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THESIS

Constructing thought
spontaneously and deliberately:
Neural bases and adaptive strategies

Presentata da: Giovanni Cantarella

Coordinatore Dottorato:

Prof. Elisabetta Crocetti

Supervisore:

Prof. Elisa Ciaramelli

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Abstract

Human thought spans a continuum from spontaneous to deliberate forms. Spontaneous thought occurs when attention shifts from ongoing activities to task-unrelated content (mind-wandering), whereas deliberate thought involves voluntarily imagining future events (mental time travel; MTT) or setting goals (prospective memory; PM). Both forms of thought engage multiple brain networks – notably, the Default Mode Network (DMN) with key hubs in the ventromedial prefrontal cortex (vmPFC) and hippocampus – while external attention is primarily mediated by the Dorsal and Ventral Attention Networks. However, there is still no consensus on the neural and cognitive mechanisms underlying spontaneous and deliberate thought, their relationship with external attention, and optimal strategies for promoting adaptive thinking. Chapter 1 explores the neural bases of mind-wandering and external attention, adopting a tDCS protocol that assesses both simultaneously. Findings reveal that the posterior parietal cortex mediates both internal and external attention, while the vmPFC uniquely supports future-oriented mind-wandering. Chapter 2 examines whether activating mental representations (self-schema and the future time) promotes adaptive mind-wandering. Results show that activating representations of future time increases aware mind-wandering, whereas activating self-schema promotes unaware mind-wandering. Chapter 3 investigates the role of the vmPFC in deliberate thought (MTT), examining the temporal unfolding of memory structures (“think aloud” method) during event construction. Patients with vmPFC damage show degraded personal semantic information and atypical, “backward” transitions from lower- to higher-level memory structures, reporting fewer specific events. Finally, Chapter 4 explores the simultaneous effect of intention offloading (use of external reminders) on both spontaneous (mind-wandering) and deliberate (PM) thought. Results indicate that offloading reduces pupil diameter, especially under high memory load, and decreases off-task thinking over time. Collectively, this work clarifies the cognitive, neural, and physiological mechanisms underlying internal (spontaneous and deliberate thought) and external attention, identifying strategies to foster adaptive thinking.

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General introduction

The reality we inhabit is undeniably complex, governed by intricate rules that often seem beyond our grasp. How, then, can humanity respond to this complexity? Perhaps our most powerful tool lies within ourselves. If complex reality is indeed as fascinating as it is intricate, in fact, one could argue that at least as much complexity resides within our minds.

The relation between human thought and the external world has long been a central topic in philosophy. This debate centered around how the mind interacts with and perceives the world, and whether the two can be understood as distinct or interdependent entities. Philosophers like René Descartes emphasized a *dualistic* view, separating the mind (the realm of thought) from the body and physical world (the realm of matter). In contrast, philosophers like Immanuel Kant have argued for a more *integrated* approach, proposing that human perception involves an interplay between sensory input and mental structures. More recently, John McDowell, rejected the view of a strict separation between the conceptual (mind) and empirical (world), asserting instead that our minds actively engage with the world through conceptual capacities, i.e., our mental framework for making sense of the world. In other words, we can apply concepts like "*tree*", "*red*", or "*justice*" – the “tools” of our thought - to the world we experience, allowing us to have structured, meaningful interactions with our environment.

The present work will focus on the scientific study of human thought within the field of cognitive neuroscience. While a significant portion of these contributions will be elaborated upon in the following sections, it is crucial at this stage to introduce a distinction between different forms of thought, which framed the overall approach of this PhD thesis. Among others, William James' (1890) seminal work "*Principles of Psychology*" identified two key forms of thought: automatic, habitual and effortless, or conscious, deliberate and effortful. This dual perspective continues to inform contemporary research on the nature of human thought.

