2002). So far, a few studies have examined if and how different monetary consequences influence PM in laboratory (e.g., Brandimonte et al., 2010; Cook et al., 2015; Horn & Freund, 2021) and in naturalistic settings (e.g., Aberle et al., 2010). In a pioneering study by Meacham and Singer (1977), for instance, people were asked to mail post cards back to the researcher on pre-specified dates over a period of eight weeks. Participants in an incentive group, who received money for returning the cards on time, did so with higher probability and more of them indicated the use of external reminders (e.g., calendars) to support their PM than participants in a no-incentive group. This suggests that monetary consequences may increase the perceived importance of a PM task and induce the use of mnemonic strategies. Relatedly, Horn and Freund (2021b, 2021a) compared the effect of monetary gain incentives (for accurate responses on PM target events) and loss incentives (deductions from a monetary endowment for missed PM responses) in EBPM across adulthood. The findings showed that the inclusion of both gaining and losing incentive led to enhanced accuracy in PM tasks when compared to a control condition lacking such incentives (Freund & Ebner, 2005; Horn & Freund, 2021b, 2021a). These and other studies suggest that monetary consequences affect PM accuracy (Aberle et al., 2010; M. A. Brandimonte et al., 2010; G. I. Cook et al., 2015; Horn & Freund, 2021b, 2021a). So far, however, the impact of incentives on monitoring has not been investigated. As argued above, a better understanding of the cost of time monitoring is particularly relevant in TBPM tasks, as many scenarios come with secondary monitoring costs. Therefore, the goal in the present study was to systematically investigate the cost of time monitoring in TBPM.

6.2.2. The cost of time monitoring

For a given TBPM task, time monitoring can be measured as the mean (or sum) of clock checks, regardless of when these clock checks are made (*absolute clock-checking*), or as the mean of clock checks over specific intervals of time. Time monitoring is called *strategic* if its pattern follows a J-shaped curve, with few checks in the initial phases of a TBPM task (when the target time is further away), followed by an exponential growth of clock checks as the relevant target time approaches (Labelle et al., 2009; Mäntylä et al., 2006; Mioni et al., 2017; Mioni, Grondin, et al., 2020; Munaretto et al., 2022; Vanneste et al., 2016). Both absolute frequency and strategy use of time monitoring tend to correlate positively with TBPM accuracy (Joly-Burra et al., 2022; Labelle et al., 2009; Mäntylä et al., 2006; Mioni & Stablum, 2014; Munaretto et al., 2022; Vanneste et al., 2016).

In the majority of TBPM studies, time monitoring has been unconstrained and self-paced, meaning that participants could check a clock whenever they wished, without imposing any cost. Only few studies have used experimental designs with restrictions on time monitoring. For example, Harris and Wilkins (1982) placed the clock behind participants' backs, requiring an overt turning around (see also Niedźwieńska & Barzykowski, 2012). Huang and colleagues (2014) instructed participants to use the timer as infrequently as possible in one of their experimental conditions, whereas Mioni and Stablum (2014) permitted participants in one experimental condition to check the clock only up to six times over the course of five minutes. Overall, all studies concluded that when restrictions were imposed on time monitoring in younger adults, the frequency of clock-checks decreased, but strategic behavior increased (Harris & Wilkins, 1982; Huang et al., 2014; Mioni & Stablum, 2014).

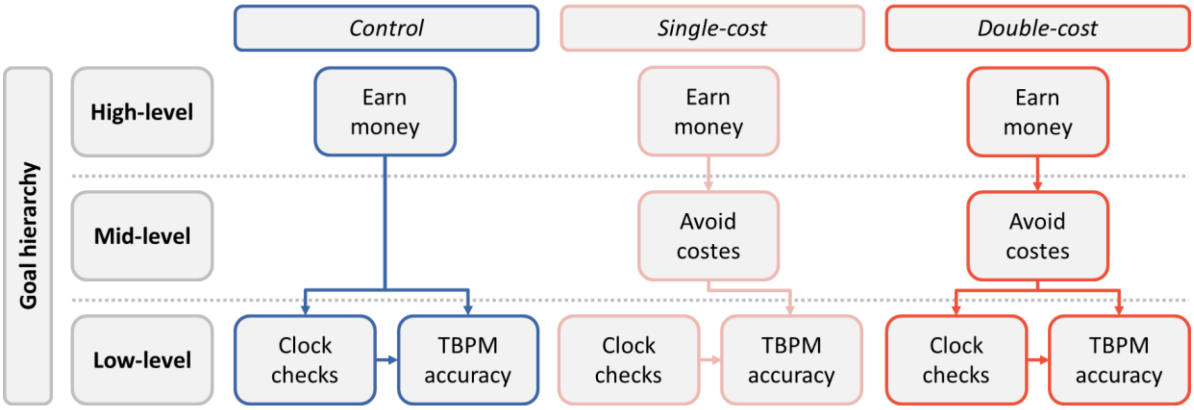
6.2.3. The present study

The “down-stream” effects (i.e., the influence of high-level goals on lower-level cognitive processes, such as attention, perception, and memory) of costs of time monitoring and TBPM failures are currently unknown (Altgassen et al., 2010). This appears surprising, given the huge importance that these effects can have in daily life (e.g., forgetting to take medication can lead to serious health issues; forgetting to pay bills on time can lead to extra fees). Moreover, it is unknown if and how motivational incentives affect the relation between time monitoring and TBPM (M. A. Brandimonte et al., 2010; Schnitzspahn, Zeintl, et al., 2011). To fill this gap, the present study investigated the effect of monetary costs on time monitoring and TBPM. Participants made ongoing lexical decisions and were additionally asked to press the ENTER-key every two minutes as TBPM task (while having the possibility to check a clock whenever they wished). Motivation to monitor time was manipulated in three experimental conditions: in one group of participants, missed PM responses were penalized with a monetary deduction from an initial endowment of £6 (single-cost condition). In a second experimental group (double-cost condition), not only missed PM responses, but also time monitoring resulted in deductions from the endowment. Lastly, in a control group, participants received no information regarding an additional incentive prior to the experiment. TBPM accuracy was measured as mean proportion of correct PM responses within an interval (±6 seconds) around the PM target time (2 minutes); for time monitoring, we measured mean frequency of clock checks over time and absolute and relative clock checks (Joly-Burra et al., 2022; Munaretto et al., 2022). *Relative clock-checking* is a quantitative index of strategic behavior based on the tendency to concentrate clock checks in the last interval before a specific PM target time; a strength of this measure is that relative clock-checking accounts for individual differences in TBPM that often considered as noise in more traditional analyses of time monitoring (Labelle et al., 2009; Maylor et al., 2002; Mioni & Stablum, 2014); for further information, see Joly-Burra and colleagues (2022).

Based on research on motivated cognition (e.g., Horn & Freund, 2021a; Kruglanski et al., 2002; Penningroth & Scott, 2007; Shah et al., 2002), we considered three different scenarios for the different conditions, as depicted in **Figure 8**. According to our theoretical considerations, in the control condition, the TBPM task was only linked to a very general and abstract “higher-level” goal (i.e., get remuneration for participation in the study); by contrast, in the single-cost condition, TBPM accuracy was charged with an additional monetary cost, and might be linked with a more concrete “mid-level” goal (i.e., “avoid monetary losses in this task”) which, in turn, could be linked to a more generic “higher-level” goal of getting money for participation. Finally, in the double-cost condition, both TBPM accuracy and time monitoring might be linked with a more concrete “mid-level goal”. Based on these ideas, we expected that participants in the double-cost condition would use the clock less frequently, but more strategically, than participants in the single-cost or control condition, as only in the double-cost condition, time monitoring would be linked with a “mid-level” goal of avoiding cost. It was also expected that strategic behavior in time monitoring correlated positively with TBPM accuracy, especially in the double-cost condition (Joly-Burra et al., 2022; Labelle et al., 2009; Mäntylä et al., 2006; Mioni, Grondin, et al., 2020; Vanneste et al., 2016). Moreover, TBPM accuracy was expected to be the highest in the single-cost condition because there was a motivational incentive to avoid losses (following PM misses) while having the opportunity to engage in time monitoring “free of charge”. In contrast, participants in the double-cost condition were expected to check the clock more parsimoniously to avoid further costs, which might decrease TBPM accuracy compared to the other conditions.

Figure 8

Cognitive-motivational framework as a function of experimental conditions



Note. The figure represents how goal hierarchy (low-, middle-, and high-level) affects behavioral performance (clock checks and accuracy) and motivational tendencies (to earn money and to avoid losses) in a time-based prospective memory task across experimental conditions (control, single-, and double-loss condition). In the control condition, participants were motivated only by the possibility to earn money for the experiment's participation (which was equal across experimental conditions). In the single-loss condition, the opportunity to earn extra payment through better performance (i.e., avoiding loss of points later converted in money) added a middle-level motivation that was selectively related to the accuracy at the time-based prospective memory task; in the double-loss condition, clock checks were also penalized with a monetary loss, adding further motivation to avoid losses. TBPM: time-based prospective memory.

6.3. Methods

6.3.1. Participants

This study was statistically powered to detect small-to-medium differences in performance between experimental conditions (control versus single-cost versus double-cost). We computed required sample size a priori, using the Software G*Power (Faul et al., 2007); given that no previous study investigated the cost related to TBPM and/or time monitoring, we calculated the power analysis establishing an a-priori effect size of $d = .20$. The power analysis indicated that detecting an effect size of .20 at 95% power (two-tailed test, $\alpha = .05$), would require a sample of a total of 102 participants in an ANOVA test with three independent groups (i.e., control, single-cost, and double-cost condition) and two repeated measures (i.e., two task blocks: OT baseline and TBPM block). To increase the statistical power, we recruited a total of 210 participants, hence doubling the sample size obtained from the power analysis, as suggested from previous online studies (Finley & Penningroth, 2015; Logie & Maylor, 2009); all participants were recruited via the online research provider *Prolific* (www.prolific.co), using the following inclusion criteria: age between 18 and 35 years, fluent in English, and following exclusion criteria no current alcohol therapy, no head injury, no long-term health condition/disability, no chronic condition/illness, no mild cognitive impairment/dementia, no mental illness/condition, and no medication intake. All participants provided informed consent before participating in the study, in accordance with the Declaration of Helsinki. The study protocol had been approved by the ethics commission of the University of Geneva (CUREG-2022-11-122). Participation was reimbursed with a fixed hourly compensation of £9. In addition, all participants could obtain a performance-contingent bonus of up to £6.

6.3.2. Materials

All tasks were programmed in *PsychoPy*, version 2021.2.3 (Peirce et al., 2019) and hosted on *Pavlovia* (https://pavlovia.org/; Bridges et al., 2020). All materials are available in the repository of the Open Science Framework (https://www.doi.org/10.17605/OSF.IO/H3SF6).

6.3.2.1. Tasks

Participants performed two task blocks: one OT block without a TBPM task and one block with an embedded TBPM task. In both blocks, the OT was the lexical decision task, in which stimuli were letter strings; participants were asked to respond whether a string formed an English word or not. All stimuli were taken from the English Lexicon Project database (Balota et al., 2007). In total, 306 stimuli (153 words) were selected based on average scores of standardized accuracy, frequency (only for words), and response times; all stimuli (words and non-words) had between 5–8 letters. Each OT trial started with a fixation cross (1000 ms), followed by the stimulus (2000 ms), and a subsequent blank period (black screen) that lasted randomly between 1000 and 2000 ms. All OT stimuli were presented in fully randomized order across the blocks. In total, 153 OT trials were included within each block; the average duration of each block was ~10 minutes and 20 seconds. During the TBPM task, participants were asked to remember to press the ENTER key on the keyboard every 2 minutes while performing the lexical decision task; in total, five PM responses were collected for each block; moreover, participants were free to check the clock as often as they wanted by pressing the SPACEBAR; if they did so, a digital clock (format: "00:00") appeared on the computer screen for 3 seconds.

6.3.2.2. Further questionnaires

After participants completed the TBPM task, they were asked to indicate which task was more important for them (OT, TBPM task, or both; 77% declared both tasks were equally important, 17% declared that the TBPM task was the most important task, and 6% declared that OT was the most important task; exploratory analyses on subjective task importance are reported in the Supplementary material, section 11.3.2.1). Other collected measures, which are beyond the scope of the present paper, were the following: Participants indicated how they perceived time during the OT baseline and the TBPM task (Thönes & Stocker, 2019), responded to a scale of loss aversion (Gächter et al., 2022), a scale of time experience (Wittmann & Lehnhoff, 2005), and a follow-up questionnaire to indicate whether any strategy to track the passage of time during the TBPM task had been used; specifically, participants were asked to give binary responses (yes/no) to this question, and in the case of a yes response, were asked to provide a brief explanation. Sociodemographic data were obtained from Prolific.

6.3.3. Procedure

Overall, a session lasted ca. 30-35 minutes. Prior to participation, all relevant information concerning the experimental procedure and data access were provided in written form on the screen; participants provided informed consent before. Participants then read instructions for the OT baseline block. However, before moving to the practice block, they went through an instruction quiz (i.e., participants had to answer correctly to all questions about task instructions before proceeding; Finley & Penningroth, 2015). If participants passed this attention check, they performed a short practice session of the OT baseline (comprising 8 trials, 4 words and 4 nonwords). Once participants reached an OT accuracy of at least 75%, they moved on to the OT baseline block, otherwise they repeated the practice block. After that, participants read instructions for the TBPM task and were randomly assigned to one of three conditions: in the single-cost and double-cost conditions, participants were informed that they would now receive an initial endowment of +100 points before performing the TBPM task. In the single-cost condition, participants were then informed that any missed PM response (i.e., missing to press ENTER during the target-time window) led to a loss of −10 points, deducted from the initial endowment of 100 points; in the double-cost condition, participants were additionally informed that time monitoring also had a cost and led to a loss of −2.5 points each time they pressed the SPACEBAR to check the clock. Participants were also told that the final points score would later be converted into a monetary bonus. However, the specific conversion rate was not stated, allowing us to adjust for any disadvantage in points retained due to the experimental condition. In the control condition, participants were simply instructed to perform the TBPM task, without explicit mentioning of any incentives (participants in the control condition received the bonus payment as well, to ensure equality of remuneration across groups; however, they were informed about it only *after* they completed the TBPM task). Participants performed another instruction quiz about the TBPM task; if participants responded correctly to all the questions, another practice block was administered (lasting approx. 2 min), allowing participants to familiarize themselves with the TBPM task. If participants correctly performed the PM response and reached an OT accuracy of at least 75%, the TBPM block started. Following this, participants responded to follow-up questionnaires and were debriefed.

6.4. Results

Data pre-processing and figures were carried out in R – version 4.2.1 (R Core Team, 2022) – with the support of ChatGPT for building R-scripts (OpenAI, 2023). The analyses were carried out in *Jamovi*, version 2.3.21.0 (The Jamovi Project, 2021). Three participants were excluded from the analyses due to technical computer problems causing bad data quality and/or missing data; one further participant was excluded because his/her rate of TBPM task completion was below the chance level (≤ 50%), regardless of the PM responses' temporal precision. In total, 206 participants were included in the final analyses; descriptive statistics of TBPM accuracy and time monitoring are in **Table 6**. The analyses are reported in two parts: first, ANOVAs were calculated to investigate the effects of the monetary cost on TBPM accuracy and time monitoring. Second, a multi-group path analysis was carried out to explore the strength of the predictive association between time monitoring and TBPM performance across experimental conditions. For all ANOVA analyses, the effect sizes were calculated using partial eta squared values (η^2_p). Post-hoc *t*-tests were carried out applying Bonferroni's correction to the *p*-values (indicated as p_{adj}). For all statistical analyses, the alpha level was set at .05.

Table 6

Descriptive statistics

	Experimental Condition	TBPM accuracy	Monitoring over time t1	t2	t3	t4	Absolute clock-c.	Relative clock-c. (%)
M	control	0.91	0.78	1.22	1.53	2.87	32.03	45.98
	single-cost	0.95	0.79	1.18	1.47	2.97	32.03	49.64
	double-cost	0.84	0.34	0.47	0.67	1.43	14.59	58.00
SD	control	0.16	0.72	0.76	0.83	1.16	15.35	12.42
	single-cost	0.10	0.72	0.88	0.83	1.12	15.48	14.45
	double-cost	0.22	0.58	0.72	0.79	1.34	16.13	25.56

Note. Descriptive statistics of time-based prospective memory accuracy, mean monitoring over time, as well as absolute and relative clock-checking, as a function of the experimental conditions (monetary cost: control, single-loss, double-loss). TBPM: time-based prospective memory; t1: time 1 (i.e.: first 30 seconds' interval before the PM target time); t2: time 2 (i.e.: second 30 seconds' interval before the PM target time); t3: time 3 (i.e.: third 30 seconds' interval before the PM target time); t4: time 4 (i.e.: fourth and last 30 seconds' interval before the PM target time); clock-c.: clock-checking.

6.4.1. Time-based prospective memory

TBPM accuracy (see **Figure 9A**) was measured as mean proportion of correct PM responses. A PM response was considered correct if it was made within ± 6 seconds around PM target time (equivalent to 10% of the total interval of 2 minutes between PM target times; e.g., Vanneste et al., 2016). The main effect of the Monetary cost (control vs. single-cost vs. double-cost) was significant, indicating that TBPM accuracy differed between conditions, $F(2, 203) = 7.82$, $p < .001$, $\eta^2_p = .072$. Post-hoc Bonferroni comparisons indicated that participants in the double-cost condition performed worse than participants in the control, $t(203) = -2.45$, $p_{adj} = .046$, as well as than participants in the single-cost condition, $t(203) = -3.91$, $p_{adj} < .001$.

6.4.2. Time monitoring

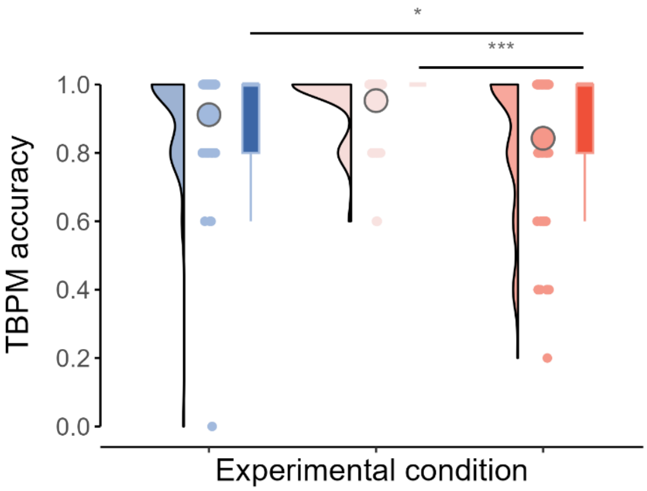
For the analysis on time monitoring, we carried out a series of ANOVAs. We aimed to investigate to what extent participants were strategic when checking the clock (see Joly-Burra et al., 2022) and whether the experimental cost manipulation affected the frequency of clock checks over time. We calculated a 3 * 4 mixed ANOVA with between-subjects factor Monetary cost (control vs. single-cost vs. double-cost) and within-subjects factor Time (t1 to t4) to analyze time monitoring (frequency of clock checks). The factor Time refers to four intervals of 30 seconds each (i.e., t1 represents the first 30 seconds before a PM target time; t2 represents the second 30 seconds; t3 represents the third 30 seconds; t4 the final 30 seconds before the target time). The results showed a significant main effect of Time, $F(2.02, 410.65) = 500.17$, $p < .001$, $\eta^2_p = .71$, a main effect of Condition, $F(2, 203) = 28.67$, $p < .001$, $\eta^2_p = .22$, and a Time * Condition interaction, $F(2.02, 410.65) = 18.14$, $p < .001$, $\eta^2_p = .15$. Post-hoc comparisons for the main effect of Time revealed that participants strategically monitored the clock, indicating that less frequent clock checks during t1 than t2, $t(203) = -9.40$, $p_{adj} < .001$, than t3, $t(203) = -14.74$, $p_{adj} < .001$, and than t4, $t(203) = -27.43$, $p_{adj} < .001$. Similarly, participants checked the clock less in t2 than t3, $t(198) = -7.39$, $p_{adj} < .001$, and than t4, $t(198) = -25.28$, $p_{adj} < .001$. Clock-checking frequency was also lower in t3 than t4, $t(198) = -22.15$, $p_{adj} < .001$. Post-hoc comparisons between conditions indicated that participants in the double-cost condition monitored time less frequently than participants in the control condition, $t(198) = -6.54$, $p_{adj} < .001$, and than participants in the single-cost condition, $t(198) = -6.54$, $p_{adj} < .001$. The difference in time monitoring between control and single-cost condition was not significant (p_{adj} = 1). Post-hoc comparisons for the Time * Condition interaction showed that participants in the double-cost condition checked the clock less frequently than participants in both the control and single-cost conditions in a consistent manner over time, whereas the pattern of monitoring did not differ between control and single-cost conditions (**Figure 9B**).

Two further one-way ANOVAs were carried out on absolute and relative time clock-checking (for further information see the Supplementary material, section 11.3.2.1), shown in **Figure 9C** and **Figure 9D**. The results showed that absolute clock-checking differed significantly between the experimental conditions, $F(2, 203) = 28.67$, $p < .001$, $\eta^2_p = .22$ (i.e., this effect was identical to the main effect of Monetary cost in the mixed ANOVA above). Post-hoc Bonferroni comparisons indicated that participants assigned to the double-cost condition checked the clock less frequently compared to participants assigned to the single-cost condition, $t(203) = -6.52$, $p_{adj} < .001$, as well as compared to participants in the control condition, $t(203) = -6.54$, $p_{adj} < .001$ (**Figure 9C**); the pairwise comparison between control and single-cost condition was non-significant (p_{adj} = 1). The analysis of relative clock-checking showed a significant effect of Monetary cost, $F(2, 197) = 7.49$, $p < .001$, $\eta^2_{\mathrm{p}} = .07$. Post-hoc comparisons revealed that the participants in the double-cost condition were more strategic than participants in the single-cost condition, $t(203) = 2.63$, $p_{adj} = .027$, and than participants in the control condition, $t(203) = 3.79$, $p_{adj} < .001$ (**Figure 9D**); the pairwise comparison between control and single-cost condition was non-significant ($p_{adj} = .728$).

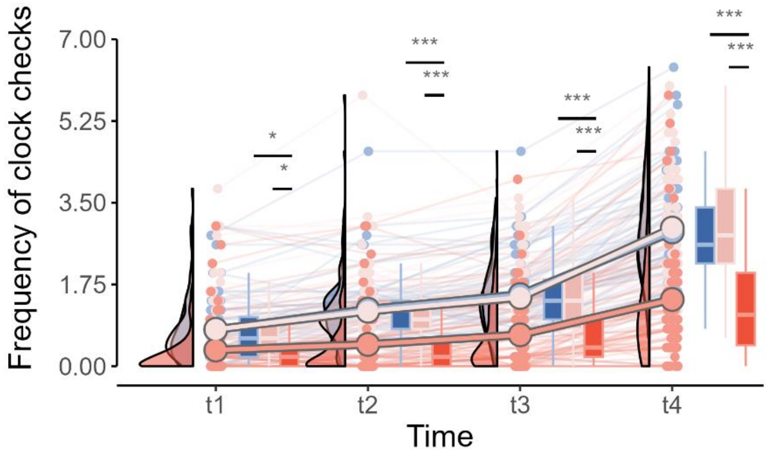
Figure 9

Main results from ANOVAs

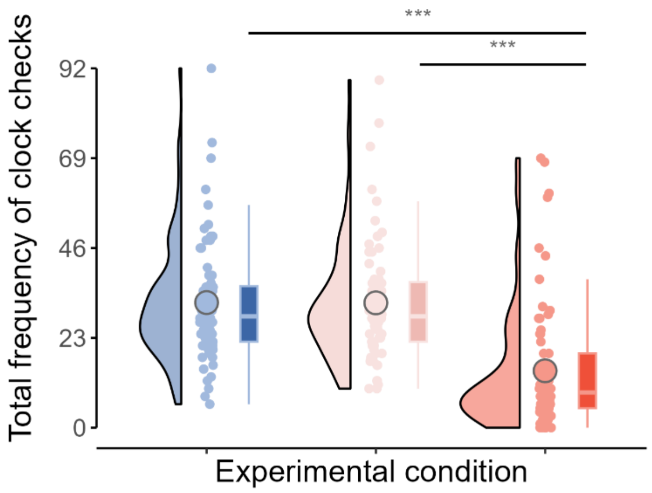
A) Time-based prospective memory



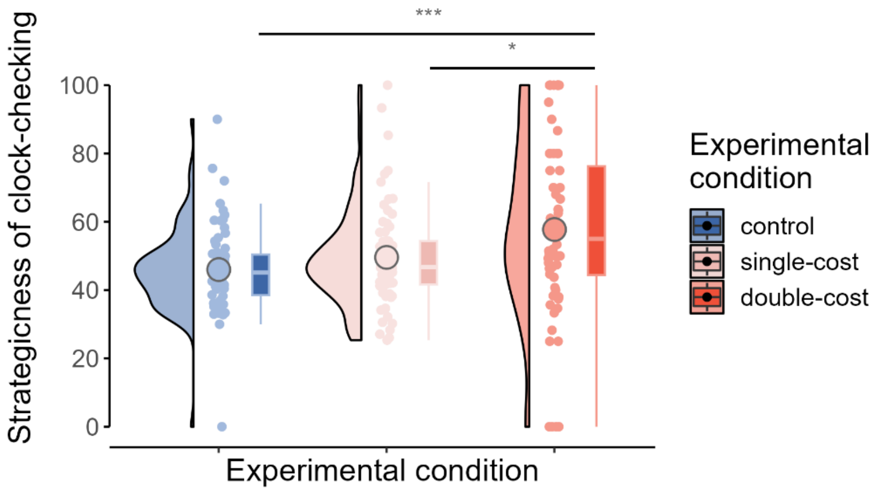
B) Frequency of monitoring over time



C) Absolute clock-checking



D) Relative clock-checking



Note. The figure represents the accuracy at the time-based prospective memory task (A), the mean frequency of clock checks over time (B), as well as absolute (C) and relative clock-checking (as a percentage; D) as a function of the experimental conditions (monetary loss: control, single-loss, double-loss). TBPM: time-based prospective memory; t1: time 1 (i.e.: first 30 seconds' interval before the PM target time); t2: time 2 (i.e.: second 30 seconds' interval before the PM target time); t3: time 3 (i.e.: third 30 seconds' interval before the PM target time); t4: time 4 (i.e.: fourth and last 30 seconds' interval before the PM target time). * $p < .05$; ** $p < .01$; *** $p < .001$.

6.4.3. Path analysis

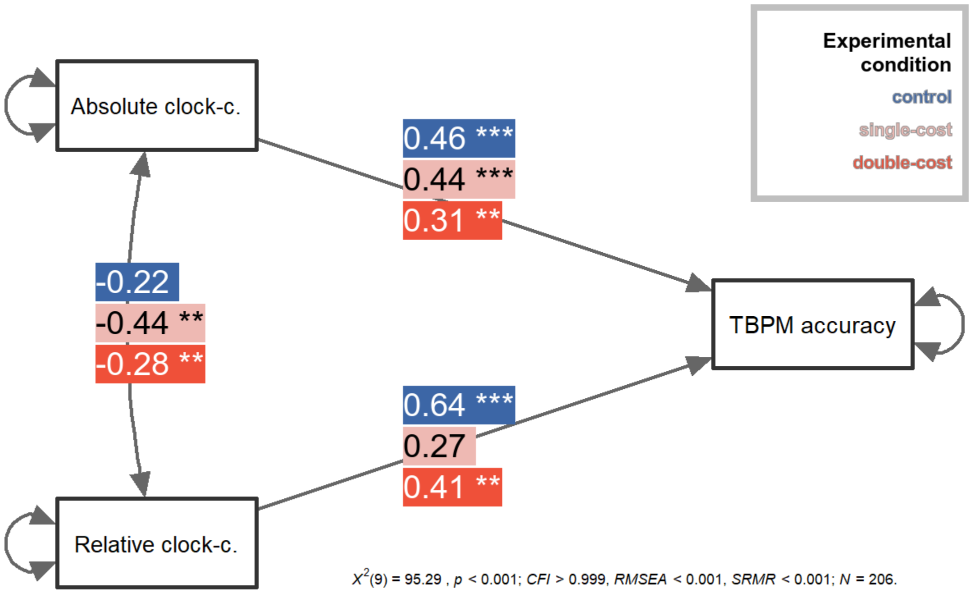
Exploratory path analyses were carried out in a multi-group framework using the package PATHj in Jamovi (Gallucci, 2021). The tested regression model (

Figure 10) comprised both absolute and relative clock-checking as predictors of TBPM accuracy across experimental conditions (control vs. single-cost vs. double-cost). The two monitoring measures were allowed to correlate. A robust maximum-likelihood algorithm was used for model estimation; adjusted bias-corrected bootstrapping with 1000 samples was performed to calculate standard errors (for further statistical details, see the Supplementary material, section 11.3.2.1).

The multi-group model with no equality constraints provided a good statistical fit to the data, $\chi^2(9) = 95.29$, $p < .001$, $CFI > .99$, $RMSEA < .001$, $SRMR < .001$, and explained a significant portion of variance in TBPM accuracy for the control group ($R^2 = .49$, $\chi^2_{\text{Wald}}(2) = 15.14$, $p < .001$), for the single-cost condition ($R^2 = .16$, $\chi^2_{\text{Wald}}(2) = 12.74$, p = .004) and for the double-cost condition ($R^2 = .19$, $\chi^2_{\text{Wald}}(2) = 10.92$, p = .004). Constraining the regression coefficients in the model to be equal across the three subgroups resulted in a statistically significant misfit ($\chi^2(4) = 19.50$, $p < .001$, $CFI = .82$, $RMSEA = .089$, $SRMR = .241$), suggesting that effects of monitoring on TBPM accuracy were different across experimental conditions. Specifically, the model showed that both absolute and relative clock-checking predicted TBPM accuracy in the double-cost condition; however, relative clock-checking better predicted TBPM accuracy ($\beta = .41$, $p = .004$) than absolute clock-checking ($\beta = .31$, $p = .012$). The same pattern was found in the control condition ($\beta_{\text{relative}} = .64$, $p_{relative} < .001$; $\beta_{\text{absolute}} = .46$, $p_{absolute} < .001$). By contrast, only absolute clock-checking predicted TBPM accuracy in the single-cost condition ($\beta = .44$, $p < .001$), whereas the effect of relative clock-checking was not significant ($p = .101$). Absolute and relative clock-checking also correlated with each other in the single-cost condition (β = -.44, *p* = .002) and double-cost condition (β = -.28, *p* = .004), but not in the control group (*p* = .151). Hence, we further assessed whether the relationship between the two monitoring measures was the same across experimental conditions by testing a further constrained model, in which the covariance between absolute and relative clock-checking was constrained to be equal across experimental conditions. The results showed that constraining covariances to be equal across the three subgroups did not lead to significant misfit, $\chi^2(2) = 3.15$, *p* = .207, *CFI* = .98, *RMSEA* = .093, *SRMR* = .058, suggesting that the relationship between monitoring measures was similar across experimental conditions (however, some error was introduced in the new constrained model, as *RMSEA* = .093).

Figure 10

Results from multi-group path analysis



Note. A graphical representation of the model tested in the path analysis, with regression and covariance coefficients for each experimental condition (monetary loss: control, single-loss, double-loss). TBPM: time-based prospective memory; clock-c.: clock-checking. ** $p < .01$; *** $p < .001$.

6.5. Discussion

PM tasks that are perceived as important are usually remembered more likely than less important ones (e.g., Kliegel et al., 2001, 2004; Smith & Bayen, 2004). Monetary incentives increase the importance of PM tasks (e.g., Cook et al., 2015; Horn & Freund, 2021a; Meacham & Singer, 1977), but the effects on monitoring strategies are hardly understood. The present study addressed the novel question of how monetary costs affect monitoring and accuracy in TBPM. In one group of participants (single-cost condition), missed PM responses were penalized with a monetary deduction from an initial endowment of £6. In a second group (double-cost condition), missed PM targets as well as clock checks were associated with a cost and resulted in deductions from an initial endowment of £6. In a control group, participants received no information regarding an additional incentive prior to the experiment.

Based on previous research on motivated cognition (e.g., Horn & Freund, 2021a; Kruglanski et al., 2002; Penningroth & Scott, 2007; Shah et al., 2002), we expected that participants in the double-cost condition use the clock less frequently, but more strategically, than participants in the single-cost or control condition; we also expected that strategic behavior in time monitoring correlates positively with TBPM accuracy, especially in the double-cost condition (Joly-Burra et al., 2022; Labelle et al., 2009; Mäntylä et al., 2006; Mioni, Grondin, et al., 2020; Vanneste et al., 2016). The findings are largely in line with these expectations: even though participants generally tended to increase clock checks over time before a target time approached (**Figure 9B**), overall clock checks were substantially lower in the double-cost than the other conditions

(**Figure 9C**). At the same time, participants in the double-cost condition showed the highest rate of strategy use (**Figure 9D**), despite the lower number of overall clock checks. Monitoring patterns over time, absolute, and relative clock checking did not differ between the single-cost and control conditions, indicating that clock-checking was only affected when time monitoring was directly charged. Both absolute and relative clock-checking correlated positively with TBPM accuracy, suggesting that providing motivational incentives just for TBPM accuracy did not affect monitoring; in the single-cost condition, the effect of relative clock checking on TBPM accuracy even failed to reach significance (**Figure 10**). Regarding TBPM accuracy, we expected highest performance in the single-cost condition, because there was a motivational incentive to avoid losses (following PM misses) and simultaneous opportunity for time monitoring that was "free of charge". In contrast, we expected participants in the double-cost condition to be more cautious about checking the clock to avoid an extra cost, which might decrease TBPM accuracy compared to the other conditions. Indeed, TBPM accuracy was highest in the single-cost condition and lowest in the double-cost condition (**Figure 9A**), with a significant difference in performance between these two conditions, as well as between double-cost and control condition. Exploratory analyses on OT performance only revealed that, in both task blocks (OT baseline and TBPM), participants in the double-cost condition performed better than participants in the other two conditions (the same comparison between control and single-cost condition was not significant); all other effects were not significant, suggesting that the effects of monetary costs was not impacting the OT performance, but only the TBPM accuracy and time monitoring (for further information, see Supplementary material, section 11.3.2.2).

6.5.1. The Interplay Between Monetary Cost and Monitoring in TBPM

Overall, our results are in line with a set of PM studies, which indicated that, when restrictions or costs are imposed on time monitoring in younger adults, the frequency of clock-checks decreased, but strategic behavior increased (Harris & Wilkins, 1982; Huang et al., 2014; Mioni & Stablum, 2014). Considering that monetary incentives may affect attention allocation and strategy use on relatively lower levels of a goal hierarchy (e.g., Kruglanski et al., 2002; Shah et al., 2002), the behavioral pattern of clock checking can also help to better understand how motivational incentives affect cognitive processes in time monitoring. Specifically, it is possible that, when clock-checking was costly (i.e., in the double-cost condition), participants might have engaged internal time mechanisms (Block & Zakay, 2006; Labelle et al., 2009), especially when the PM target time was expected to not occur soon, allowing participants to concentrate the majority of the overall clock checks temporally closer to the PM target time (Huang et al., 2014). In contrast, if monitoring was not costly, the strategic involvement of time estimation processes might have been reduced, especially in the single-cost condition, in which the strategic use of time monitoring did not significantly predict TBPM accuracy; this pattern suggests that the tendency of being strategic was not essential for good performance when misses in the TBPM task came with a cost, but clock-checking was "free of charge". However, these are speculations that need to be investigated in future studies, as the relationship between internal time-estimation processes and relative/absolute clock-checking is unknown (Joly-Burra et al., 2022).

Monetary cost had clear effects on time monitoring, but effects on TBPM accuracy were subtler, even though the pattern was in line with our expectations. This might be due to the specific combination of a monetary cost for clock checks and misses in the

TBPM task. Considering that TBPM correlated positively with absolute clock-checking across experimental conditions, it appears reasonable to argue that this pattern reflects the differential effects of motivational incentive(s) on time monitoring. The results might suggest that participants achieved fairly high accuracy (> 85%), but through the use of different time-monitoring strategies across conditions: in the double-cost condition, time monitoring was linked with a “mid-level goal”, whereas this was not the case in the single-cost and control conditions; indeed, monitoring behavior was very similar between these two latter conditions, whereas participants in the double-cost condition exhibited a more strategic monitoring behavior.

Another interesting point is that the present study focused on the “downstream effect” of monetary incentives on TBPM performance (i.e., the effects of monetary incentives on attention and monitoring on a concrete task-level). However, it will be relevant in the future to examine the role of “up-stream effects” too (e.g., if and how specific features of the memory tasks moderate the motivational influence from a higher-level goal, such as making money). For example, the difficulty of the TBPM task, the number of intentions (Cicogna et al., 2005; Occhionero et al., 2010), or possibilities to check the clock (Huang et al., 2014; Mioni & Stablum, 2014) can modulate the allocation of attention and strategy use in TBPM and possibly affect goals on “higher levels” of the goal hierarchy (Kruglanski et al., 2002; Penningroth & Scott, 2007; Shah et al., 2002). Future studies are needed to further explore the interplay of such up-stream effects and motivational incentives in PM.

6.5.2. Limitations and Outlook

The present experiment was conducted online. Some studies suggest that performance is comparable across laboratory and online settings (Finley & Penningroth, 2015; Germine et al., 2012; Greene & Naveh-Benjamin, 2022; Uittenhove et al., 2023), also in the domain of PM (see Gilbert, 2015; Zuber et al., 2022). We included several attentional checks in our study; only participants who passed these checks were included in our analyses. Nonetheless, a replication in the laboratory would be useful to account for potentially higher levels of noise in the data from online studies (Uittenhove et al., 2023; Webb & Tangney, 2022). Moreover, TBPM accuracy was generally high, suggesting that the task used in this study was easy for participants. It is possible that effects of motivational incentives (e.g., differences between control and incentivized conditions) are better detected if accuracy is lower and variability in TBPM is higher. Therefore, it will be interesting to investigate incentive effects with tasks that vary in difficulty/demands. Moreover, the use of monetary incentives may not well capture the consequences and types of cost encountered in some daily-life settings. For instance, consequences of PM misses (e.g., missing an important deadline or appointment), could have different motivational and cognitive implications in daily life. It will be interesting to investigate these issues in naturalistic settings as well (Meacham & Singer, 1977). Finally, it will be important to systematically compare the cost of monitoring and the benefit of successful remembering across different levels of cost and incentives.

Overall, the present findings show for the first time that monetary costs affect time monitoring as well as accuracy in TBPM. If the cost of time monitoring is high, people check their clocks more strategically and parsimoniously. However, more parsimonious monitoring can detrimentally affect prospective remembering (as in the present study). This highlights the importance of carefully weighing the costs of monitoring (e.g., “Do I look at my watch again?”) against the benefits of successful remembering (“Do I leave the meeting now to catch my train?”).

7. The Test-Wait-Test-Exit model revised

7.1. Abstract

In this chapter, a new model of strategic time monitoring called TWTE-r is introduced as an improved version of the TWTE model. The TWTE-r model incorporates the "test" phase, operationalized as overall clock-checking frequency, and the "wait" phase, operationalized as relative strategicness of clock-checking. The relationship between the "test" and "wait" phases represents a proxy of the strategy used during the TBPM task: a positive correlation suggests that participants anticipate the PM target time based on the *numerical* proximity between ongoing clock time and the PM target time, involving attentional control mechanisms; a negative correlation indicates that individuals estimate the PM target time based on *temporal* proximity with the ongoing clock time. The TWTE-r model assumptions were derived from additional analyses carried out on data from Study 1, which further confirmed that the slower clock facilitated time estimation, while the faster clock disrupted this mechanism. The TWTE-r model was used also to explain results from Study 3, indicating that the effect of monetary costs on time monitoring and TBPM performance, as well as their relationship, were related with differential effect of internal time processes in time monitoring: specifically, internal time processes had a beneficial effect on monitoring strategy when clock-checking was charged with money loss, and on self-initiated processes when TBPM performance was charged with money loss. Although further empirical testing is needed, the TWTE-r model appears to explain the kind of strategy used in time monitoring, as well as the underlying cognitive processes.

7.2. Introduction

The findings from Study 3 indicated differential effects monetary deductions, with participants in the double-cost group showing fewer clock checks (**Figure 9C**) but higher strategic use (**Figure 9D**); such changes in strategic time monitoring were associated with TBPM accuracy, which was the highest in the single-cost group, and the lowest in the double-cost group (**Figure 9A**). Absolute and relative clock-checking did not differ between the single-cost and control conditions and negatively correlated among each other, but such negative relationship was significant only in the single- and double-cost condition, and not in the control condition. Interestingly, in the article by Joly-Burra and colleagues (2022), both absolute and relative clock-checking were positively correlated among each other, indicating that the more clock checks individuals make overall, the more clock checks they will make right before PM time. Although there is a contradiction between results from Study 3 and findings from Joly-Burra and colleagues, such contradiction might be only apparent, and instead it can reflect different strategies adopted by different participants, or potentially induced by specific manipulations.

A positive correlation between absolute and relative clock-checking, as shown by Joly-Burra and colleagues, would indicate that clock checks done temporally far from PM time were important for later clock checks carried out in the last interval before the PM target time. Considering the distinction between *numerical* and *temporal* proximity between the ongoing time and the PM target time illustrated in Study 1 (see section 4.2.1), this suggests that individuals anticipate the occurrence of the PM target time according to the *numerical* proximity between the ongoing clock time and the PM target time: the more the clock is checked, the more amount of evidence about the external time is accumulated, the higher is the likelihood that people check the clock in the last interval before the PM target time, and perform accurate PM responses (Marsh et al., 2006; Smith, 2003). In terms of cognitive processes, monitoring time via *numerical* proximity would be supported by attentional mechanisms of evidence accumulation, which increases response thresholds for switching between the OT and time monitoring (Heathcote et al., 2015; Strickland et al., 2017).

The opposite scenario (i.e., when absolute and relative clock-checking are negatively correlated among each other, as found in Study 3) would indicate that the less clock checks the individual makes overall, the more clock checks s/he will make right before the PM target time; in other words, clock checks done temporally far from PM time interfere with later clock checks made in the last interval before the PM target time. Such interference might be due to the possibility that individuals try to estimate the remaining duration until the occurrence of the PM target time at each clock check. If a person has poor time estimation abilities, the internal representation of the PM target time would be noisier compared to another person with better temporal abilities (Turgeon et al., 2016); therefore, the likelihood of losing track of time internally is higher for the person with poor time estimation abilities (Gu et al., 2015), and s/he will try to avoid this by checking the clock more often during the whole duration of the TBPM task (Block & Zakay, 2006). However, since time estimation abilities are related to time monitoring especially during the last interval before the PM target time (Mioni et al., 2012; Mioni, Grondin, et al., 2020; Mioni & Stablum, 2014; Vanneste et al., 2016), a person with poor abilities of time estimation would likely fail to estimate the PM target time (i.e., s/he could under- or over-estimate its duration), experiencing difficulties in anticipating temporally the critical window around the PM target time in which is useful to check the clock more frequently, decreasing in turn the accuracy at the TBPM task

(Block & Zakay, 2006). Diversely, a person with good time estimation abilities would have an internal representation of the PM target time that is less noisy; consequently, the likelihood of losing internally the track of time is lower compared to the person with poorer time estimation abilities. Hence, s/he will need fewer clock during the initial moment of the task, being able to anticipate temporally the critical window around the PM target time in which is useful to check the clock more frequently, increasing in turn the accuracy at the TBPM task. The involvement of time estimation abilities in strategic time monitoring would suggest that individuals anticipate the occurrence of the PM target time according to the *temporal* proximity between the ongoing clock time and the PM target time (Gan & Guo, 2019; Labelle et al., 2009; Zakay & Block, 2004). In other words, people try to estimate the duration of the PM target time, basing their monitoring strategy on the temporal features of the external clock (i.e., the constant duration between clock ticks), rather than on its numerical properties (i.e.: the numerical progression of clock digits). Finally, it is also possible that no significant relationship between absolute and relative clock-checking is found, which would indicate that there was no preferential strategy adopted by the participants or induced by a given experimental manipulation, like in the control condition in Study 3.