1. Phenomenology of spontaneous thought

“A series of flights and perchings”: this is how William James described the enigmatic nature of human thought. James envisioned a mental state, a *“perching”*, as a container for diverse mental experiences like worries, imaginings, and inner speech. Transitions between these states, the *“flights”*, represented instead the dynamic shifts of our mind. Exemplifying this experience is not difficult: simply imagine being on a subway ride in a large metropolis. In such a context, it is undoubtedly important to pay attention to the myriad of external stimuli, but once (hopefully) one has found a seat, the subway ride proceeds in parallel with a mental journey, which can be much more crowded. As happened to me on the subway ride that preceded the writing of this paragraph: even though I was in such a chaotic environment, my mind was able to disconnect from the outside and recreate an equal amount of dynamism within itself. And so, a sequence of mental images unfolded, depicting past scenes, accompanied by inner speech about them, and commentary on what I was witnessing on the subway. There were also spontaneous fluctuations between such thoughts related to the immediate experience and more abstract ideas about the nature of human thought, ultimately connecting this concept to concrete possibilities for how to explain it in this PhD thesis work. The complexity of this mental picture is further complicated by the fact that it all happened in a matter of minutes. Hoping that this example has conveyed the concept as spontaneous thought—and keeping it in mind—let us delve into the trajectory that led scientific research to become interested in studying this phenomenon.

Prior to the mid-1990s, the dominant view within cognitive psychology and the nascent field of cognitive neuroscience was *task-centric* (Christoff et al., 2016). The dominance of behaviorism throughout the 20th century, in fact, significantly hampered research on self-generated mental activity. From the 1940s to the 1970s, senior researchers often viewed topics related to internalized experience with disfavor, while the pervasiveness of Watson and Skinner’s behaviorist theory resulted in the widespread adoption of behaviorist methodologies and a dismissal of alternative approaches in many

psychology departments and journals (e.g., Skinner, 1965; Watson, 1913). Experimental designs were meticulously constructed to minimize the influence of task-unrelated thoughts, often dismissed as *experimental noise*. Pioneering work by Jerome Singer and his students, John Antrobus and Kenneth Pope (e.g., Singer & Antrobus, 1965; Antrobus, 1968; Pope & Singer, 1978; Singer & Pope, 1978), laid the groundwork for this field. Similarly, Klinger's (1971) research and investigations by Giambra (1974, 1993) made significant contributions. However, their findings often found publication in monographs (e.g., Singer, 1966, 1975) or less prestigious journals, reflecting the prevailing climate of the time. Undoubtedly, those early works (e.g., Singer & Antrobus, 1965; Klinger, 1971) provided the essential foundation upon which isolated researchers continued to build throughout the late 20th century (e.g., Einstein & McDaniel, 1997; Wegner, 1997).

The first decade of the 21st century determined a remarkable shift in the scientific landscape for research on spontaneous activity. In stark contrast to the earlier prevailing disinterest or dismissal, a growing consensus emerged within the research community acknowledging the broad implications of self-generated mental activity for various aspects of psychological and neural function. No longer relegated to the periphery, research in this domain began to emerge from the shadows and increasingly find its way into high-credibility scientific journals. Investigations explored the potential links between spontaneous thought and both physical health (Epel et al., 2013) and mental well-being (Killingsworth & Gilbert, 2010). Research examined its influence on attentional control (Smallwood & Schooler, 2006; McVay & Kane, 2009; McVay et al., 2009; Smallwood, 2010) and its potential impact on educational outcomes (Smallwood et al., 2007). Studies also delved into the relationship between self-generated mental activity and psychiatric conditions like depression (Smallwood et al., 2005, 2007, 2009).

Research on spontaneous thought, however, lacked a universally adopted terminology, with various studies employing a plethora of terms to describe the phenomenon. These terms include, for example: *task-unrelated* thought (Singer & Antrobus, 1965), *task-unrelated* thoughts and images

(Giambra, 1995), *stimulus-independent* thought (Antrobus, 1968; Teasdale et al., 1995; 1993), *mind pops* (Shulman et al., 1997), and *zone outs* (J. Schooler, 2002; Schooler et al., 2005). To bridge the gap between ongoing research and psychological discourse, the pioneering work by Smallwood & Schooler, (2006) integrated these well-established phenomena into executive models of attention. This marks the dawn of the term "*mind-wandering*", which would later become a new area of investigation within contemporary psychological research (Callard et al., 2013). From this point onward, the renewed interest in studying mind-wandering has been evidenced by the increasing number of publications in this field over the years (see Figure 1).