7.3. Clock-speed and strategic time monitoring

To further test the assumptions above empirically, the data from Study 1 were re-analyzed using absolute and relative clock-checking, as well as the respective relationship with TBPM accuracy, as a function of the clock-speed. In Study 1, results showed that both faster and slower clock condition did not differ from the control condition in terms of both TBPM performance and time monitoring (**Figure 2** and **Figure 3**), thus supporting the hypothesis that people “waited” for the PM target time following the numerical metrical events, rather than the temporal relationship between them (i.e., the constant interval between clock ticks); hence, it is likely that participants used the clock not to estimate internally the temporal occurrence of the PM target time, but to detect the *numerical* proximity between the ongoing clock time with the PM target time, regardless of the duration between clock digits. Nonetheless, the results also indicated that participants in the slower clock condition increased time monitoring in the second TBPM block (i.e., the block *with* clock-speed manipulation) compared to the first TBPM block (i.e., the block *without* clock-speed manipulation), especially during the last minute before the PM target time. Hence, it is possible that participants, having more time to complete the task in presence of the slower clock, perhaps were expecting the PM target time earlier than the moment of its actual occurrence; if such anticipatory processes were engaged – especially before the PM target time occurrence – it cannot be excluded that internal time processes are involved in TBPM: in this sense, slower clock might have facilitated such anticipatory processes, so people might have used the clock to estimate the temporal occurrence of the PM cue based on the constant duration between clock digits (i.e., the *temporal* proximity between the ongoing time and the PM target time).

If slower clock facilitated the estimation of the PM target time – as speculated above – a negative correlation between the absolute and relative clock-checking should be found specifically for participants exposed to slower clock, which in turn should be associated positively with TBPM accuracy. Conversely, if faster clock facilitated the engagement of attentional processes exclusively, the correlation between absolute and relative clock-checking should be positive, suggesting that individuals anticipated the PM target time based on the *numerical* proximity between ongoing clock time and the PM target time, involving mechanisms of evidence accumulation and task-switching

(Marsh et al., 2006; Peper & Ball, 2022; Smith, 2003; Strickland et al., 2017); if this latter scenario is true, it can be argued that, while the slower clock facilitated the engagement of time estimation abilities, faster clock facilitated the engagement of attentional control processes. Moreover, in the section above in this chapter, it was argued that no significant relationship between absolute and relative clock-checking when no preferential strategy is adopted by the participants or induced by a given experimental manipulation. For this reason, absolute and relative clock-checking should not be significantly correlated during the first TBPM task, in which no clock-speed manipulation was administered, and therefore no specific modulation of strategic monitoring was expected. In other words, participants would not prefer any monitoring strategy when clock-speed was not manipulated, but then they would prefer a strategy based on time estimation when, during the second TBPM block, the clock was slower, and a strategy based on attentional control processes when, during the second TBPM block, the clock was faster.

7.3.1. Methods

7.3.1.1. Participants

In Experiment 1, analyses were carried out on a sample of 64 participants (age-range: 18-36 years; M_{age} = 23.2; SD_{age} = 4.26; 47 females), while in Experiment 2 analyses were carried out on a sample of 114 people (age-range: 18-35 years; M_{age} = 27.1; SD_{age} = 4.66; 62 females). The two samples from Experiment 1 and 2 were pooled together for the integrated analyses illustrated in this chapter; the final sample size comprised 140 participants (age-range: 18-35 years; M_{age} = 25.50; SD_{age} = 4.15; 87

females): 63 assigned to the faster clock condition, and 77 assigned to the slower clock condition[17].

7.3.1.2. Data processing

The behavioral data from Study 1 were re-processed in R – version 4.2.1 (R Core Team, 2022) – with the support of ChatGPT for building R-scripts (OpenAI, 2023). There were some minor methodological differences across Experiment 1 and 2 (i.e., the language, the number of OT trials), but the most important concerned the number of PM tasks within each TBPM block: in Experiment 1, five PM responses each block were collected, whereas in Experiment 2, two PM responses for the first TBPM block were collected (i.e., the block *without* clock-speed manipulation), and four PM responses were collected for the second TBPM block (i.e., the block *with* clock-speed manipulation: faster vs. slower clock-speed). This difference is not important for relative clock-checking because it is a standardized indicator that accounts of differences in the number of PM task as well as in the number of intervals used to calculate time monitoring (Joly-Burra et al., 2022). However, this difference is important for absolute clock-checking because it is a raw indicator that, as such, it is influenced by the number of PM tasks performed within a TBPM block (e.g., absolute clock-checking tends to be higher for the TBPM block with four PM tasks compared to the TBPM block with two PM tasks, simply because more PM tasks comes with more clock checks in order to be performed by participants). Hence, to overcome this limit, instead of computing the sum of all clock checks within a TBPM block, we calculate absolute clock-checking by

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[17] In Experiment 2, there was a third group of participants assigned to a control condition, which was not present in Experiment 1. Given that the aim was to pool together the samples from the Experiment 1 and 2, only data of participants in faster and slower clock conditions were retained from Experiment 2 (N = 76; M_{age} = 24.72; SD_{age} = 4.91; 50 females), because both conditions were administered across the two experiments identically, thus leaving out participants assigned in the control condition.

averaging the sum of clock checks for each PM task within a TBPM block; in this way, TBPM blocks with different number PM tasks can be compared via mean values of absolute clock-checking[18].

In Study 1, we used two indicators of TBPM performance: (1) the rate of TBPM task completion (in percentage) as a measure of whether people remembered (or not) to perform the PM task (Bastin & Meulemans, 2002; Yang et al., 2013), and (2) the timing error of the PM responses (in seconds) between the time-point when people performed the TBPM task and the time-point required by the TBPM task, as a measure of the temporal precision of the PM responses (Guo & Huang, 2019). These measures are not conventional in TBPM literature and were used because the dissociation between remembering of the PM task and the temporal precision of the PM responses was the main interest in Study 1. However, in the TBPM literature, a unique standardized TBPM accuracy score is often preferred, which is calculated as a binary score based on whether participants completed the task within a specified interval around the PM target time (see also Study 2, section 5.2.1); some studies have used lenient criteria with larger intervals (e.g.: Mioni & Stablum, 2014), while others used stricter criteria with smaller intervals (e.g.: Vanneste et al., 2016). Although there is no agreement on the interval used to compute a correct answer, which is completely arbitrary (Laera et al., 2023; Yang et al., 2013), the unique standardized TBPM accuracy score accounts for both whether people remembered (or not) to perform the PM task, as well as the temporal precision of the PM responses. In the following analyses, this standardized score of TBPM accuracy was used instead of both the percentage rate of TBPM task completion

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[18] The sum of clock checks over the whole TBPM block and the average sum for each PM tasks are mathematically similar, as their correlation is $r > .75$ (see Supplementary materials, section 11.4).

and the timing error of the PM responses, in order to simplify the multi-group path model, and to facilitate the parallel interpretation also with Study 3, in which the unique indicator of TBPM accuracy was used, but with a different TBPM task duration (i.e., 2-minutes PM tasks were used in Study 3, while 4-minutes PM tasks were used in Study 1). For these reasons, the same standard criterion of 10% used in Study 3 was used in the present study, so that a PM response was considered correct if it was made within ±12 seconds around PM target time (equivalent to 10% of the total interval of 4 minutes between PM target times).

7.3.2. Results

The analytical approach was equivalent to the approach used in Study 3: first, ANOVAs were calculated to investigate the effect of clock-speed on TBPM accuracy and time monitoring (controlling for the effect of the assessment setting: laboratory vs. online). Second, two multi-group path analyses were carried out – one for each TBPM block – to explore the strength of the predictive association between time monitoring and TBPM performance across clock-speed conditions (controlling for the effect of the assessment). For all ANOVA analyses, the effect sizes were calculated using partial eta squared values (η^2_p). Post-hoc *t*-tests were carried out applying Bonferroni's correction to the *p*-values (indicated as p_{adj}). For all statistical analyses, the alpha level was set at .05. The analyses were carried out in *Jamovi*, version 2.3.21.0 (The Jamovi Project, 2021). Descriptive statistics of TBPM accuracy and time monitoring are in **Table 7**.

Table 7

Descriptive statistics

		TBPM accuracy		**Absolute clock-checking**		**Relative clock-checking (%)**	
	Experimental condition	**First TBPM block**	**Second TBPM block**	**First TBPM block**	**Second TBPM block**	**First TBPM block**	**Second TBPM block**
M	faster	0.82	0.72	6.54	6.05	48.94	48.13
	slower	0.79	0.83	8.19	9.59	45.42	50.83
SD	faster	0.28	0.28	4.07	3.79	16.71	15.62
	slower	0.31	0.24	6.53	7.34	14.10	13.42

Note. Descriptive statistics of time-based prospective memory accuracy, absolute and relative clock-checking, as a function of the experimental conditions (clock-speed: faster, slower) and TBPM block (first, second). TBPM: time-based prospective memory.

7.3.2.1. Time-based prospective memory

The effect of clock-speed on TBPM accuracy (see **Figure 11A**) was computed using a mixed-design ANOVA, with one repeated measure (TBPM block: first vs. second) and two between-subject factors: Clock-speed (faster vs. slower), and Assessment (laboratory vs. online). The results showed that only the interaction effect TBPM block * Clock-speed was significant, $F(1, 136) = 10.91$, $p = .001$, $\eta^2_p = .074$. Post-hoc comparisons indicated that participants exposed to the faster clock dropped their TBPM accuracy from the first TBPM block ($M = .82$; $SD = .28$) to the second one ($M = .72$; $SD = .28$), and such drop in performance was statistically significant, $t(136) = 3.09$, $p_{adj} = .014$. Participants in the slower clock conditions did not show any difference in their performance across TBPM blocks ($p_{adj} = .821$). Furthermore, participants in the faster clock condition ($M = .72$; $SD = .28$) performed worse than participants in the slower clock condition ($M = .83$; $SD = .24$), but only during the second TBPM block, $t(136) = –2.93$, $p_{adj} = .024$; the same comparison for the first TBPM block was not statistically significant (p_{adj} = 1). The main effect of Assessment was significant, $F(1, 136) = 25.47$, $p < .001$, $\eta^2_p = .158$, with participants assessed in the laboratory ($M = .69$; $SD = .03$) performing worse than participants online ($M = .88$; $SD = .03$), $t(136) = –5.05$, $p_{adj} < .001$. All other effects were not significant ($p > .05$).

7.3.2.2. Time monitoring

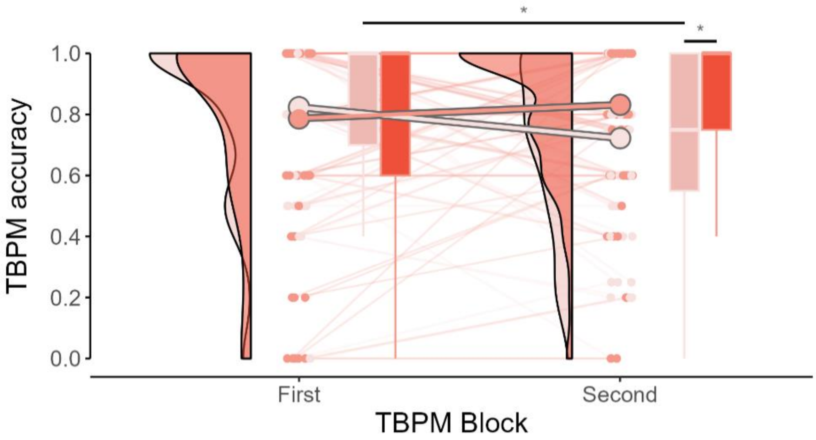
Two mixed-design ANOVAs were carried out on absolute and relative time monitoring separately, shown in **Figure 11B** and **Figure 11C**. Both ANOVAs comprised one repeated measure (TBPM block: first vs. second) and two between-subject factors: Clock-speed (faster vs. slower), and Assessment (laboratory vs. online). The results showed a significant interaction effect TBPM block * Clock-speed on absolute clock-checking, $F(1, 136) = 9.77$, $p = .002$, $\eta^2_p = .067$. Post-hoc comparisons indicated that participants exposed to the slower clock increased their overall frequency of clock checks in the second TBPM block ($M = 9.59$; $SD = 7.34$) compared to the first one ($M = 8.19$; $SD = 6.53$), and such increase in clock-checking frequency was statistically significant, $t(136) = 3.50$, $p_{adj} = .004$. Participants in the faster clock conditions did not show any difference in the frequency of absolute clock-checking across TBPM blocks (p_{adj} = 1). Participants in the faster clock condition ($M = 6.05$; $SD = 3.79$) checked the clock less often than participants in the slower clock condition ($M = 9.59$; $SD = 7.34$), but only during the second TBPM block, $t(136) = -4.10$, $p_{adj} < .001$; the same comparison for the first TBPM block was not statistically significant ($p_{adj} = .152$). The main effect of Assessment was significant too, $F(1, 136) = 37.73$, $p < .001$, $\eta^2_p = .217$, with participants assessed in the laboratory ($M = 4.87$; $SD = .08$) performing worse than participants online ($M = 9.98$; $SD = .07$), $t(136) = -6.14$, $p_{adj} < .001$. The analysis of relative clock-checking showed only a significant interaction effect TBPM block * Clock-speed, $F(1,$

136) = 5.49, p = .021, η^2_p = .039. Post-hoc comparisons indicated that participants exposed to the slower clock increased their monitoring strategicness from the first TBPM block (M = 45.94; SD = 14.10) to the second one (M = 50.83; SD = 13.43), and such increase was statistically significant, $t(136) = -3.07$, p_{adj} = .016. Participants in the faster clock conditions did not show any difference in the strategicness of clock-checking across TBPM blocks (p_{adj} = 1).

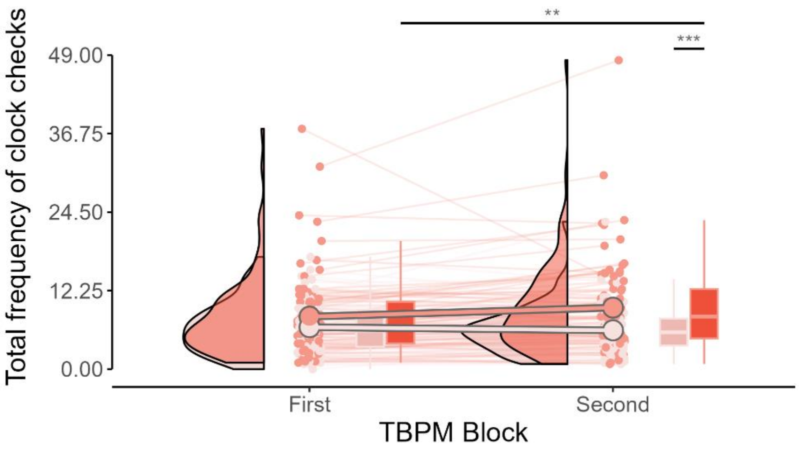
Figure 11

Main results from ANOVAs

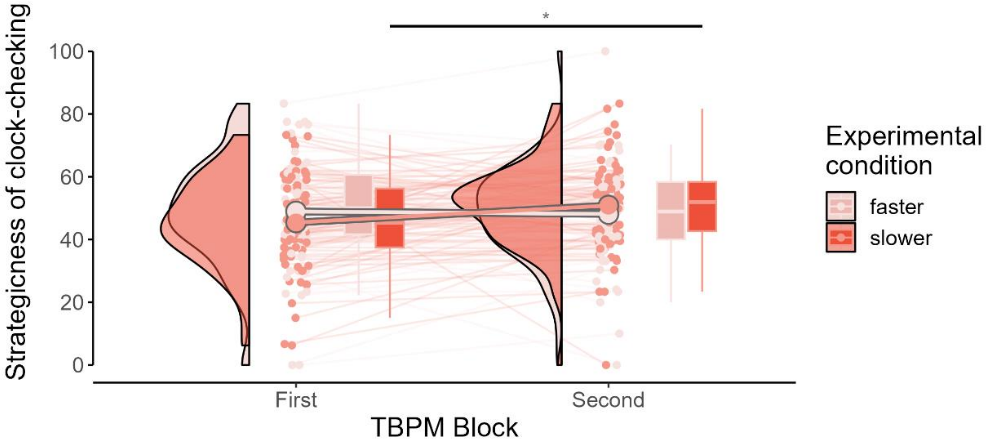
A) Time-based prospective memory



B) Absolute clock-checking



C) Relative clock-checking



Note. A graphic representation of the accuracy at the time-based prospective memory task (A) as well as absolute (B) and relative clock-checking (as a percentage; C) as a function of the experimental conditions (clock-speed: faster, slower) and TBPM block (first, second). TBPM: time-based prospective memory. * *p* < .05; ** *p* < .01; *** *p* < .001.

7.3.2.3. Path analysis

Multi-group path analyses were carried using the package *PATHj* in Jamovi (Gallucci, 2021) similarly to the path analysis carried out in Study 3 (see Path analysis); two identical models were tested separately: one for the first TBPM block (*without* clock-speed manipulation) and one for the second TBPM block (*with* clock-speed manipulation). The tested regression models (see **Figure 12**) comprised both absolute and relative clock-checking as predictors of TBPM accuracy across clock-speed conditions (faster vs. slower), controlling for the effect of assessment (laboratory vs. online); the two monitoring measures were allowed to correlate. A robust maximum-likelihood algorithm was used for model estimation; adjusted bias-corrected bootstrapping with 1000 samples was performed to calculate standard errors (for further statistical details, see the Supplementary material, section 11.3.2.1).

Concerning the first TBPM block (i.e., *without* clock-speed manipulation; **Figure 12A**), the multi-group model with no equality constraints provided a good statistical fit to the data, $\chi^2(12) = 124.38$, $p < .001$, $CFI > .99$, $RMSEA < .001$, $SRMR < .001$, and explained a significant portion of variance in TBPM accuracy for both groups of participants exposed to faster clock ($R^2 = .37$, $\chi^2_{\text{Wald}}(3) = 19.05$, $p < .001$) and slower clock condition ($R^2 = .49$, $\chi^2_{\text{Wald}}(3) = 75.45$, p < .001). Constraining the regression coefficients in the model to be equal across clock-speed conditions did not result in a statistically significant misfit ($\chi^2(5) = 6.22$, $p = .285$, $CFI = .99$, $RMSEA = .059$, $SRMR = .083$), suggesting that effects of monitoring on TBPM accuracy were similar across experimental conditions. Specifically, the model showed that both absolute and relative clock-checking predicted TBPM accuracy in the faster clock condition; however, relative clock-checking better predicted TBPM accuracy ($\beta = .45$, $p = .001$) than absolute clock-checking ($\beta = .32$, $p = .018$). The same pattern was found in the slower clock condition ($\beta_{\text{relative}} = .32$, $p_{relative} = .022$; $\beta_{\text{absolute}} = .48$, $p_{absolute} < .001$). Absolute and relative clock-checking did not correlate significantly with each other ($p > .05$).

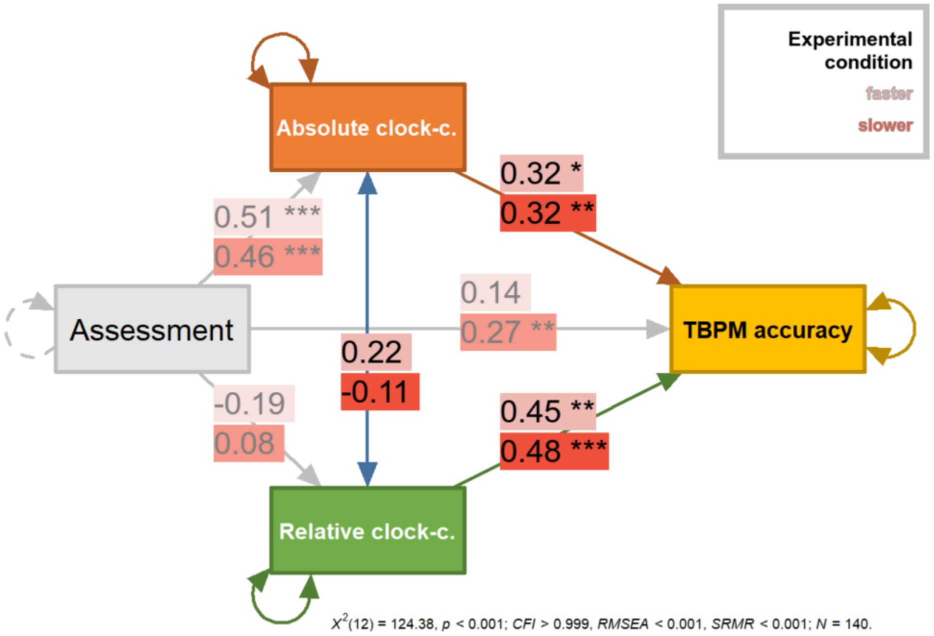
Concerning the second TBPM block (i.e., *with* clock-speed manipulation; **Figure 12B**), the multi-group model with no equality constraints provided a good statistical fit to the data, $\chi^2(12) = 116.47$, $p < .001$, $CFI > .99$, $RMSEA < .001$, $SRMR < .001$, and explained a significant portion of variance in TBPM accuracy for both groups of participants exposed to faster clock ($R^2 = .42$, $\chi^2_{\text{Wald}}(3) = 41.92$, $p < .001$) and slower clock ($R^2 = .36$, $\chi^2_{\text{Wald}}(3) = 27.63$, p < .001). Constraining the regression coefficients in the model to be equal across clock-speed conditions did not result in a statistically significant misfit ($\chi^2(5) = 9.51$, $p = .09$, $CFI = .96$, $RMSEA = .114$, $SRMR = .064$), suggesting that effects of monitoring on TBPM accuracy were similar across experimental conditions; however, some error was introduced in the constrained model, as $RMSEA$ =

.114 (well above the acceptance threshold of *RMSEA* = .06). Hence, the free model was retained for interpretation. The model showed that both absolute and relative clock-checking predicted TBPM accuracy in the slower clock condition; however, relative clock-checking better predicted TBPM accuracy (β = .39, *p* = .002) than absolute clock-checking (β = .36, *p* = .004). In the faster clock condition, only relative clock-checking predicted TBPM accuracy (β = .55, *p* < .001), whereas the effect of absolute clock-checking was not significant (*p* = .261). Absolute and relative clock-checking also correlated with each other in the slower clock condition (β = -.30, *p* = .043), but not in the faster clock condition (*p* = .985).

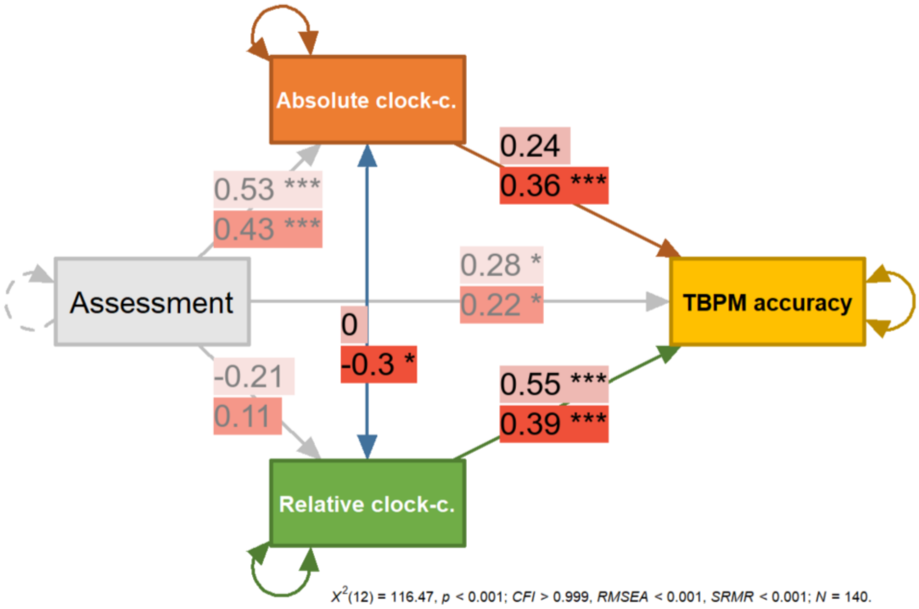
Figure 12

Results from multi-group path analysis

A) First block (without clock-speed manipulation)



B) Second block (with clock-speed manipulation)



Note. A graphical representation of the models tested in the path analysis, with regression and covariance coefficients for each experimental condition (clock-speed: faster, slower); effects in the models are controlled for the confounding effect of Assessment (laboratory, online). TBPM: time-based prospective memory; clock-c.: clock-checking. ** $p < .01$; *** $p < .001$.

7.3.3. Discussion

Results from Study 1 indicated no difference in TBPM performance between clock-speed conditions, which supported the hypothesis that time monitoring was driven by attentional mechanisms of evidence accumulation, which increases response thresholds for switching between the OT and time monitoring (Heathcote et al., 2015; Strickland et al., 2017). However, slower clock participants increased time monitoring in the second TBPM block, suggesting the possible engagement of internal time processing to anticipate the PM target time better. The slower clock possibly allowed participants to expect the PM target time earlier, facilitating anticipatory processes and the time estimation of the PM target time. According to the assumptions in 7.2, this should be observed in a negative relationship between absolute and relative clock-checking for participants in the slower clock condition (especially during the second TBPM block), which should be associates in turn with higher TBPM accuracy. The negative correlation between absolute and relative clock-checking would reflect a monitoring strategy based on internal time processes that individuals recruited to estimate the remaining duration until the PM target time, basing the strategic time monitoring on the *temporal* proximity between ongoing clock time and the PM target time. The results supported this prediction: as expected, during the first TBPM block, absolute and relative clock-checking were not related significantly with each other, suggesting there was no preferential strategy adopted by the participants when no clock-speed manipulation was administered; however, absolute and relative clock-checking correlated with each other during the second TBPM block, but only in the slower clock condition.

Results from faster clock condition did not confirm the predictions. It was expected that, if faster clock facilitated the engagement of attentional processes, the correlation between absolute and relative clock-checking should be positive, suggesting that individuals anticipated the PM target time based on the *numerical* proximity between ongoing clock time and the PM target time, involving mechanisms of evidence accumulation and task-switching (Marsh et al., 2006; Smith, 2003). The results showed that the correlation between absolute and relative clock-checking was close to zero in the faster clock condition during the second TBPM task; moreover, while both clock-checking indicators predicted TBPM accuracy in both faster and slower clock-speed condition during the first TBPM block (**Figure 12A**), in the second TBPM block only relative – and not absolute – clock-checking predicted TBPM accuracy in the faster clock condition (**Figure 12B**). This pattern of results suggested not only that faster clock did not induce any preferential strategy of time monitoring, but also that it might have caused interference specifically related the self-initiated decisional mechanism that allows participants to check the clock, regardless of when clock checks are made. Such interference was evident in the ANOVAs (**Figure 11**), which showed that participants exposed to the faster clock had significantly lower TBPM accuracy in the second compared to the first TBPM block, as well as compared to participants in the slower clock condition (but only during the second TBPM block). Such difference in TBPM accuracy was not associated with differences in relative clock-checking (which always predicted TBPM accuracy in multi-group path models), but rather with differences in absolute clock-checking, as participants in the faster clock condition checked the clock less often than participants in the slower clock condition, only during the second TBPM block (the same comparison for the first TBPM block was not statistically significant). In summary, while the slower clock facilitated the engagement of time estimation abilities, faster clock did not facilitate the engagement of attentional control processes, as predicted, but rather seemed to disrupt cognitive processes underlying time monitoring.

7.4. General discussion

In summary, results from both Study 1 and 3 can be furtherly interpreted using absolute and relative clock-checking and how they relate with each other. Specifically, results from Study 1 indicated that in the first TBPM block absolute and relative clock-checking were unrelated, suggesting no preference for a strategy when the clock speed was constant. In the second block, they correlated only in the slower clock condition, indicating engagement of internal time processes. Interestingly, in the faster clock condition, the frequency of clock checks didn't correlate with strategy, and overall clock checks didn't predict TBPM performance, which was worse in the faster condition. This suggests participants adopted different strategies in the faster condition, but it hindered their cognitive resources, resulting in lower TBPM accuracy. Results from study 3 suggested that internal time estimation might be employed only when strategic money losses were imposed on the TBPM task; this is also in line with other experimental studies that imposed motivational constraints on TBPM tasks, which concluded that, when these constraints were imposed, the TBPM accuracy improved, and such improvement was associated with lower frequency of clock-checks, but higher strategic monitoring behavior, which is presumably due to the engagement of time estimation abilities (Harris & Wilkins, 1982; Huang et al., 2014; Mioni & Stablum, 2014; Niedźwieńska & Barzykowski, 2012).

These empirical findings should be interpreted using the TWTE model (Block & Zakay, 1996; Harris & Wilkins, 1982), which is still the state-of-the-art in the field into (see section 2.2 for an overview on the theoretical and empirical framework of time monitoring). However, the interpretation in the context of the TWTE model might be challenging principally because the model assume that internal time processes are *always* engaged during time monitoring (especially in the test-wait cycles carried out during the initial moments of the TBPM tasks), regardless of external constraints or individual differences; yet, the results above indicated rather that this is the case only in specific circumstances (i.e., with slower clock, or when monetary deductions were applied to time monitoring). Moreover, the model does not explain neither how the person decide that another test is needed, nor the cognitive mechanisms through which people strategically monitor for the PM target time; furthermore, it assumes that people passively wait during the initial moment of the TBPM task, but it does not address the possible cognitive processes engaged while a person is waiting, and how they are eventually modulated over the time course of the TBPM task. Overall, beyond its descriptive power, the TWTE model in its current shape is an old theory that needs to be revised (Block et al., 2018; Block & Zakay, 2006) to further elucidate the cognitive processes underlying the engagement of different monitoring strategies during TBPM tasks. Hence, in the following section, a revised version of the TWTE is presented, which integrated both absolute and relative clock-checking and how they related to each other.

7.4.1. The TWTE-revised

The original TWTE model (Harris & Wilkins, 1982) and its new – revised – version (from now on referred in the text as *TWTE-r*) are graphically represented in **Figure 13**. The original version of the TWTE model by Harris and Wilkins (1982) stated that, after checking the clock and deciding that more time is needed for a given TBPM task, the individual waits until it's time to check the clock again, which gives him/her the opportunity to engage in the OT; such discontinuous monitoring behavior is formalized by test-wait cycles, followed by a test-exit sequence (see **Figure 13A**). In the new TWTE-r, both "test" and "wait" are integrated with two indicators of time monitoring (i.e., absolute, and relative clock-checking, respectively). The two indicators, formalized by Joly-Burra and colleagues (2022), reflect two interdependent aspects of time monitoring, namely the overall frequency of clock checks (absolute clock-checking), and the tendency to concentrate the clock checks for a given TBPM task in the last interval before the PM target time (relative clock-checking). Nonetheless, the cognitive processes underlying both absolute and relative clock-checking are currently unknown (Joly-Burra et al., 2022). The TWTE-r aim to elucidate them by integrating the two monitoring indicators within the TWTE model.

One of the conceptual limits of the TWTE is that it does not explain whether the "test" within the test-wait cycles underlie the same cognitive processes supporting the "test" within the test-exit cycles. One of the assumptions of the TWTE-r is that all clock-checks, regardless of when they are made, are necessarily supported by a self-initiated decisional mechanism; the absolute clock-checking indicator is the direct operationalization of such decisional mechanism (i.e., the "test"). However, the cognitive processes that lead to such decision cannot be disentangled only by considering absolute clock-checking (i.e., the "test" component alone); rather, it is the relationship between absolute and relative clock-checking that can elucidate that. A second conceptual limitation of the TWTE model is that it assumes that people simply "wait" during the initial moment of the TBPM task; yet such "passive" view of the wait phase is not realistic because people decide intentionally to wait until the PM target time, rather than passively pushed to do so. This limitation can be overcome by including the relative clock-checking as direct operationalization of the "wait" phase, which is rather "active" because it does not only account whether people wait, but also whether such "wait" phase is followed by a strategic increase of clock checks immediately before the PM target time. To summarize, in the TWTE-r (**Figure 13B**), the absolute clock-checking is a measure of the "test" phase, and constitutes the self-initiated component of time monitoring, while the relative clock-checking is a measure of the "wait" phase, and constitutes the active strategic component of time monitoring; the "exit" phase is measured by the TBPM accuracy, and it is the only phase that remains equivalent between the original and the revised TWTE model.

The correlation between "test" and "wait" (i.e., between absolute and relative clock-checking) is perhaps the most important conceptual aspect of the TWTE-r because it can be a measure of the strategy used during the TBPM task: a positive correlation would suggest that clock checks far from the PM time are important for accurate responses in the last interval before the PM target time (e.g., participants anticipate the PM time based on the *numerical* proximity between ongoing clock time and the PM target time, accumulating evidence through mechanisms of attentional control). Conversely, a negative correlation would indicate that clock checks done far from the PM time interfere with later checks, which may arise from individuals attempting to estimate the remaining duration until the PM target time based on the *temporal* proximity between ongoing clock time and the PM target time.

Hence, according to the assumptions of the TWTE-r, results from Study 1 suggested that differences in time monitoring across TBPM blocks in the slower clock condition could be due to the engagement of internal time processes that might have been facilitated in presence of the slower clock. During the first TBPM block, absolute and relative clock-checking did not correlate with each other, indicating that participants did not prefer any strategy over another when clock-speed was not manipulated. During the second TBPM block, absolute and relative clock-checking significantly correlated with each other, but only in the slower clock condition. Interestingly, the absolute frequency of clock checks did not correlate with the strategicness of time monitoring for participants exposed to faster clock, and the overall frequency of clock checks did not predict TBPM performance which, in turn, was impaired compared to the slower clock condition. The nearly-zero correlation between the two monitoring indicators suggested that, when exposed to the faster clock, participants adopted different strategies without preferring one over the other: some relied on internal time processes based on temporal proximity, while others used evidence accumulation processes linked to attentional control based on numerical proximity. Yet, regardless of the chosen strategy, the exposure to the faster clock appeared to hinder cognitive resources needed for effective clock-checking, leading to lower accuracy in the TBPM task compared to the slower clock condition, as shown by the ANOVAs. This pattern of results suggested not only that faster clock did not induce any preferential strategy of time monitoring, but also that it might have caused interference specifically related to the test phase, “which” is a measure of the self-initiated decisional mechanism that allows participants to check the clock, regardless of when clock checks are made.

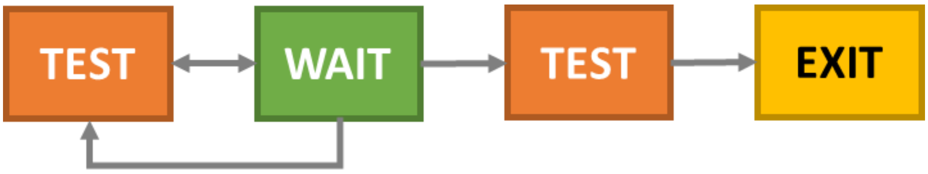
The results from Study 3 suggested that the involvement of time estimation was likely to be in place when motivational incentives were associated with the TBPM task (with the PM performance alone, as well as with time monitoring). However, when clock checking was costly (i.e., in the double-cost condition), internal time processes might have enhanced the strategic component of time monitoring, allowing participants to concentrate most of the clock checks temporally closer to the PM target time, thus avoiding further money losses. Diversely, in the single-cost condition, there was a motivational incentive to avoid losses only following PM misses, while having the opportunity to monitor time freely. Hence, although participants adopted a monitoring strategy based on time estimation also in the single-cost condition (as demonstrated by the negative correlation between absolute and relative clock-checking), good TBPM performance did not depend on strategic monitoring, as demonstrated by the empirical finding that the effect of relative clock-checking on TBPM accuracy failed to reach significance only in the single-cost condition. Hence, time estimation in the single-cost condition was not engaged to increase the strategicness of time monitoring (i.e., the wait phase), but rather to enhance the self-initiated decisional mechanism underlying time monitoring (i.e., the “test” phase) which was the only component of time monitoring associated with higher TBPM performance.

In summary, both jointed secondary data analyses from Study 1 and results from Study 3 showed that the TWTE-r model can explain the effect of clock-speed and monetary deduction in terms of strategic engagement (or not) of time estimation in a better way compared to the traditional analyses (see Study 1) and to the original TWTE model. The TWTE-r model is not only theoretically simple, but it is methodologically solid because it is based on reliable indicators of time monitoring (Joly-Burra et al., 2022), and it is easily testable with regression models.

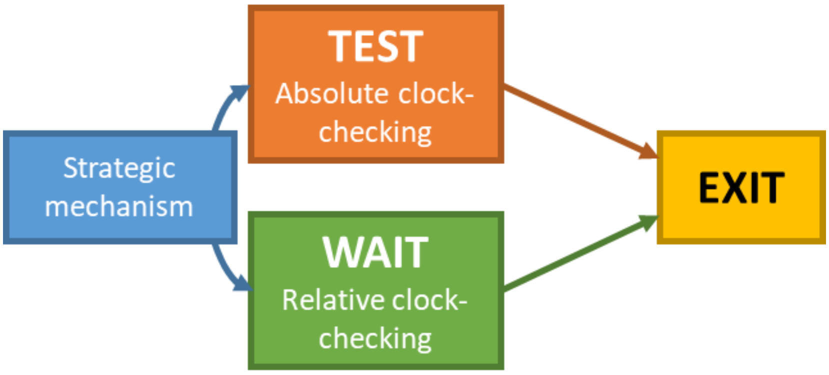
Figure 13

Graphic representation of the Test-Wait-Test-Exist model's versions

A) Original TWTE model



B) Revised model (TWTE-r)



Note. Graphic representation of the original version of the Test-Wait-Test-Exit model (TWTE; A) and its revised version (TWTE-r; B).

7.4.2. Limitations and future outlooks

The TWTE-r model have limitations that future studies need to address. For example, in both Study 1 and 3 there are no direct measures of time estimation, which is one of the main empirical limits in this context; future studies are needed to furtherly test the TWTE-r model, including correlational measures of time estimation tasks (Labelle et al., 2009), or experimental manipulations tackling internal time processes involved in time monitoring (Huang et al., 2014; Varley et al., 2021). Furthermore, it is currently unknown how participants chose one strategy over another; many studies in the literature highlighted the role of metacognition in explaining the choice of a given monitoring strategy which, in turn, affects PM performance (Cauvin et al., 2019; Gilbert, 2015; Scarampi & Gilbert, 2020; Schnitzspahn, Zeintl, et al., 2011). Hence, it would be interesting to evaluate this in future studies by assessing metacognitive processes related to time estimation and strategic monitoring. It is reasonable to expect that participants with better time estimation abilities (either objective and subjective – i.e., metacognitively) would preferentially engage internal time processes during strategic monitoring (which would be evident in a negative relationship between absolute and relative clock-checking), while other participants with poorer time estimation abilities would preferentially engage attentional control processes (which would be evident in a positive relationship between absolute and relative clock-checking). These aspects cannot be tested using the data from Study 1 and 3; therefore, future studies are needed to systematically investigate the role of metacognition and internal time processing in strategic monitoring and TBPM performance (see also section 8.3.3).

One further interesting question is whether and how the TWTE-r model explains self-initiated monitoring in EBPM too. According to the multi-process framework, self-initiated monitoring can take place also in EBPM, involving to top-down resource-demanding attentional processes (Einstein et al., 2005; McDaniel & Einstein, 2000; Smith & Bayen, 2004). Some authors suggested that strategic time monitoring in TBPM may be like strategic monitoring in EBPM, where participants use contextual information to improve PM accuracy (for an overview, see section 2.2.3). However, as mentioned above, there is one important difference between the TBPM and EBPM laboratory paradigms, so that contextual information in the EBPM are externally cued, whereas in a TBPM, the temporal information is maintained internally (Block & Zakay, 2006; Labelle et al., 2009; Vanneste et al., 2016); for this reason, at its current formulation, the multi-process model do not explain how self-initiated monitoring potentially occur during strategic time monitoring, because all the cognitive processes in the multi-process model are thought to be elicited rather externally from the environment (Scullin et al., 2013; Shelton & Scullin, 2017). The TWTE-r could overcome this major theoretical limitation as it is conceived specifically as a model of self-initiated monitoring.

In a recent paper (Laera et al., in preparation), this hypothesis was tested by assessing the effect of contextual information in EBPM that participants could check whenever they wished. Results showed that PM accuracy and cost increased with the presence of contextual information, and that participants monitored for the PM cue occurrence with uniform frequency over time (i.e., clock-checking followed a flat line – unlikely the "J-shaped" function found for time monitoring in TBPM), checking more often when the cue was non-focal compared to focal. Overall these results not only confirmed that elaboration of contextual information was likely to be related to attentional resources dedicated to the PM task, but also that the monitoring pattern was governed by different cognitive processes compared to TBPM: while the "J-shaped" function of time monitoring in TBPM is likely to be supported by time estimation abilities, the flat line function of "event" monitoring in EBPM is likely to be supported by mechanisms of accumulation evidence concerning the state of the PM cue occurrence at a given time-point (Bugg & Ball, 2017; Peper & Ball, 2022; Strickland et al., 2017). However, the reader should be aware that data from this study were not analyzed using the assumptions of the TWTE-r model; hence, a secondary-data analysis is needed to confirm the involvement of accumulation evidence mechanisms in self-initiated monitoring during EBPM, which should be evident in a positive correlation between absolute and relative checking of the PM cue. Moreover, this work was the first one to investigate self-initiated monitoring directly in EBPM, and future studies are needed to test assumptions of TWTE-r by assessing absolute and relative checking in EBPM (with contextual information), comparing monitoring across TBPM and EBPM to investigate whether the self-initiated processes involved in the two types of PM tasks are shared among each other.

8. General discussion

8.1. Discussion of individual research questions

8.1.1. Research question 1: How do participants monitor the target time in TBPM tasks? Do participants actively use internal timing processes?

The aim of Study 1 was to investigate whether a manipulation of the external time (i.e., clock-speed) affected time monitoring and TBPM performance. The results showed that, in both experiments, clock-speed had no impact on people's performance at the TBPM task (**Figure 2A** and **Figure 3A**, right panels) and, regardless of clock-speed, participants consistently remembered to perform the delayed intention to be performed (**Figure 2A** and **Figure 3A**, left panels). This suggested that participants attended the PM target time according to numerical events (i.e., clock ticks) rather than the constant interval between clock ticks, gauging the *numerical* proximity between the ongoing clock time and the PM target time, instead of estimating the target time internally. However, when the clock was slower, people tended to check the clock more frequently, especially in the last minute before the PM target time (**Figure 2B** and **Figure 3B**). This indicated that participants had more time to complete the task when they were assigned to the slower clock condition; for this reason, they perhaps were expecting the PM target time earlier than the moment of its actual occurrence. However, if such anticipatory processes were engaged – especially before the PM target time occurrence – it cannot be excluded that internal time processes are involved in TBPM: in this sense, slower clock might have facilitated such anticipatory processes, so people might have used the clock to estimate the temporal occurrence of the PM cue based on the constant duration between hierarchically-organized clock digits (i.e., the *temporal* proximity between the ongoing and the PM target time).

The TWTE-r model (**Figure 13B**) presented in the previous chapter further confirmed this interpretation (see chapter 7). Concerning the first TBPM block (**Figure 12A**), the findings suggested that both the overall frequency of clock checks and strategicness of clock-checking predicted TBPM accuracy similarly across clock-speed condition, and they were not related significantly with each other, suggesting the involvement of different strategies used by participants when no clock-speed manipulation was administered. Concerning the second TBPM block (**Figure 12B**), the findings indicated that effects of monitoring on TBPM accuracy were unlikely to be similar across experimental conditions. The overall frequency of clock checks and strategicness of clock-checking correlated with each other in the slower clock condition, but not in the faster clock condition; hence, this result confirmed the assumptions of the TWTE-r model, thus supporting the interpretation that the slower clock helped participants to estimate when the target time occurred based on the constant duration between clock digits (i.e., on the *temporal* proximity between the ongoing clock time and the PM target time). The engagement of internal time processes induced by slower clock affected TBPM performance; in fact, both the overall frequency of clock checks and strategicness of clock-checking predicted TBPM accuracy, but only in the slower clock condition; by contrast, only the strategicness of clock-checking predicted TBPM accuracy in the faster clock condition, whereas the effect of the overall frequency of clock checks was not significant.