Given the complex phenomenology in mind-wandering episodes and the diverse terminology associated with them, Seli et al., (2018) have recently challenged the notion of mind-wandering as a unitary construct. These authors have proposed that researchers should instead adopt a *family-resemblance view*, which accounts for the heterogeneity of mind-wandering states and allows for the delineation of the specific features of thought under investigation each time. By contrast, as we will see later (see paragraph 1.6.), a different approach has focused on delineating the characteristics that define the phenomenology of mind-wandering, distinguishing it from other related constructs (Christoff et al., 2016).

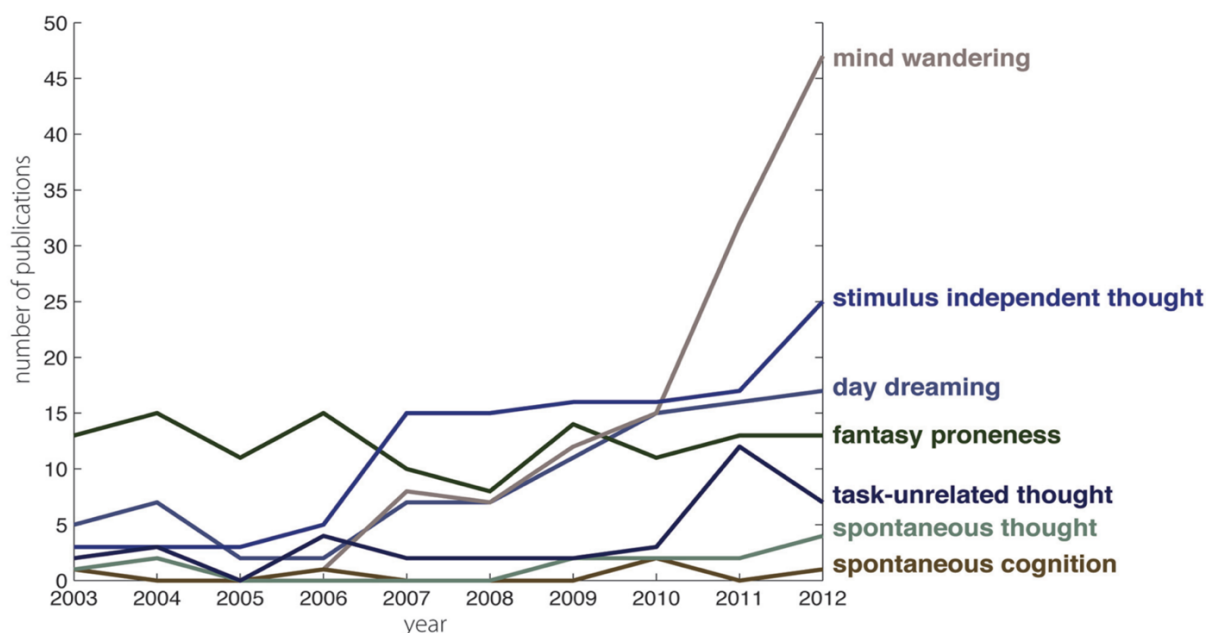


Figure 1. Changes in citation frequency of mind-wandering and other related terms over the ten years leading up to 2013. Notably, the term mind wandering saw a rapid rise in usage during this period, while research employing other related terms remained relatively stable (Callard et al., 2013).