While the slower clock facilitated the involvement of time estimation, in the faster clock condition the correlation between the overall frequency of clock checks and strategicness of clock-checking was close to zero, meaning that there was not a clear tendency by participants to engage one kind of strategy over another: some of them might have engaged internal time processes based on the *temporal* proximity between the ongoing clock time and the PM target time, while others might have engaged accumulation evidence processes driven by attentional control mechanisms, based on the *numerical* proximity between the ongoing clock time and the PM target time. In this regard, there is apparently a contradiction between results from traditional analyses presented in chapter 4 and the integrated analyses illustrated in chapter 7. Specifically, the results from traditional analyses revealed that, especially in the faster clock condition, participants engaged a monitoring strategy based on accumulation evidence processes (driven by attentional control mechanisms that rely on the elaboration of the *numerical* proximity between the ongoing clock time and the PM target time). The integrated analyses presented in chapter 7 challenged this conclusion, at least partially: if the *numerical* proximity between the ongoing clock time and the PM target time was used by individuals in the faster clock condition, this should have been evident in a significantly positive correlation between the overall frequency of clock checks and strategicness of clock-checking; yet, such correlation was close to zero, hence it did not support the conclusion derived from the traditional analyses. Instead, it seemed more likely not only that faster clock did not induce any change in the tendency towards a specific monitoring strategy, but also that the exposition to the faster clock induced an impairment in cognitive resources supporting strategic time monitoring and, consequently, the correct execution of the TBPM task, as demonstrated by the impairment in TBPM accuracy for participants in the faster compared to slower clock condition (**Figure 11**).

The results from Study 1, as well as from the re-analysis in chapter 7, can be interpreted considering the involvement of executive functions in internal time processing, as well as in light of the IR-AGM (Block, 1990; Block et al., 2018; Block & Zakay, 2006; Zakay, 1992; Zakay & Block, 1997). As mentioned above, several evidence showed that executive functions as attentional control processes are essential to estimate durations (Block & Gruber, 2014; Block & Zakay, 2006; Coull & Nobre, 1998; Jones, 2006), and are recruited during TBPM tasks too, in the evaluation of the current time with respect to the PM target time (Block et al., 2018; Block & Zakay, 2006; Cruz et al., 2017). Following the IR-AGM (Block, 1990; Block & Zakay, 2006; Zakay, 1992; Zakay & Block, 1997), in the TBPM block with the regular clock, people used a representation of seconds and minutes that is consolidated throughout the task via time monitoring. However, when they were exposed again to the same TBPM task, but with a faster clock, such representation would be no longer adequate (e.g.: it would contain more "pulses", so it would be "too long"); hence, people might wait "too much time" to reach the critical temporal window around the PM target time in which it is ideal to increase clock checks, decreasing in turn the mean clock check frequency – especially at last minute before target time – and consequently impairing the TBPM performance. On the contrary, people in the slower clock condition perhaps based their time monitoring on "shorter" time estimations, leading to higher clock check frequency which, in turn, improve TBPM accuracy. If interpreted within this framework, then it can be concluded that results from additional analyses reported in chapter 7 were in line with previous correlational and empirical evidence supporting the involvement of time estimation abilities in strategic time monitoring (Lecouvey et al., 2017; Mackinlay et al., 2009; Mioni et al., 2012, 2017; Mioni, Grondin, et al., 2020; Vanneste et al., 2016).

In summary, the engagement of internal time processes seemed to be beneficial only in presence of the slower clock; therefore, differential effects of different clock-speed are likely to occur: the slower clock likely facilitated strategic time monitoring and TBPM performance, promoting the engagement of time estimation; the faster clock interfered with self-initiated monitoring and TBPM performance, and involved time estimation to a less extent. To date, this was the first study that introduced clock-speed manipulation in TBPM, and future studies are needed to replicate the results and to further elucidate the cognitive processes underlying strategic time monitoring.

8.1.2. Research question 2: What are the age-related differences in time monitoring assessed in the laboratory setting? How do specific task-related factors affect age-related differences in TBPM?

Previous research indicates that age-related differences in TBPM performance and time monitoring when assessed using laboratory-based tasks (e.g., Lecouvey et al., 2017; Mioni & Stablum, 2014; Vanneste et al., 2016), but the extent of the age impact on time monitoring was unclear (Varley et al., 2021). The study reported in chapter 4 aimed to measure meta-analytically age-related differences in TBPM and time monitoring in laboratory-based TBPM tasks, as well as the link between these age effects, and to assess how task-specific factors (e.g., the duration of the PM target time, the frequency of PM tasks, and the interval criteria used to compute accuracy at the TBPM task) influence age-related differences in TBPM and time monitoring. The meta-analysis confirmed that younger adults outperformed older adults in TBPM tasks (**Figure 5A**), with a larger effect size compared to the previous meta-analysis in the literature (Henry et al., 2004). Moreover, the meta-analysis showed for the first time that younger adults exhibited higher clock-checking frequency than older adults (**Figure 5B**), and significant age effects in TBPM performance were likely to coincide with significant age effects in time monitoring (**Figure 6**).

The cognitive processes underlying age-related differences in TBPM remain debated; some argue impairments stem from time estimation in monitoring, while others attribute it to attentional processes like task-switching. Other authors argued that shorter PM target time times (e.g., < 2 minutes) might tap attentional control (Conte & McBride, 2018) impaired with age (Craik, 1986; Varley et al., 2021), while longer PM target time times (e.g., ≥ 2 minutes) allow older adults to allocate attention resources better over time, and to engage more time estimation processes, reducing age differences with the younger counterpart (Mioni, Capizzi, et al., 2020; Mioni et al., 2021; Varley et al., 2021). Nonetheless, it was still not clear whether and how the duration of the PM target time affect attention and/or time estimation processes in aging (Block & Zakay, 2006; Mioni & Stablum, 2014). To fill this gap, a meta-regression analysis was carried out (**Figure 7**), measuring the effect of PM task duration on age differences in TBPM performance and time monitoring. The results confirmed the hypothesis above, showing that, especially for shorter intervals (less than 4 minutes), younger adults were more accurate at the TBPM task and checked the clock more frequently. Hence, it is likely that age differences for shorter intervals are due to the involvement of attentional control processes (Conte & McBride, 2018), particularly impaired with aging (Craik, 1986; Varley et al., 2021). Diversely, longer PM target times (i.e., ≥ 4 minutes) may either allow more time to better distribute the attentional resources between OT and PM task, as well as engage more time estimation abilities compared to short PM target times, reducing the age differences in time monitoring and TBPM accuracy (Mioni, Capizzi, et al., 2020; Mioni et al., 2021; Varley et al., 2021).

Another task-related factor investigated in the meta-analysis was the PM task frequency, which might enhance learning processes that can compensate age differences in TBPM (Gan & Guo, 2019; D. C. Park et al., 1997). The first study that systematically investigated the effect of PM task frequency on aging in TBPM found no significant differences in accuracy and time monitoring between 6- and 12-event PM tasks (D. C. Park et al., 1997). However, a recent study has shown that repeating the same PM task with the same target time can lead to learning effects in younger adults (Gan & Guo, 2019); nonetheless, it is still unclear which processes are responsible for such learning effect, as it could be due either to better distribution of the attentional resources between OT and PM task, or to an improvement of time estimation abilities involved in the monitoring of the PM target time. Moreover, it is currently unknown whether and how the frequency of the TBPM task has similar effects on older adults' performance too. The results from the meta-analysis confirmed the presence of possible learning effects as a function of the PM task frequency. Specifically, the results showed that shorter PM target times and higher PM task frequencies was associated with smaller age effects in both TBPM performance and time monitoring; however, PM task frequency per se had no effect on age differences in time monitoring, indicating that such differences were not influenced by the PM task repetition, but only by the PM target time duration. Indeed, age differences in time monitoring were reduced by PM task frequency, but only when the PM target time was longer, suggesting that learning from task repetition could counteract or attenuate age effects in time monitoring which, in turn, affect age differences in TBPM performance.

Finally, the meta-analysis contributed methodologically by investigating the effect of the criterion chosen to compute PM accuracy on age-related TBPM differences. Typically, PM accuracy is measured as a binary score based on whether individuals complete a task within a specific time window around the PM target time. So far, only two studies explored how different interval criteria affected age-related differences in TBPM. One study found older adults struggled more with TBPM tasks than younger adults, regardless of interval chosen by the researcher (D. C. Park et al., 1997). In contrast, a recent study showed a larger interval cancelled out age differences in TBPM performance (Yang et al., 2013). Despite limited findings, no systematic exploration of how interval criteria impact age-related TBPM differences exists; yet the impact of this task-related factor is potentially huge because it can seriously affect the validity of the results' interpretation about age effects in TBPM. The meta-analysis showed for the first time that the effect of the criterion chosen to compute PM accuracy on age-related differences in TBPM performance was null; this finding is methodologically important, as it demonstrated that age effects are detected regardless of the arbitrary criterion chosen by the researcher to compute PM accuracy.

In summary, although the cognitive processes underlying age-related differences in TBPM remain debated, the present meta-analysis contributed, at least partially, to fill this gap. It was the first to quantify meta-analytically the age effects in time monitoring and its relationship with TBPM performance as well as the influence of task-related factors, enhancing the comprehension of cognitive mechanisms driving age-related effects in TBPM, and offering a methodological groundwork for future studies on aging.

8.1.3. Research question 3: How do monetary costs affect time monitoring and TBPM, as well as their relationship? Do people change time monitoring strategy?

Study 3 investigated the effect of monetary costs on time monitoring and TBPM. Participants were assigned to three experimental conditions: in one group of participants, missed PM responses were penalized with a monetary deduction (single-cost condition); in a second experimental group (double-cost condition), not only missed PM responses, but also time monitoring resulted in deductions from the endowment; in a control group, participants received no information regarding an additional incentive prior to the experiment. Based on research into motivated thinking (such as Horn & Freund, 2021a; Kruglanski et al., 2002; Penningroth & Scott, 2007; Shah et al., 2002), three scenarios were hypothesized (**Figure 8**). The hypothesis was that, compared to the other conditions, participants in the double-cost condition would use the clock less frequently, but more strategically, as only they would associate time monitoring with avoiding money losses, possibly lowering TBPM accuracy. Diversely, TBPM accuracy was expected to be highest in the single-cost scenario, due to the incentive to avoid losses while being allowed to monitoring time freely.

The results were in line with such predictions. Compared to other conditions, participants in the double-cost situation checked the clock less frequently overall (**Figure 9C**) but, despite fewer checks, they used the clock more strategically (**Figure 9D**). Clock-checking behavior did not differ between the single-cost and control conditions, suggesting that only money losses related to time monitoring influenced clock-checking. The highest accuracy in TBPM was observed in the single-cost condition, while the lowest accuracy was observed in the double-cost condition, as predicted (**Figure 9**). The multi-group path analysis (**Figure 10**) indicated that the total number of clock checks and the strategicness of clock-checking were negatively connected; this negative relationship was significant in the single- and double-cost conditions but not in the control condition. According to the TWTE-r model discussed in chapter 7, this negative correlation indicated the engagement of time estimation abilities guiding strategic monitoring and, consequently, TBPM performance. Since negative relationship was significant in the single- and double-cost conditions (but not in the control condition), time estimation was presumably involved specifically when motivational incentives were associated with the TBPM task (either on PM performance alone, as well as on time monitoring). However, in the double-cost condition, internal time processes might have enhanced the strategic component of time monitoring, which allowed participants to make fewer clock checks overall (thus minimizing money losses) and at the same time to concentrate most of them closer to the PM target time (maximizing the chances of higher TBPM performance). Conversely, when monitoring wasn't costly (i.e., in the single-cost condition), the TBPM performance might not have required strategic monitoring, as demonstrated by the finding that, only in the single-cost condition, the impact of relative clock-checking on TBPM accuracy wasn't statistically significant.

In summary, monetary costs affected time monitoring and TBPM, as well as their relationship and, according to the TWTE-r model, such effects were related to changes in the effect of time estimation on time monitoring: on the one hand, internal time processes may have had a beneficial effect on the strategic component of time monitoring (i.e., the “wait” phase) in the double-cost condition, allowing participants to prevent money losses linked to clock-checking; on the other hand, internal time processes may have had a beneficial effect on the self-initiated decisional mechanism underlying time monitoring (i.e., the “test” phase) in the single-cost condition, allowing participants to prevent money losses linked to the TBPM performance.

8.2. Integrated discussion

By integrating the answers to the individual research questions discussed above, a bigger and more comprehensive picture of the cognitive processes underlying strategic time monitoring and TBPM emerges. Participants used internal timing with slower clocks, benefiting strategic monitoring and TBPM performance; faster clocks hindered self-initiated monitoring and TBPM performance, disrupting internal time processing. Participants with a slower clock may have anticipated the PM target time earlier, having implicitly more time to complete the task. Hence, the results from Study 1 suggested that the more time people they have, the more the involvement of time estimation is facilitated. Study 2 further confirm this interpretation in the context of aging, showing that older adults perform worse than younger adults, and the clock less frequently, especially for shorter intervals (≤ 4 minutes). Age differences in shorter intervals may stem from attention control processes, which are particularly compromised in aging (Conte & McBride, 2018; Craik, 1986); longer intervals (> 4 minutes) might instead involve more time estimation abilities, potentially reducing age-related discrepancies in time monitoring and TBPM accuracy (Mioni et al., 2021; Mioni, Grondin, et al., 2020; Varley et al., 2021). Lastly, monetary costs influenced time monitoring and TBPM performance; the TWTE-r model suggested that these effects were tied to changes in how time estimation impacted time monitoring: enhancing the strategic monitoring component in the double-cost condition, to avoid losses from clock-checking, and bolstering the self-initiated decision component in the single-cost situation, to prevent losses related to TBPM performance with highest possible number of checks.

Taken together, these results can be explained with differential effects of internal time processes in guiding strategic monitoring behavior, which are influenced by task-related feature such as the duration of the PM target time (Bastin & Meulemans, 2002; D. C. Park et al., 1997), or constraints imposed on the TBPM task (Huang et al., 2014; Mioni & Stablum, 2014). In terms of cognitive processing, the only theoretical framework conceived specifically for TBPM is the IR-AGM (Block et al., 2018; Block & Zakay, 2006).

Although the IR-AGM is theoretically appealing and can be used to explain some of the results from this thesis (e.g., see section 4.5.1 and section 8.1.1), it has little empirical support, and is overlooked by most researchers in the field (Huang et al., 2014; Mioni & Stablum, 2014; Vanneste et al., 2016; Varley et al., 2021). Moreover, more solid and refined conceptual frameworks of subjective time and models of time perception have been advanced in the literature (Gu et al., 2015; Jones, 2006; Matell & Meck, 2004; Mondok & Wiener, 2023; Walsh, 2003), which found much more empirical support than the IR-AGM. As such, these other models and conceptual frameworks of time perception might be more helpful to explain the differential involvement of attentional processes and time estimation in TBPM observed in the studies of this thesis, and can be integrated with the TWTE-r model.

8.2.1. Subjective time and time-based prospective memory

The most recent and comprehensive conceptual framework of subjective time has been proposed by Thönes and Stocker (2019); according to this integrative framework, subjective time is the set of conscious and unconscious mental representations of physical temporal information. Three types of mental representations of time can be distinguished: (1) temporal processing (of order and simultaneity); (2) time-passage experience, or perceived time speed; (3) estimation of duration. While temporal processing represents basic (primarily unconscious) processes, time perception is conscious, and encompasses both the estimation of duration and the time-passage experience. Temporal processing abilities are modality-specific, while time perception is cross-modal and affected by higher level cognitive processes such as attention and memory (Thönes & Stocker, 2019).

8.2.1.1. *Elapsing time and duration estimation*

The relationship between duration and experience of time-passage is still debated in the literature of time perception: some studies showed that effects of induced expectations about duration affected experience of time-passage, supporting the idea that the two concepts are related (Tanaka & Yotsumoto, 2017); other studies showed that duration estimation and experience of time passage were uncorrelated (Droit-Volet & Wearden, 2016; Wearden, 2015), suggesting a dissociation between the concepts of passage and duration. Indeed, any perception of duration is related to the perception of time-passage, and a certain amount of passed time may be viewed as a specific duration (Thönes et al., 2018). Yet, having a concept of duration does not seem to be a prerequisite for the impression of time passage or vice versa: for example, imagine one is standing by a road, watching cars pass by; the person does not need to have a precise estimation of the cars' velocity to get a sense of cars motion. The cars moving by, whether fast or slow, create the impression of progressing without needing to calculate the duration or speed of cars. Similarly, the impression of time progressing does not necessarily needs the duration estimation of such time progression (Thönes & Stocker, 2019). Moreover, building a bridge between the concepts of passage and duration requires an implicit quantification of passage (e.g., "a certain amount period of passed time") that necessarily implies a metric duration-specific terminology; however, time passage is a "feeling", and as such is vaguer and often does not consist of metric terms (Wearden, 2015). Consequently, the application of pacemaker-accumulator models like the IR-AGM, which are intrinsically formulated in metric terms (i.e., countable temporal units as the correlate of duration perception), should be restricted to the representation of duration, and not extend to the perception of time passage (Thönes & Stocker, 2019).

Surprisingly, the TBPM paradigm is not mentioned within the conceptual framework proposed by Thönes and Stocker (2019) which, however, could still provide useful insights on the nature of TBPM tasks, as well as how people view and perform them. Time perception is likely to be involved in TBPM (Gan & Guo, 2019; Huang et al., 2014; Labelle et al., 2009); however, it is not established yet whether individuals check the clock relying more on time estimation abilities or the experience of time-passage. If the IR-AGM is applied to TBPM, then strategic time monitoring should be guided by the representation of duration, and not by the perception of time-passage. However, as mentioned above, the IR-AGM is problematic because it lacks of behavioral and neural evidence (see footnote 4); moreover, it cannot be excluded that some individuals still prefer to check the clock based on feelings of time-passage (e.g., some might feel that it is time to perform the task) instead of explicitly estimate the duration of the PM target time as instead assumed by the IR-AGM; in such scenario, the clock checks are made because of such feeling of time, rather than being a function of an estimated duration. Therefore, the IR-AGM can explain only partially how individuals use the external clock, and the usage of time estimation abilities and/or the experience of time-passage remains an open question.

8.2.1.2. Prediction and quantification of time

A further methodological framework of time perception that can be helpful for TBPM too has been proposed in a recent meta-analysis by Naghibi and colleagues (2023). The authors reviewed the time perception literature, distinguishing two typologies of tasks: (1) quantification, and (2) prediction. The quantification tasks required that duration is explicitly estimated, like in time re-production tasks (see footnote 3); in these tasks, the goal is inherently temporal. By contrast, prediction tasks allowed the participant to make use of temporal information to predict the onset of an upcoming event to respond to it more quickly or accurately; in these tasks, the goal is sensorimotor (i.e., inherently non-temporal). The distinction between quantification and prediction of time overlaps with the distinction between explicit and implicit timing (Droit-Volet et al., 2019): in explicit tasks, participants are explicitly instructed that they had to learn or respond to durations; in implicit tasks, the temporal pattern of sensory stimuli is used to achieve non-temporal goals. For example, the velocity parameters of an incoming vehicle can be used to estimate when it would likely reach someone to determine whether s/he can safely cross the road; in this scenario, temporal predictions are used to achieve a non-temporal goal (i.e., to safely cross the road) rather than being used to provide explicit estimates of time (Coull et al., 2011; Turgeon et al., 2016). In terms of cognitive mechanisms, the time quantification (i.e., explicit timing) is related to temporal information conveyed by the duration to be estimated as a function of the elapsed time, while time prediction (i.e., implicit timing) is related to temporal information conveyed by the elapsed time as statistical likelihood of the occurrence of a given time-point (Naghibi et al., 2023).

TBPM is an interesting case within this methodological perspective, because any TBPM task can be viewed either as inherently temporal, if the duration of the PM target time is explicitly estimated, or as non-temporal, if the person focuses on the action of the TBPM task, thus using the clock time only to predict the onset of the PM target time. This methodological perspective can be integrated with the TWTE-r model illustrated in chapter 7: a monitoring strategy driven by the estimation of the PM target time (empirically evident as a negative correlation between frequency of clock checks and monitoring strategicness) should aim to quantify the PM target time; hence, strategic time monitoring should be based on duration rather than time-passage. Conversely, a monitoring strategy based on the numerical match between clock time and the PM target time (empirically evident as a positive correlation between frequency of clock checks and monitoring strategicness) should aim to predict the occurrence of the PM target time and, because the match involves numerical (i.e., non-temporal) features, the PM target time should not be tracked via time estimation, but rather according to the experience of time-passage (i.e., the progression of clock ticks) and on the *numerical* proximity with the ongoing task time. Interestingly, using the methodological framework by Naghibi and colleagues (2023) integrated with the TWTE-model allows to address, at least partially, the open question on how individuals use the external clock, whether engaging time estimation abilities or the experience of time-passage. Since TBPM tasks can be viewed either as temporal or non-temporal, participants can engage both time estimation abilities or the experience of time-passage according to the TBPM task's view (i.e., temporal, or non-temporal, respectively).

8.2.1.3. Time perception in time-based prospective memory

Results from all studies comprised within the present thesis can be furtherly interpreted using these integrated frameworks (Naghibi et al., 2023; Thönes & Stocker, 2019). For example, in Study 1, the exposition to the slower clock might have promoted a view of the TBPM task as a temporal task; hence, participants tried to quantify the PM target time using a monitoring strategy driven by the estimation of the PM target time; this is empirically evident in the negative correlation between frequency of clock checks and monitoring strategicness, found selectively when the clock was slower. However, in the faster clock condition, such tendency was not so clear, as the correlation was close to zero. Hence, faster clock did not induce any change in the TBPM task's view, as well as no clear monitoring strategy since it is not possible to determine whether it was driven by time estimation, or rather by the experience of time-passage (i.e., the progression of clock ticks). However, faster clock might have interfered with cognitive processes involved in TBPM because accuracy was impaired in the faster compared to the slower clock condition, and participants exposed to faster clock checked the clock less often compared to participants exposed to the slower clock (despite having the same degree of monitoring strategicness).

Results from Study 2 revealed that age differences for TBPM tasks with shorter target times may be originated by attention control processes, which are particularly compromised in aging (Conte & McBride, 2018; Craik, 1986), while longer intervals (>4 minutes) might instead involve more time estimation abilities, potentially reducing age-related differences in time monitoring and TBPM accuracy (Mioni et al., 2021; Mioni, Grondin, et al., 2020; Varley et al., 2021). Older might tend to view TBPM tasks as inherently temporal, thus trying to estimate the duration of the PM target time, especially for tasks with longer PM target times; hence monitoring based on duration (rather than time-passage) should be preferred by older adults as it can potentially compensate age-related decline in attentional control. Diversely, if the TBPM task comprises shorter PM target times, the involvement of attention control processes is more likely, which implies that the TBPM task might be viewed as non-temporal, and the clock time are used to predict the onset of the PM target time, rather than to estimate its duration. However, such processes might be particularly difficult for older adults, which might fail to engage a monitoring strategy based on the experience of time-passage (i.e., the progression of clock ticks) and on the *numerical* proximity with the ongoing task time. Studies from time perception and aging confirm this speculation, as they shown not only that the pace of the internal clock “slows down” with increasing aging (Baudouin et al., 2019; Lamotte & Droit-Volet, 2017) – which affects the perception of time-passage (Wearden et al., 2017) – but also that older adults fail mainly in predicting time, rather than in time estimation (Lamotte & Droit-Volet, 2017; Turgeon et al., 2016).

In study 3, results showed that monetary costs influenced time monitoring and TBPM performance. Specifically, charging the TBPM tasks might have induced participants to view the TBPM task temporal as evident by the negative correlation between frequency of clock checks and monitoring strategicness in both single- and double-cost condition. However, the effects of monetary costs on time monitoring were tied to changes in how time estimation impacted indicators of time monitoring: in the double-cost condition, time estimation enhanced the strategic monitoring component, to avoid losses from clock-checking; in the single-cost condition, time estimation bolstered the self-initiated decision-making component, to prevent losses related to TBPM performance while having the possibility to make the highest possible number of checks. Diversely, in the control condition, no manipulation was delivered, and therefore no clear TBPM task's view and monitoring strategy was induced: some participants might have viewed the TBPM task as non-temporal, preferring to predict the PM target time occurrence, while others might have viewed the TBPM task as temporal, preferring to estimate the duration of the PM target time.

In summary, both the conceptual framework of subjective time by Thönes and Stocker (2019), and the methodological framework proposed by Naghibi and colleagues (2023), are potentially able to refine the empirical findings from Study 1 and 3, as well as the meta-analytical findings from Study 2, fostering the theoretical discussion around the involvement of time perception in TBPM, and providing useful insights on how people use time to execute delayed intentions at the appropriate moment in the future.

8.2.2. Event- and time-based strategy

Based on the discussion above, it is possible to further improve conceptually the TWTE-r model presented in chapter 7 by establishing a novel theoretical characterization of strategic time monitoring in TBPM. Overall, the kind of strategy used depends on several aspects: different views of the TBPM task (i.e., temporal vs. non-temporal) induced by a given manipulation, or preferred by participants in a given sample, can determine the external temporal feature (i.e., passage or duration) associated with specific internal elaboration of time (i.e., prediction or quantification) engaged by the cognitive system to guide strategic time monitoring, as well as the cognitive mechanisms (evidence accumulation or time estimation); the empirical evidence to support the usage of a specific strategy is determined by the direction of the correlation between the frequency of clock checks (absolute clock-checking) and the strategicness of time monitoring (relative clock-checking).

Overall, two kinds of strategies can be distinguished: a time-based strategy (TBS), and an event-based strategy (EBS). The TBS is engaged when the TBPM task is viewed as temporal which, in turn, promotes a monitoring behavior based on time quantification, and guided by the temporal feature of duration; the main cognitive mechanisms engaged is therefore the estimation of the PM target time. The empirical evidence to support the usage of the TBS is the negative correlation between absolute and relative clock-checking. Conversely, the EBS is engaged when the TBPM task is viewed as non-temporal which, in turn, promotes a monitoring behavior based on time prediction, and guided by the temporal feature of time-passage; the main cognitive mechanisms engaged is therefore attentional, and it relies on the accumulation evidence about the occurrence of the PM target time. The empirical evidence to support the usage of the

EBS is the positive correlation between absolute and relative clock-checking. A schematic representation of the two strategic approaches is reported in **Table 8**.

Interestingly, a recent article provided a further distinction between time-period and time-point PM tasks (Gan et al., 2023). The time-period PM tasks hold ambiguous time information and provide individuals with a time range rather than a specific time in the future (e.g., water will boil in 5-10 minutes); by contrast, the time-point PM holds clear time information and can provide individuals with accurate information to predict when PM cues occurs (e.g., appointment with the doctor at 10:00 a.m.). The authors further argued that PM involves two aspects of attention. The first is internal attention, which refers to the individual's efforts in internal cognitive processing (e.g., time estimation and monitoring cues) and it is operationalized as OT performance; the second is external attention, which refers to the individual's attention to external information, for example, checking the clock and setting reminders, and it is operationalized in the frequency of clock-checking, Although this perspective is interesting under a taxonomical perspective (i.e., it is the first attempt to further classify TBPM tasks, so far conceived as a monolithic typology of PM task; for a similar classification, see Del Missier et al., 2021), it comes at least with a couple of limitations: (1) The nature of the TBPM task (i.e., time-point or time-period) might not be related on how people see the TBPM itself (i.e., as temporal or as non-temporal), because this does not only depends from the external constraints like (or from specific experimental manipulations), but also from metacognitive strategies and individual differences in attentional control processes and time estimation abilities. (2) Attention towards external and internal stimuli cannot be operationalized only with OT and time monitoring respectively, because, on the one hand, the OT is supported by the elaboration of external stimuli (i.e., the OT trials) and might not only reflect time estimation, and on the other hand, it cannot be excluded that clock-checking might be driven strategically by internal processes of temporal attention (Block & Zakay, 2006; Labelle et al., 2009; Waldum & McDaniel, 2016). Moreover, the distinction between external and internal attention might be deceptive because the function of attention is to act as "interface" between internal and external stimuli (Braver, 2012; Corbetta & Shulman, 2002; Raichle & Snyder, 2007); in the context of PM, there is a constant interplay between elaboration of environmental stimuli and internal intention-related processes of maintenance and retrieval (Cona, Scarpazza, et al., 2015; Cruz et al., 2017; Strickland et al., 2023) which makes the distinction between external and internal attention theoretically weak. In summary, this approach might be limited in explaining the cognitive processes underlying time monitoring, also because it considers the individual as rather passively affected by the nature of the PM task; the approach taken by the TWTE-r model, as well as the formalization of strategic approaches (i.e., TBS and EBS), assume instead an active role of individuals interacting with the environment, therefore providing much more solid theoretical arguments on the active engagement of strategic time monitoring and the underlying cognitive processes.

Table 8

Monitoring strategies in prospective memory

Strategy	**TBPM task's view**	**External temporal feature**	**Internal temporal elaboration**	**Main cognitive process**	**Correlation between absolute & relative clock-c.**
Event-based (EBS)	Non-temporal	Passage	Prediction	Evidence accumulation	Positive
Time-based (TBS)	Temporal	Duration	Quantification	Time estimation	Negative

Note. Schematic illustration of the two monitoring strategies (event- and time-based) conceptualized with the TWTE-r model. Along with each specific strategy, it is reported TBPM task's views by participants (non-temporal vs. temporal), the main temporal feature that guides time monitoring (time passage vs. duration), the main cognitive mechanism (evidence accumulation vs. time estimation), and the empirical measure as a correlation between the frequency of clock checks (i.e., the absolute clock-checking) and the monitoring strategicness (i.e., the relative clock-checking); clock-c.: clock-checking.

8.2.2.1. Strategic approaches in time-based prospective memory

According to the distinction between TBS and EBS, it is possible to further conceptualize the kind of strategy put in place by participants in the three studies of the present thesis. Overall, the results from all studies suggested the engagement of TBS in TBPM. In Study 1, the results showed a negative correlation between frequency of clock checks and monitoring strategicness, found selectively in the slower clock condition, only during the second TBPM block (i.e., with clock-speed manipulation); diversely, faster clock might have interfered with cognitive processes involved in TBPM because accuracy was impaired and participants checked the clock less often compared to the slower clock condition. Hence, while the exposition to the slower clock might have promoted a TBS, the exposition to the faster clock was not associated with a clear monitoring strategy. The engagement of TBS might be beneficial also for older adults: results from Study 2 revealed that age differences for TBPM tasks with shorter target times may stem from attention control processes, which are particularly compromised in aging (Conte & McBride, 2018; Craik, 1986), while longer intervals might instead involve more time estimation abilities, potentially reducing age-related differences in time monitoring and TBPM accuracy (Mioni et al., 2021; Mioni, Grondin, et al., 2020; Varley et al., 2021). Hence, it is likely that older adults preferred the TBS because they can engage explicit time estimation processes, reducing age-related differences, but if the TBPM task comprises shorter PM target times, then this is more difficult, as TBPM tasks with shorter PM target times are more likely to induce an EBS based on time-passage, heavily related to the speed of the internal clock, which slows down with age (Baudouin et al., 2019; Lamotte & Droit-Volet, 2017; Wearden et al., 2017). In study 3, results showed that monetary costs influenced time monitoring and TBPM performance. Charging TBPM task induced the engagement of the TBS, as shown by the negative correlation between frequency of clock checks and monitoring strategicness in both single- and double-cost condition, but not in the control condition. In the double-cost condition, the TBS affected the strategic monitoring component, presumably because participants avoided losses from clock-checking maximizing the strategic behavior and TBPM accuracy with the fewest number of clock checks; in the single-cost condition, the TBS affected the self-initiated decision-making component, to prevent losses related to TBPM performance with highest possible number of checks. Diversely, in the control condition, no manipulation was administrated, and therefore no clear strategy was found (this is also consistent with the results from Study 1, which showed that in the first TBPM block – the block *without* clock-speed manipulation – participants did not show any tendency towards the TBS or the EBS).

8.2.2.2. Strategic approaches in event-based prospective memory

The distinction between TBS and EBS is like the well-established distinction between TBPM and EBPM. As argued in chapter 2, the difference between EBPM and TBPM tasks is in the way the PM cue is monitored, namely in response to external time during TBPM tasks, or in response to some features in the environment during EBPM tasks, presented along the OT that people perform while remembering the delayed intention. Hence, it is reasonable to argue that TBPM tasks induce TBS because the PM cue (i.e., the PM target time) can be monitored estimating the remaining duration until its occurrence; diversely, EBPM tasks should induce EBS because the PM cue occurrence cannot be estimated temporally, but only matching the ongoing environmental cues with the internal representation of the PM cue. However, several studies showed the impact of contextual information in the environment on EBPM performance and cue monitoring (see section 2.2.3), indicating that the presence of context information about the next PM cue occurrence improved PM performance. Since clock time is a predictable stream of environmental information, it cannot be excluded that strategic time monitoring in TBPM may be similar to strategic "event" monitoring in EBPM, where participants use contextual information (e.g., trial counters) to improve PM accuracy (Graf & Grondin, 2006; Peper & Ball, 2022). Hence, it cannot be excluded that TBS can be engaged also in EBPM tasks (Laera et al., in preparation), but only when it is possible to approximately infer how much time is left to the occurrence of the PM cue. Conversely, EBS can be engaged in TBPM tasks too, especially for shorter PM target times, as shown indirectly by Study 2, or when participants see the TBPM task as non-temporal. Overall, the role of TBS and EBS in EBPM and TBPM is currently unknown, and it is a matter for future research.

Another interesting aspect that future studies need to address is related to the possibility that participants might adapt the monitoring strategy across PM tasks within a block, similarly to the dynamic interplay between strategic monitoring and spontaneous retrieval described by the dynamic multi-process framework (Scullin et al., 2013; Shelton & Scullin, 2017); for example, one could start a given TBPM block using an strategy based on attentional processes (i.e., EBS), and only later engaging a strategy based on internal time processes (i.e., TBS). So far it was assumed that participants chose one strategy over another for the whole duration of a given PM block; yet, such scenario might be unrealistic, while the dynamic interplay between the two kind of strategic approaches would more adaptive, as it should guarantee flexibility in task execution (Shelton & Scullin, 2017), and would promote optimal learning of repeated PM tasks over time (Gan & Guo, 2019), as well as a strategic allocation of attentional resources between the OT and the PM task (Heathcote et al., 2015).

8.3. Future perspectives and methodological considerations

TBPM is a hot topic of research, and it is likely that, in the next years, the number of research in this field will rise. The first promising venue for future research is replicating the present findings. Study 1 needs to be replicated in the laboratory including the control condition which was present only in Experiment 2. Similarly, effects of monetary losses on TBPM needs to be replicated in the laboratory too, as Study 3 was conducted only online. Meta-analytical results from Study 2 can help future research in the field; specifically, the results indicated that, regardless how researchers code accuracy, TBPM paradigm can detect age-related differences consistently; yet researchers should be aware that changing task-related parameters such as the frequency of the PM task and the duration of the PM target time can affect the magnitude of the age effect in both time monitoring and TBPM performance. In this regard, the meta-analysis calls for further investigation on the effects of task-related factors on the modulation of the cognitive processes involved in TBPM, and how they are affected by aging. Finally, more research is needed to further validate the TWTE-r model, especially including direct measures of time estimation that were not administered in both Study 1 and 3.

8.3.1. Prospective memory and time perception: a necessary connection

PM is a bridge between the attentional and memory domains (Cona, Scarpazza, et al., 2015; Roediger, 1996). However, as extensively argued above, TBPM is likely to involve time perception along with memory and attentional control processes. Yet, despite the specific role of time perception in TBPM is still not fully understood. Besides all reasons illustrated in sections above, this is partially due also to the lack of communication between TBPM research field and the field of time perception. As already mentioned in footnote 3, Block and colleagues (2018) already argued that TBPM tasks are similar to the dual-task time-production paradigm: in both paradigms, participant have to prospectively attend a given duration while engaged in a secondary – non-temporal – task (i.e., the OT in TBPM, and a secondary non-temporal task in the time production paradigm); however, in the time production task, this is achieved without the aid of an external clock, which is present in the TBPM tasks instead (Block et al., 2018, p. 45). Therefore, TBPM and time estimation share some similarities; hence, the two fields of research need to be bridged because, although it is helpful to dissociate cognitive functions at both behavioral and neural level, in daily life time estimation and TBPM exist because they are integrated in a more complex system, where the interplay between functions is essential to understand how the brain deals with delayed intentions based on time.

One possible way to disentangle the interplay between time perception and TBPM is to investigate time- and motor-related processes. In daily life, intentions have not the same meaning: for some of them, the temporal aspect is more important, while for others, the action is more important than the moment of its execution. For example, imagine someone is working on a project. If the project deadline is very strict, the person might prioritize completing the project by the set date, even if this means sacrificing some of the finer details of the project; conversely, if the project deadline is less strict, the person might focus on the quality of the work, taking the time to refine and polish it, without worrying too much about meeting the deadline. In the laboratory setting, such scenario can be reproduced manipulating the importance towards specific aspects of the TBPM task, either via task instructions or using motivational incentives (like in Study 3): in one condition, being on time is more important than performing the action, while in a second condition, performing the action is more important than performing it on time. According to the TWTE-r model, increasing the importance of the intention's time should be associated with a TBS, because it is likely that such condition would induce a view of the TBPM task as temporal which, in turn, should promote a monitoring behavior based on time quantification and guided by the temporal feature of duration; diversely, increasing the importance of the intention's action should be associated with an EBS, because it is likely that such condition would induce a view of the TBPM task as non-temporal which, in turn, should promote a monitoring behavior based on time prediction and guided by the temporal feature of time-passage. Although further studies need to address empirically such speculative predictions, the future of research at the intersection of TBPM and time perception looks promising and exciting, not only to further understand cognition underlying strategic monitoring, but also to develop interventions helping vulnerable populations to improve functional autonomy and well-being (see section below).

8.3.2. Applied perspective

The bridge between time perception and TBPM can be extremely helpful to support novel research aiming to improve quality of life and autonomous functioning in people that have difficulties in daily TBPM tasks. There are many studies showing impairments in TBPM tasks within several psychopathological disorders, such as psychosis, depression, obsessive-compulsive disorder, and attention deficit/hyperactivity disorder (Au et al., 2017; Bhat et al., 2018; Mioni et al., 2017; Zhou et al., 2017), as well as neurological conditions, such as brain injury, dementia, and stroke (Kant et al., 2014; Liu et al., 2021; Mioni et al., 2012). However, the link between impairments in TBPM and alterations in time perception within these clinical conditions has rarely been investigated systematically (correlational measures are reported in Mioni et al., 2012, 2017). The only exception is the narrative review by Liu and colleagues (2021), which elegantly explained the importance of the connection between difficulties in time perception and TBPM in the context of dementia, directly linking disruptions in time perception with difficulties in TBPM tasks (Liu et al., 2021). PM deficits are well-established in Alzheimer's disease and frontotemporal dementia (for a review, see Van Den Berg et al., 2012), and such difficulties are linked to the integrity and brain changes in prefrontal, medial temporal, and posterior parietal regions (Dermody et al., 2016; Kamminga et al., 2014). As mentioned above, these regions are important also for time perception: for example, the anterior cingulate cortex, crucial for cognitive control in timing tasks (Akam et al., 2021; Riemer et al., 2019; van Veen et al., 2004), has been found also in time monitoring during TBPM tasks (Cona, Scarpazza, et al., 2015; Cruz et al., 2017). Inferior parietal regions like pre-cuneus reflect associative mechanisms related to time estimation (Coull et al., 2011; Walsh, 2003, 2015), and it is also thought to be involved in monitoring delayed intentions (Cona, Scarpazza, et al., 2015). Pre-frontal regions like the dorso-lateral or the inferior gyrus were related to both TBPM retrieval and time processing of intervals higher than 1 seconds (Bornkessel-Schlesewsky & Schlesewsky, 2013; Gu et al., 2015; Ogden et al., 2011; Zakay & Block, 2004). Although studies on subjective time in dementia remain sparse (Liu et al., 2021), investigating the functional relevance of subjective timing and TBPM disturbances in dementia is paramount. Moreover, further research is needed to deepen the knowledge about the cognitive mechanisms underlying time perception and PM in everyday life, and this is very important also in an applied perspective because uncovering such neurocognitive mechanisms may be fruitful in helping families, caregivers, older adults, or individuals with dementia to navigate disruptions to their fundamental capacities for subjective timing and, consequently, daily TBPM tasks.

The results from the present thesis can have important implications for the field in this regard: while the findings overall confirmed that the important role of time perception in TBPM, the way it impacted strategic time monitoring changed according to specific internal processes, like age and motivation, and external task features, like the frequency of the PM task and/or the duration of the PM target time. According to the results of this thesis, as well as on the previous findings in the literature (e.g., Gan & Guo, 2019), an intervention on time estimation should improve TBPM, especially when the task is longer and repeated multiple times, perhaps counterbalancing the decline associated with aging (Bastin & Meulemans, 2002; Varley et al., 2021) or with specific neurological and psychopathological disorders (Liu et al., 2021; Mioni et al., 2012, 2017). However, interventions should consider the link between motivational processes and time monitoring. In daily life, often people fail to execute TBPM tasks on time because of the constraints imposed to time monitoring by many social and work situations. Accounting for the way people check the clock under these circumstances can help to promote, for example, a more productive behavior in work contexts (Dismukes, 2012; Loft et al., 2021), as well as more tailored psycho-social interventions aiming to improve social and functional autonomy (Altgassen et al., 2010; Guo, 2023; Hering et al., 2014), and to increase well-being (Laera et al., 2021).

8.3.3. Metacognition in time-based prospective memory

The adoption of a specific clock-checking strategy requires a degree of awareness about the inaccuracy of one’s internal time perception, and a level of awareness that clock monitoring will be required to successfully fulfil one's intention; the capacity to reflect on and control other cognitive processes is defined as *metacognition* (Nelson, 1990), often referred to as "thinking about thinking" (e.g., Kuchling et al., 2022). Metacognition operates at two distinct levels: the object- and the meta-level. Information at the object level about any cognitive function and representation is re-represented at the meta-level via a process of monitoring; in turn, information at the meta-level controls processing at the object-level via cognitive control (Fleming & Lau, 2014). For instance, if someone has low confidence that s/he will miss the bus for the appointment with a friend (metacognitive monitoring), s/he might check the clock more often, engage in less ongoing activities before the appointment, or even try to be at the appointment earlier than the scheduled time (metacognitive control).

Recent research on the psychological mechanisms of cognitive offloading has revealed that the flexible use of external reminders in TBPM tasks depended on reliable metacognitive insight (Gilbert, 2015; Scarampi & Gilbert, 2020). Moreover, other studies with both TBPM and EBPM showed that younger adults were underconfident with laboratory-based tasks, but overconfident in the naturalistic tasks compared to older adults (Cauvin et al., 2019; Schnitzspahn, Zeintl, et al., 2011) – which in part can explain the age PM paradox too (see 5.2.2, footnote 14). Few studies investigated the role of metacognition on time perception. Overall, these studies showed that individuals have high awareness about both the direction and the magnitude of their timing errors (Akdoğan & Balcı, 2017), even in the absence of any feedback (Riemer et al., 2019); moreover, the metacognitive response was shown to be more variable for time estimation tasks that comprise shorter (1.5 seconds) than to longer (3 seconds) intervals (Cropper et al., 2023). Beside these few evidence, to date the role of metacognition in TBPM and time perception has never been investigated in the literature.

Both time perception and TBPM involve temporal information: time perception tasks tackle specifically ability of representing time internally, whereas TBPM tackle more how people use (external) time to execute TBPM tasks at the right moment (Block et al., 2018). Therefore, although there might be a functional dissociation in metacognitive processes between time perception and TBPM, it is reasonable to assume that confidence in time estimation might explain not only how strategic participants are when checking the clock, but also why some people tend to be too late (or too early) when performing TBPM tasks. If this relationship exists, this would help to explain the cognitive function involved in TBPM (i.e., attentional control and time estimation) and their metacognitive determinants; moreover, it could justify potential interventions that tackle metacognitive processes of time estimation – which are fairly easy to implement as well (e.g., Moritz et al., 2014) – and, in turn, to increase TBPM accuracy and strategic time monitoring behavior, thus enhancing functional autonomy and quality of life. Future research should fill this gap in the literature by investigating the complex relationship between metacognition about time perception and TBPM on objective task performance at time estimation tasks and TBPM.

8.4. Strengths and limitations

The present work has several strengths. Overall, it provides experimental approaches that can tackle directly internal time processes and motivational mechanisms, introducing for the first time in TBPM the manipulations of clock-speed (Study 1) and monetary losses (Study 3), respectively. Although replications are needed, both manipulations appeared to work. In addition, the present work compiled the first meta-analysis (Study 2) that comprised a quantification of age effects in time monitoring, as well as the association with age differences in TBPM performance, providing guidance for future research in the field, and indicating that TBPM paradigm is a solid paradigm that can consistently detect age-related differences. Moreover, the meta-analysis systematically investigated for the first time effects of both the PM task frequency and the duration of the PM target on time monitoring and TBPM, shedding light to the possible cognitive processes modulated by such task-related feature. Finally, the present work provided a theoretical contribution by revisiting the TWTE model for the first time since it has been formalized in 1982; the model attempted to overcome limits of previous model, shedding light on the type of strategic behavior: the distinction proposed between TBS and EBS is a promising novel taxonomy of strategic monitoring behavior that might be involved in PM tasks.

The present work comes also with several limitations. Perhaps the biggest practical limitation was related to the timeline of the data collection (2020-2022), which overlapped with the COVID-19 pandemic, and thus required a re-adaptation of the experimental protocols to be assessed online. Although the tasks were administered in a fairly similar way across laboratory and online settings (Finley & Penningroth, 2015; Laera et al., under review; Uittenhove et al., 2023), the lack of control over the participants' performance as well as the re-adjustments in the experimental procedure for online assessment can be problematic, especially if novel experimental manipulations are tested, such as the ones administered in Study 1 and 3. Hence, a replication of the results from these studies in the laboratory is mandatory at this stage (this is particularly true for Study 3, which was only administered online). Concerning specifically Study 1, the main methodological limitation was the lack of a control condition in Experiment 1, which was included only in Experiment 2: future studies need to include it in a laboratory-based assessment. The main limitation of Study 2 was related to the lack of analysis on strategic clock-checking, which limited the integrated discussion about aging effects related specifically to the strategic component of time monitoring. As explained in the article, this was not possible because each study used different PM target times and analyzed monitoring using different intervals, thus not allowing any meta-analytical comparison; related to this problem, it was not possible to apply the meta-analysis on the relative clock-checking, as it required necessarily the raw data (Joly-Burra et al., 2022), which were not available. The main limitation of Study 3 was related to the lack of comparison between monetary losses and gains (e.g., Horn & Freund, 2021b); indeed, we included only conditions of money loss, but the effects of gains of time monitoring are currently unknown. Lastly, the TWTE-r model, although promising, is empirically supported to a limited extent, because in all studies of the thesis, used to support the model, there were no direct measures of time estimation that allowed to confirm the predictions of the model with correlational data. Future studies are strongly encouraged to include such measures to further understand the relationship between time perception and TBPM.

9. Conclusions

The overarching goal of the present work was to address the research gap on how internal time processing affects strategic time monitoring and TBPM performance. This dissertation provided an updated account of the literature, new insights, and data from two experimental studies tackling cognitive and motivational mechanisms, a quantitative account of the age effects in TBPM through a meta-analysis, and a review of the main theoretical model in the field. Overall, it is possible to conclude that it was easier for participants to perform the TBPM task by estimating the PM target time when the task was carried out in presence of the slower clock (Study 1), and that time estimation might help older adults especially with longer and repeated TBPM tasks (Study 2), perhaps fostering learning processes enhancing of memory for durations; however, time estimation can also be engaged as strategic compensation, especially when accessibility at the clock is limited (Study 3). In summary, the interaction between time perception and strategic time monitoring is a complex and multi-faceted phenomenon, shaped by a variety of external and internal factors. If the goal is to have a more comprehensive understanding of how time perception impacts different monitoring strategies, it is time for researchers to bring together knowledges that have been, so far, largely developed in isolation and scattered over different literatures.

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11. Supplementary materials

11.1. Study 1

As mentioned in the main article, we collected additional data for another condition in which clock-speed was not manipulated during the second TBPM block, but people were not allowed to check the time whenever they wished; instead, the clock appeared on the screen automatically at specific pre-set time points. This further condition, called *external-control condition*, was not relevant for the research aims of this article, and it was introduced to measure the effect of self-retrieved aspect of time monitoring, because the clock appeared on the screen automatically at specific pre-set time points, so participants did not have the possibility to check the time whenever they wished. The external-control condition was administered in both Experiment 1 and 2. In this supplementary section, we included analyses on the external-control condition, and jointed analyses on OT, as well as retrospective power analysis for the ANOVAs reported in the main article.

OT was analyzed separately for (1) OT accuracy – computed as mean proportion of correct responses dividing the number of correct responses by the total number of OT trials – and (2) reaction times (RTs) for correct trials (in seconds). For both analyses, the between-subjects independent variable was Clock-speed (faster vs. slower vs. external-control clock), whereas the within-subjects independent variable was Block (OT before TBPM tasks vs. first TBPM block vs. second TBPM block vs. OT after TBPM tasks). These analyses allowed to investigate the PM cost (Conte & McBride, 2018; McBride & Flaherty, 2020) as well as any possible practice or fatigue effect on the OT accuracy and RTs.

11.1.1. Experiment 1

11.1.1.1. Methods

Participants. On top of the sample described in the main article, we collected data from a further sub-group of 40 participants that were assigned to the external-control condition (age-range: 18-35 years; M_{age} = 23.9; SD_{age} = 4.76; 30 females). Five participants reported to have a history of neurological or major psychiatric disease within the last 5 weeks (e.g.: epilepsy, depression, anxiety), or to take psychotropic drugs or others affecting the central nervous system; these participants were excluded. The final sample consisted of 35 participants (age-range: 18-35 years; M_{age} = 24.1; SD_{age} = 4.85; 25 females).

External-control condition. Participants performed two identical TBPM blocks on the computer. For both blocks, the TBPM task was to remember to press the ENTER key on the keyboard every 4 minutes; in total, five PM responses were collected for each block; during the first TBPM block, clock-speed was not manipulated (1 second = 1000 ms), whereas in the second TBPM block, clock-speed was manipulated, and participant were assigned randomly to an experimental or control condition (faster vs. slower vs. control vs. external-control; between-subject manipulation – see main article for more information about both the faster and slower clock conditions). The clock-speed was not manipulated in the external-control condition (1 second = 1000 ms), and the external clock appeared on the screen automatically at specific pre-set time points (i.e.: 1 time during the 1st task minute; 2 times during the 2nd task minute; 3 times during the 3rd task minute; and 6 times during the 4th task minute; the last clock appearance before the PM target time occurred always 10 seconds before its occurrence); we chose to use these specific distribution of clock appearance to resemble the “J-shaped” monitoring curve.

11.1.1.2. Results

External-control condition – analyses on PM performance. Two mixed-design ANOVA were carried out separately for (1) the rate of TBPM task completion – as standardized mean proportion of the number of PM tasks accomplished, regardless of the timing of the PM responses – and (2) the timing error of the PM responses (i.e.: the ratio between the time-point when people performed the TBPM task and the time-point required by the TBPM task; values above 1 indicated later PM responses; values below 1 indicated earlier PM responses). For both analyses, the between-subjects independent variable was Clock-speed (faster vs. slower vs. external-control), whereas the within-subjects independent variable was Block (first TBPM block vs. second TBPM block). The analysis on the rate of TBPM task completion revealed no significant main effect of Block ($p = .856$) and Clock-speed ($p = .161$), and no significant interaction Block * Clock-speed ($p = .104$). The analysis on the timing error of the PM responses revealed no significant main effect of Block ($p = .856$) and no significant interaction Block * Clock-speed ($p = .104$). However, the main effect of Clock-speed was significant, $F(2, 97) = 5.02$, $p = .008$, $\eta^2_p = .09$; post-hoc comparisons revealed that participants exposed to faster clock had lower temporal precision in their PM responses ($M = 8.28$, $SD = 10.96$) compared to participants exposed to slower clock ($M = -.38$, $SD = 10.97$), $t(97) = 3.14$, $p_{adj} = .008$. All other comparisons were not statistically significant ($ps_{adj} > .05$).

OT performance. Analysis on OT accuracy showed no significant main effect of Block ($p = .110$), Clock-speed ($p = .125$) as well as no significant interaction Block * Clock-speed ($p = .064$). Analysis on RTs for correct OT trials revealed a main effect of the Block, $F(1.70, 165.28) = 20.12$, $p < .001$, $\eta^2_p = .17$; the main effect of Clock-speed ($p = .681$) as well as the interaction effect of Block * Clock-speed ($p = .362$) were not significant. When the OT was performed alone (i.e.: without the TBPM task), RTs did not differ between the OT performed before ($M = .767$, $SD = .109$) and after the TBPM blocks ($M = .742$, $SD = .150$; $p_{adj} = 1$). Instead, people were significantly faster at the OT performed before the TBPM blocks compared to both the OT performed during the first TBPM block ($M = .870$, $SD = .144$), $t(97) = -5.61$, $p_{adj} < .001$, and the second TBPM block ($M = .846$, $SD = .140$), $t(97) = -4.40$, $p_{adj} < .001$. Moreover, people were significantly slower at the OT during the first TBPM block compared to the second TBPM block, $t(97) = 4.26$, $p_{adj} < .001$, and compared to the OT performed after the two TBPM tasks, $t(97) = 5.11$, $p_{adj} < .001$. Finally, participants were slower during the second TBPM block than during OT performed after the TBPM blocks, $t(97) = 4.29$, $p_{adj} < .001$.

Retrospective power analyses. A series of retrospective power analyses was carried out for each ANOVA using the *WebPower* R-package (Zhang & Yuan, 2018). All power analyses were conducted with the observed effect size f for the sample size ($N = 65$). The effect size f was derived from the observed partial eta squared (η^2_p) calculated for each ANOVA model, using the formula provided by Cohen (1988) as follows:

$$f = \sqrt{\frac{\sum_{j-1}^{p}(\mu_j - \mu)^2/p}{\sigma^2}} \tag{1}$$

where p is the number of groups. For the interaction effect Block * Clock-speed on the rate of TBPM task completion ($f = .28$), 61% power was estimated. For the interaction effect Block * Clock-speed on the timing error of PM responses ($f = .24$), 49% power was estimated. For the interaction effect Block * Clock-speed on time monitoring ($f = .38$), 85% power was estimated, whereas for the interaction effect Time * Block * Clock-speed ($f = .27$), 50% power was estimated.

11.1.2. Experiment 2

11.1.2.1. Methods

Participants. As in Experiment 1, on top of the sample described in the main article, we collected data from a further sub-group of 40 participants that were assigned to the external-control condition (age-range: 18-35 years; M_{age} = 27.6; SD_{age} = 4.88; 18 females).

11.1.2.2. Results

External-control condition – analyses on PM performance. As in Experiment 1, two mixed-design ANOVA were carried out separately for (1) the rate of TBPM task completion – as standardized mean proportion of the number of PM tasks accomplished, regardless of the timing of the PM responses – and (2) the timing error of the PM responses (i.e.: the ratio between the time-point when people performed the TBPM task and the time-point required by the TBPM task; values above 1 indicated later PM responses; values below 1 indicated earlier PM responses). For both analyses, the between-subjects independent variable was Clock-speed (faster vs. slower vs. control vs. external-control), whereas the within-subjects independent variable was Block (first TBPM block vs. second TBPM block). The analysis on the rate of TBPM task completion revealed no significant main effect of Block (p = .854) and Clock-speed (p = .211), and no significant interaction Block * Clock-speed (p = .531). The analysis on the timing error of the PM responses revealed no significant main effect of Block (p = .352) and Clock-speed (p = .719), and no significant interaction Block * Clock-speed (p = .062).

OT performance. We analyzed the data using mixed-design ANOVA separately for (1) OT accuracy – computed as mean proportion of correct responses dividing the number of correct responses by the total number of OT trials – and (2) reaction times

(RTs) for correct trials (in seconds). For both analyses, the between-subjects independent variable was Clock-speed (faster vs. slower vs. control vs. external-control condition), whereas the within-subjects independent variable was Block (OT before TBPM tasks vs. first TBPM block vs. second TBPM block). Analysis on OT accuracy showed a significant main effect of Block, *F*(1.57, 240.81) = 16.42, $p < .001$, $\eta^2_p = .10$; the main effect of Clock-speed ($p = .127$) as well as the interaction Block * Clock-speed ($p = .233$) were not significant. Post-hoc comparisons showed that OT accuracy was significantly higher for the OT performed alone (i.e.: without the TBPM task; *M* = .968, *SD* = .031), compared to the OT performed during the first TBPM block (*M* = .957, *SD* = .030), *t*(153) = -4.19, $p_{adj} < .001$, as well as compared to the OT performed during the second TBPM block (*M* = .956, *SD* = .031), *t*(153) = 4.64, $p_{adj} < .001$. No significant difference was found between the two TBPM blocks ($p_{adj} = 1$).

Analysis on RTs for correct OT trials showed a significant main effect of Block, *F*(1.51, 231.67) = 10.37, $p < .001$, $\eta^2_p = .06$, as well as a significant interaction Block * Clock-speed, *F*(4.54, 231.67) = 2.49, $p = .037$, $\eta^2_p = .05$; the main effect of Clock-speed ($p = .851$) was not significant. Post-hoc comparisons showed that RTs for correct OT trials were significantly faster for the OT alone (i.e.: without the TBPM task; *M* = .823, *SD* = .203), compared to the OT performed during the first TBPM block (*M* = .860, *SD* = .172), *t*(153) = -4.17, $p_{adj} < .001$, but not compared to the OT performed during the second TBPM block (*M* = .845, *SD* = .160; $p_{adj} = .072$). A significant difference was found between the two TBPM blocks, showing that participants were slower during the first TBPM block compared to the second TBPM block, *t*(153) = 2.78, $p_{adj} = .018$. Post-hoc comparisons for the interaction Block * Clock-speed showed that the significant differences between blocks emerged only for the external-control condition: the results showed that RTs for correct OT trials were significantly faster for the OT alone (i.e.:

without the TBPM task; M = .786, SD = .273), compared to the OT performed during the first TBPM block (M = .850, SD = .252), $t(153) = -3.72$, p_{adj} = .019, as well as compared to the OT performed during the second TBPM block (M = .852, SD = .248) , $t(153) = -3.56$, p_{adj} = .032. All other comparisons were not statistically significant ($p_{adj} > .05$).

Retrospective power analyses. A series of retrospective power analyses was carried out for each ANOVA using the *WebPower* R-package (Zhang & Yuan, 2018). All power analyses were conducted with the observed effect size f for the sample size (N = 114). For the interaction effect Block * Clock-speed on the rate of TBPM task completion (f = .06), 9% power was estimated. For the interaction effect Block * Clock-speed on the timing error of PM responses (f = .25), 65% power was estimated. For the interaction effect Block * Clock-speed on time monitoring (f = .22), 54% power was estimated, whereas for the interaction effect Time * Block * Clock-speed (f = .38), 94% power was estimated.

11.2. Study 2

In the present document, all the details of the statistical analyses were reported, along with relevant references and formulas.

11.2.1. Statistical analyses

All analyses were carried out using the standardized mean difference (Hedge’s g) of TBPM performance (i.e.: proportional accuracy, sum scores, z-values) and total time monitoring (i.e., number of clock checks) as outcome measures (Hedges, 1981); the effect sizes were calculated using the difference in means between the two independent groups ($\bar{x}_1$ and $\bar{x}_2$, for younger and older adults, respectively), standardized by the pooled standard deviation (s_{pooled}), as follows:

$$g = \frac{\bar{x}_1 - \bar{x}_2}{s_{pooled}} \tag{2}$$

$$s_{pooled} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{(n_1 - 1) + (n_2 - 1)}} \tag{2.1}$$

where n_1 and n_2 are the sample sizes of younger and older adults, respectively, and s_1 and s_2 are the standard deviation of younger and older adults, respectively (Harrer et al., 2021; Hedges, 1981).

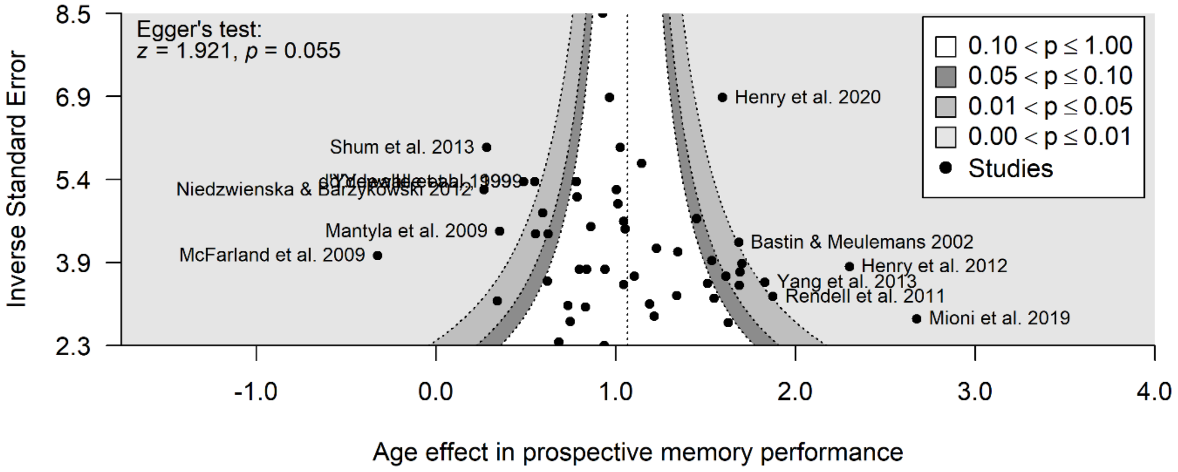
11.2.1.1. Publication bias, outliers & sensitivity analyses

Figure 14 illustrates the funnel plots for estimating publication bias in the overall study set for TBPM accuracy (**Figure 14A**), and for total time monitoring (**Figure 14B**). Egger statistic was not significant for TBPM accuracy (z = 1.91, p = .055) and time monitoring (z = 1.43, p = .153), indicating no funnel plot asymmetry and, therefore, no publication bias. Outliers were defined identifying all the studies with extremely small or large effects, for which the lower/upper bound of the 95% confidence interval is lower/higher than the lower/upper bound of the pooled effect confidence interval (Viechtbauer & Cheung, 2010). Overall, 11 studies were identified as outliers for TBPM performance (Bastin & Meulemans, 2002; d'Ydewalle et al., 1999; Henry et al., 2012, 2020; Mäntylä et al., 2009; McFarland & Glisky, 2009; Mioni, Grondin, et al., 2020; Niedźwieńska & Barzykowski, 2012; Rendell et al., 2011; Shum et al., 2013; Yang et al., 2013), while 2 studies were identified as outliers for time monitoring (Mäntylä et al., 2009; Mioni, Grondin, et al., 2020). Interestingly, these studies were the same that fell outside of the funnel shapes. Moreover, the distribution plot (**Figure 14C**) showed that the potential flagged outliers were uniformly distributed; thus, there was no clear indication of effect size's bias for both TBPM performance (**Figure 14C**, left panel) and time monitoring (**Figure 14C**, right panel). These studies brought some extreme values that contributed substantially to the combined effect size and/or studies heterogeneity (Harrer et al., 2021); thus, sensitivity analyses were carried out to investigate the contribution of outliers on either the combined effect size and/or on studies heterogeneity (see 5.4.1).

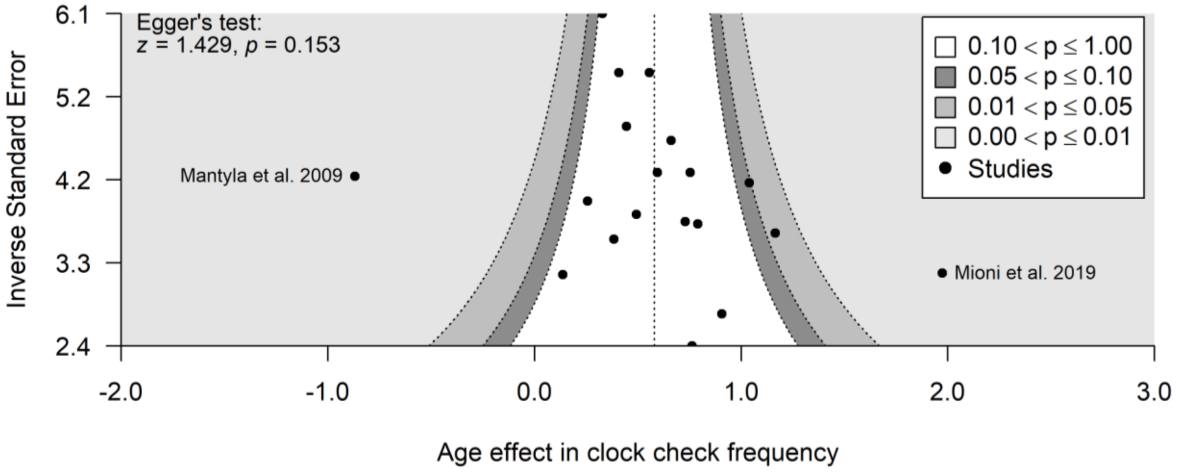
Figure 14

Publication bias & outliers' distribution

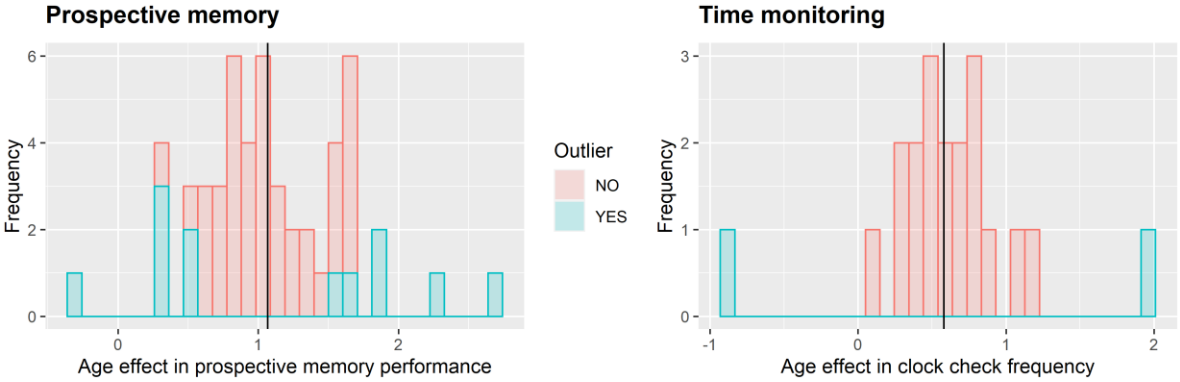
A) Time-based prospective memory



B) Time monitoring



C) Distribution plots



Note. Funnel plots estimating publication bias of age differences (younger vs. older adults) on time-based prospective memory accuracy (A), and on total time monitoring (B). Asymmetry of points around the line by the standard error and presence of imputed data points indicate evidence for publication bias. In these cases, *p* values were > .05, indicating no funnel plot asymmetry. (C) outliers' distribution for TBPM performance (left panel) and time monitoring (right panel).

11.2.1.2. Association between age effects in time-based prospective memory performance & time monitoring

Multivariate meta-analyses can quantify the relationship between time monitoring and TPM performance by estimating the effect sizes for both outcomes jointly in one model; moreover, such approach can be used to determine if studies with a high effect size on one outcome also have higher effect sizes on the other outcome. To achieve this, the multivariate approach takes the correlation between the two outcomes into account; however, among the studies that were included in this meta-analysis, only 3 reported correlations between time monitoring and TBPM performance, separately between younger and older adults. Therefore, we have calculated the correlation between age effects in the two outcomes by transforming the effect sizes into Pearson's *r* coefficients (McGrath & Meyer, 2006) as follows:

$$r = \frac{g}{\sqrt{g^2 + \frac{N^2 - 2N}{n_1 n_2}}} \tag{3}$$

where n_1 is the sample size of younger adults, n_2 is the sample size of older adults, and N is the sum of participants from both age groups. Then, the correlation coefficients were converted into z-scores using Fisher's Z-transformation (R. A. Fisher, 1915), as follows:

$$z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right) \tag{3.1}$$

where "ln" is the natural logarithm function. Then, the z-scores of age effects of both time monitoring and TBPM performance were averaged, and converted back as mean correlation coefficients as follows:

$$r_{1,2} = \frac{\exp(2z_{1,2}) - 1}{\exp(2z_{1,2}) + 1} \tag{3.2}$$

From the averaged coefficients $r_{1,2}$, the co-variance of the studies was calculated using the following formula (Schwarzer et al., 2015, chap. 7):

$$\mathrm{Cov}(\theta_1, \theta_2) = SE_{\theta 1} \times SE_{\theta 2} \times\ r_{1,2} \tag{3.3}$$

11.2.1.1. Effect of predictors

The multi-variate meta-regression model was carried out with three task-related features as continuous predictors: (1) the duration of the PM target time (i.e.: the delay of the PM cue in minutes), (2) the PM task frequency (i.e.: how many PM task in a TBPM task block), and (3) arbitrary criterion chosen to compute PM accuracy (see manuscript for more information). To facilitate interpretation, we rescaled all predictors centering the values to their respective means (Afshartous & Preston, 2011; Bauer & Curran, 2005; Hainmueller et al., 2018), so that the intercept can be interpreted as mean age effect when predictors were set to their means (i.e.: 4-minutes PM target time, and 6 PM tasks

– values approximated to the integer; the mean interval used for PM accuracy corresponded to 20% of the total duration of the PM target time); this solution also allowed to establish possible rules of thumbs for designing future TBPM paradigms in aging (see discussion for more information).

Before fitting the two mixed-effect models, multi-collinearity among predictors was assessed, as it is very common in meta-regression (Berlin & Antman, 1992). Multi-collinearity describes the scenario in which two or more independent variables are highly correlated, violating the assumption of predictors' independence that is necessary to correctly fit linear regressions (Mansfield & Helms, 1982). As rule of thumb, we establish substantial multi-collinearity if predictors showed a correlation $r \geq .80$. Overall, only duration of the PM target time negatively correlated with the frequency of the PM task ($r=-0.41$, $p=.005$); however, even though variables are correlated, the degree of the correlation did not warrant the exclusion of these variables. Furthermore, these results also suggested that the interaction between these two variables should be considered in the model, as it was reasonable to assume that longer durations were likely to be associated with fewer number of PM tasks. Therefore, modelling the interaction allowed to estimate the relationship between PM duration and the estimated age effect changes as a function of different values of the PM task frequency.

11.3. Study 3

In the present document, all the details of the statistical analyses were reported, along with relevant references and formulas. Furthermore, we reported exploratory analyses on OT performance and subjective task importance.

11.3.1. Questionnaires

In this study, several questionnaires have been administered. However, the data from these questionnaires were not analyzed in the main paper, as they are meant for future analyses.

11.3.1.1. Perceived time passage

This was 5-points Likert scale that tested the subjective time experience of participants during both the OT and the TBPM task (Thönes & Stocker, 2019). The questions were formulated for each of the two tasks separately, and were administered at the end of each task:

- *Question*: “During the task you just carried out, how fast did time pass for you?”
- *Likert scale*:
    a. *1*: “very slow”;
    b. *2*: “slow”;
    c. *3*: “neither fast nor slow”;
    d. *4*: “fast”;
    e. *5*: “very fast”.

11.3.1.2. Loss aversion scale

This was a brief task that tested loss aversion (Gächter et al., 2022); participants indicated whether they accept or not the amount of an hypothetical money during a fictional head and tail coin game. Several scenarios of hypothetical bets were administered, and participants had to indicate whether they accept or reject each hypothetical bet. The scenarios were the following:

- *Scenarios*: “In the next slides, you will be asked whether you would accept or reject hypothetical coin flip bets. Please decide by your initial preference and don't think too long.”:
    a. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 3$.”;
    b. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 2$.”;
    c. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 4$.”;
    d. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 5$.”;
    e. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 6$.”;
    f. “If the coin shows tails, you win 6 $, but if the coin is heads you lose 7$.”.
- *Response categories*:
    a. *0*: “REJECT”;
    b. *1*: “ACCEPT”.

11.3.1.3. Subjective time experience

This was a questionnaire that tested the subjective time experience (Gächter et al., 2022) using a 5-point Likert scale. It assessed two mains constructs (personal time experience of present and past, and statements/metaphors on subjective time experience); both constructs comprise several sub-constructs, each of them assessed with few items as follows:

- *Construct 1 – Personal time experience of present and past*:
    a. *Sub-construct 1 – Personal time experience of present time*:
        i. “How fast does time usually pass for you?”;
        ii. “How fast do you expect the next hour to pass?”.

- b. *Sub-construct 2 – Personal time experience of past time*[19]:
    - i. “How fast did the previous week pass for you?”;
    - ii. “How fast did the previous month pass for you?”;
    - iii. “How fast did the previous year pass for you?”;
    - iv. “How fast did the previous 10 years pass for you?”;
    - v. “How fast did your childhood (before 12 years old) go by?”;
    - vi. “How fast did your youth (13-19 years old) go by?”.
- c. *Likert scale*:
    - i. *1*: “very slow”;
    - ii. *2*: “slow”;
    - iii. *3*: “neither fast nor slow”;
    - iv. *4*: “fast”;
    - v. *5*: “very fast”.

- *Construct 2 – Statements/metaphors on subjective time experience*:
    - a. *Sub-construct 1 – Time pressure*:
        - i. “I haven't enough time to complete my tasks.”;
        - ii. “I often feel time pressure.”;
        - iii. “I often haven't enough time to devote myself to important things.”;
        - iv. “I often think time is running out.”;
        - v. “I have to establish my priorities, because I cannot do all the things I would like to do.”.
    - b. *Sub-construct 2 – Time expansion*:

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[19] In the original questionnaire, there were two further questions (i.e., “How fast did your adulthood between 20 and 29 years go by?”, and “How fast did your adulthood between 30 and 39 years go by?”), as this was a questionnaire originally thought to assess aging in time perception. Since we tested only younger adults, we removed these two questions as they were not pertinent for our sample.

        i. "My time seems empty.";
        ii. "I often think that time just does not want to pass.";
        iii. "I often feel bored.";
        iv. "I have a lot of time.";
        v. "I often have spent my time without doing anything.".
    c. *Sub-construct 3 – Metaphors (time speed)*:
        i. "Time is a speeding train.";
        ii. "Time is a galloping horse.";
        iii. "Time is a tumbling waterfall.".
    d. *Sub-construct 4 – Metaphors (time slowness)*:
        i. "Time is a vast expanse of sky.";
        ii. "Time is a quiet, motionless sea.";
        iii. "Time is a tedious song.".
    e. *Likert scale*:
        i. *1*: "strong rejection";
        ii. *2*: "rejection";
        iii. *3*: "neutral";
        iv. *4*: "approval";
        v. *5*: "strong approval".

11.3.1.4. Follow-up questionnaire

This was a brief questionnaire that tested whether participants reported any strategy to track the passage of time during the TBPM task; specifically, participants were asked to give binary responses to this question, and only if they reported to have used a strategy, they were asked furtherly to provide a brief explanation, as follows:

- *Question 1*: "Did you use a strategy to control the passage of time during this task?".
    a. *Response categories*:
        i. *0*: "NO";
        ii. *1*: "YES".
- *Question 2* [only if participants indicated "YES"]: "What strategy did you use?". *Response*: written text.

11.3.2. Statistical analyses

In this sections, further details of statistical analyses are reported along with additional – exploratory – analyses on OT performance and subjective task importance.

11.3.2.1. Main analyses

Below are reported further statistical details on the main analyses reported in the paper (ANOVAs and multi-group path analysis).

ANOVAs. Two one-way ANOVAs are reported in the main paper for absolute and relative clock-checking, respectively. Absolute clock-checking was calculated as the sum of clock checks over five PM target windows (i.e., total frequency of clock checks over the entire TBPM task block). Relative time monitoring was computed starting from the frequency of clock checks over four intervals of 30 seconds (t1 to t4, as in the above analysis), considered separately for each of the five TBPM tasks; then, for each TBPM task, the number of clock checks during the last time interval (t4) was divided by the total number of clock checks (i.e., from t1 to t4), and averaged across the five TBPM tasks for each participant, as follows:

$$Relative\ clock{-}checking = \left(\frac{\sum_{i=1}^{n} \frac{t4_t}{t1_t + t2_t + t3_t + t4_t}}{n}\right) * 100 \qquad (4)$$

where t = trials, and n = number of PM task for a given block (i.e., 5 in Study 3). This index is a percentage score ranging from 0% to 100%, with 100% representing the highest strategic behavior possible (i.e., all clock checks made in the last interval before the PM target time; for further details see Joly-Burra et al., 2022).

Path analysis. For the multi-group path analysis, R^2 was computed as one minus the standardized residual variance of the endogenous variable (i.e., TBPM accuracy); moreover, the confidence intervals were estimated by converting R^2 to R, then to z-scores using the Fisher *Z*-transformation (R. A. Fisher, 1915); afterwards, the confidence interval for z-scores were estimated, and then back transformed them to R^2 (for more information and precise formulas, see Carlson, 2013). The inferential tests associated with the R^2's were obtained using the Wald's chi-squared tests (χ^2_{Wald}) comparing the original model with a constrained model in which regression coefficients leading to the endogenous variable (i.e., TBPM accuracy) were set to zero (except the intercept). The Comparative Fit Index (*CFI*), the Root Mean Squared Error of Approximation (*RMSEA*), and the Standardized Root Mean Square Residual (*SRMR*) were used to assess goodness of fit (see Bentler, 1990; Hu & Bentler, 1999; Steiger, 1990). Model fit was considered good when the CFI was higher than .95, the *RMSEA* was lower than .06, and the *SRMR* was lower than .08 (Hooper et al., 2008). Cross-group invariance was tested comparing two nested models: the model of interest, in which no constraints were specified (i.e., the free model), was compared with a second – constrained – model where regression coefficients were constrained to be equal between groups (i.e., experimental conditions of monetary cost). Comparison of models was achieved using the nested robust χ^2 test

(Bentler & Satorra, 2010; Pavlov & Kotchoubey, 2020): if a model comparison was statistically significant, the null hypothesis was rejected, meaning that the fit of a constrained model was worse than that of the free model (Chen, 2007).

11.3.2.2. Exploratory analyses

Several exploratory analyses were conducted on OT and subjective task importance. These analyses are reported below.

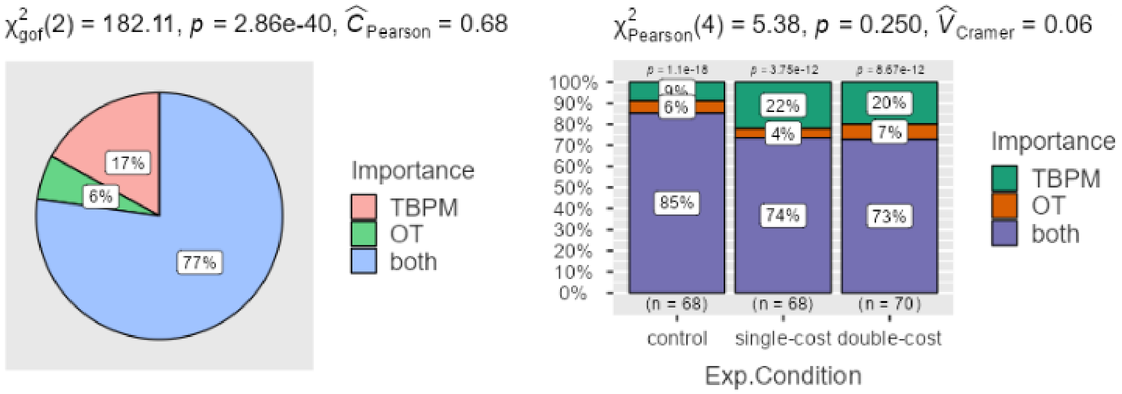
OT performance. We analyzed OT performance separately for average accuracy and RTs (in seconds) at correct OT trials. For both analyses, a 3 * 2 mixed ANOVA was used, with between-subjects factor Monetary cost (control vs. single-cost vs. double-cost) and within-subjects factor Task (OT baseline – i.e., OT with no intention to be remembered – vs. TBPM). The results for OT accuracy showed that only the main effect of Monetary cost was statistically significant, $F(2, 203) = 5.47$, $p = .005$, $\eta^2_p = .05$, whereas the main effect of Task ($p = .674$) and the interaction Monetary cost * Task ($p = .262$) were not significant. Post-hoc Bonferroni comparisons indicated that, in both task blocks (OT baseline and TBPM) participants in the double-cost condition performed better than participants in the control, $t(203) = 3.07$, $p_{adj} = .007$, and in the single-cost condition, $t(203) = 2.58$, $p_{adj} = .032$; the difference between control and single-cost condition was not statistically significant ($p_{adj} = 1$). The results for RTs at correct OT trials showed no significant effect for any of the two independent variables ($p > .05$). We furtherly tested the PM cost in OT accuracy and in the RTs at the correct OT trials, separately. The PM cost was computed as difference (either in accuracy or in the RTs) between the OT baseline block (in which participants perform only the OT) to a TBPM block in which they perform the OT in the presence of a PM intention. The two one-way ANOVAs revealed that the Monetary cost did not exert any significant effect on PM cost, neither in terms of OT accuracy (p = .262) nor in terms of RTs for correct OT trials (p = .946).

Subjective task importance. We explored the data on the subjective task importance, which was assessed by asking participants to respond to the following question. "During the task you just did, what was more important for you to carry out?", and to indicate whether they perceived the OT or the TBPM task as more important, or whether both were perceived as equally important. We ran three exploratory analyses. In a first step, a χ^2 goodness-of-fit test (χ^2_{gof}) was used to test whether the observed distribution of a subjective task importance differed across the three options ("OT", "TBPM", "both"). In the second step, we tested whether the distribution of choices of task importance differ across experimental conditions (control, single-cost, and double-cost) using a Pearson's χ^2 test ($\chi^2_{Pearson}$). Finally, in the last step, we used a hierarchical multinomial logistic regression to investigate the effect of the experimental condition and behavioural performance (i.e., TBPM accuracy, absolute and relative clock-checking) on the perceived task importance.

The χ^2 goodness-of-fit test showed that participants chose the option "both" significantly more often (77%) than "TBPM" (17%) and "OT" (6%), $\chi^2_{gof}(2) = 182.11$, $p < .001$ (**Figure 15**, left panel); however, the Pearson's χ^2 test revealed that such choice distribution was not significantly affected by the experimental condition (p = .250; **Figure 15**, right panel). The hierarchical multinomial logistic regression was carried out testing three models: in model 1, only TBPM accuracy was included as predictor; in model 2, both absolute and relative clock-checking and the correspondent interaction were included furtherly as predictors; in model 3, the experimental condition (control vs. single-cost vs. double-cost) was introduced as predictor. The reference level for the subjective task importance was set to "both", whereas the reference level for the subjective task importance was set to “control”. Results indicated that the fit between the baseline model containing only the intercept and data improved with the addition of the TBPM accuracy in model 1, χ^2 (2) = 6.49, $R^2_{Nagelkerke}$ = .03, p = .039, and with the addition of the time monitoring measures in model 2, χ^2 (8) = 24.53, $R^2_{Nagelkerke}$ = .11, p = .002, as well as with the inclusion of the Monetary cost in model 3, χ^2 (12) = 28.87, $R^2_{Nagelkerke}$ = .13, p = .004. However, model comparisons showed that model 2 – which included both measures of time monitoring and TBPM accuracy – fitted significantly better than model 1, which included only TBPM accuracy (χ^2(6) = 18.05, p = .006); however, adding the experimental condition as predictor in model 3 did not improve the model fit compared to model 2 (p = .362). Among the independent variables, only TBPM accuracy and absolute clock-checking predicted subjective task importance (**Figure 16**). Specifically, TBPM accuracy positively predicted the odds that participant choose the TBPM task as most important, *OR*: 5.85 (*95% C.I.*: 1.97, 17.41), p = .001, and negatively predicted the odds that participant choose the OT as most important task, *OR*: .03 (95% C.I.: .008, .091), p < .001 (**Figure 16**, left panel); absolute clock-checking negatively predicted the odds that participants choose the TBPM task as most important, *OR*: .90 (*95% C.I.*: .81, 1.00), p = .048 (**Figure 16**, right panel). All other effects were not statistically significant (p > .05). Overall, the analysis indicated that higher TBPM performance increased the probability of choosing the TBPM task as most important of ~485%, and decreased the probability of choosing the OT as most important of ~97.3%; moreover, higher absolute clock-checking reduced the probability of choosing the TBPM task as most important of ~9.70%.

Figure 15

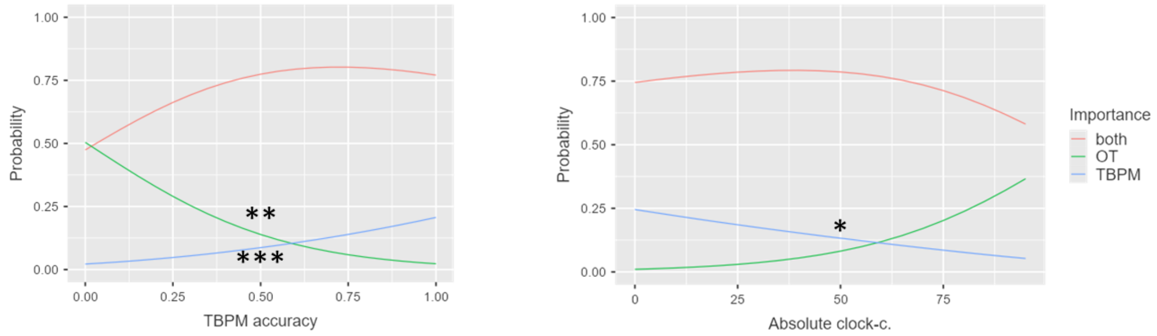
Subjective task importance and experimental manipulation



Note. The figure represents how choices of subjective task importance (both, OT, and TBPM) are distributed in the sample (left panel), and how they are distributed across experimental conditions (control, single-cost, double-cost). TBPM: time-based prospective memory; OT: ongoing task.

Figure 16

Main results from hierarchical multinomial logistic regression



Note. The figure represents probabilities of subjective task importance (both, OT, and TBPM) as a function of the time-based prospective memory accuracy (left panel) and absolute clock-checking (right panel). TBPM: time-based prospective memory; OT: ongoing task; Absolute clock-c.: absolute clock-checking. * p < .05; ** p < .01; *** p < .001.

11.4. Chapter 7

In this section, the correlations between the sum of clock checks over the whole TBPM block and the average sum for each PM tasks are reported for each TBPM block (see section 7.3.1.2 for more information). Overall, these two measures are mathematically similar as correlations are very high (r > .75). The correlations are reported below in **Table 9.**

Table 9

Correlations between average and total frequency of clock-checking

TBPM block	**Pearson's *r***	***p*-value**
First	0.756	< .001
Second	0.985	< .001

Note. Pearson's r correlations between average absolute clock-checking and the total absolute clock-checking frequency as a function of the TBPM block (first and second).