1.1. Experimental measures of the wandering mind

The terminological heterogeneity for the mind-wandering field could only lead to an equal degree of heterogeneity in the research methods aimed at exploring its phenomenology. Investigations into mind-wandering often rely on *experience sampling* (ES) techniques (Kahneman et al., 2004) to capture moments of conscious awareness of either internal or external stimuli. This research method captures participants' ongoing mental experience in real time through self-reports. Several distinct approaches, however, fall under the ES umbrella:

1. *Probe-caught method:* this approach employs intermittent prompts, known as probes, to inquire about participants' current mental state (Smallwood & Schooler, 2006). These probes can be random, quasi-random, or even triggered by changes in performance, such as fluctuations in reading speed (Franklin et al., 2011). A crucial consideration of this method is the time interval between probes, as research has shown that longer intervals are associated with increased reports of off-task thoughts (Seli et al., 2013).
2. *Self-caught method:* in contrast to the probe-caught method, participants in this approach autonomously signal the emergence of mind-wandering episodes (Smallwood & Schooler, 2006). When combined with probe-caught data, this method can offer insights into participants' ability to introspect on their conscious experience (Schooler et al., 2011). The paragraph 1.4. (see below) will provide a more extensive discussion of this topic.
3. *Retrospective method:* This approach gathers ES data through questionnaires administered after a task has been completed (e.g., Barron et al., 2011). This helps preserve the natural flow of the task and can be valuable to obtain covert measures of resting-state mental activity. However, a limitation arises from potential biases due to individual differences

in memory for past mental activity. Mitigating it requires multiple measurements within the same participant (Gorgolewski et al., 2014).

4. *Open-ended method*: This approach allows participants to describe their mental experiences during a task in their own words (e.g., Baird et al., 2011). This method avoids imposing pre-defined categories on participants' reports, potentially leading to richer and more nuanced data.

Both self-caught and probe-caught measures provide complementary evidence about the nature of spontaneous thought (Smallwood & Schooler, 2006). An important research strategy, therefore, is to combine these methods to capture the different sides of mind-wandering.

In psychological research, a compelling case can be made for the significance of carefully controlling participants' beliefs about the aim of an experiment. Understanding a psychological phenomenon is particularly crucial when the focus of investigation is on self-report measurements (Nisbett & Wilson, 1977). Building from this perspective, it is possible that the *self-classification* method of mind-wandering episodes (Antrobus, 1968; Giambra, 1995) could encourage individuals to assign an artificially high priority to their current mental experience (Smallwood & Schooler, 2006). The *experimenter-classified* approach to mind-wandering (e.g., Smallwood et al., 2003; Teasdale et al., 1993, 1995), on the other hand, merely requires that individuals report what is passing through their minds, without overt mention of the category in question. Giving participants a retrospective questionnaire at the end of the task allows for the subsequent confirmation of these ratings. According to several studies ($r \geq .50$, Smallwood, Davies, et al., 2004; $r \geq .50$, Smallwood, O'Connor, et al., 2004; $r \geq .60$, Smallwood et al., 2003), these two measures are reliably correlated.

While research focuses on the cognitive processes that drive thoughts away from the present moment, however, typical ES methods capture only the content of conscious experience at specific time points. While this approach offers valuable insights, it inherently lacks the ability to track real-

time transitions between mental states. This limitation highlights the need for *indirect* measures as a complementary approach to studying spontaneous thought (the paragraph 1.6. will provide a more detailed overview of these innovative methods).

After reviewing some crucial steps that have defined this field of research, the following paragraphs will adopt a different approach to describe various aspects of spontaneous thought, highlighting its phenomenology. Later, will focus instead on more recent contributions that outline new areas of research into spontaneous thought.

1.2. Distracted from the inside or the outside?

Consider, again, the example of me riding a subway train: while in a crowded environment, one's mind may begin to wander, focusing on a series of dynamic and abstract images and thoughts. Despite the impressiveness of the surrounding crowd, however, it would be futile to maintain focus on it for the entire duration of the journey. Similarly, it may not be necessary to focus entirely on a laboratory task for its entire duration to complete it. In such contexts, a core element emerges: a *shift in attention* away from the primary task at hand towards internal information, such as memories (Christoff et al., 2004; Smallwood et al., 2004; 2003). Building upon this framework, mind-wandering occurs when attention disengages from the external environment and instead focuses on internally generated information.

Is it possible to conceive mind-wandering as a *shift in attention*? To answer this question, it is necessary to refer to some crucial characteristics of the human attentional system (see the paragraph 3.4.2. for a more extensive overview of the characteristics and the neural bases of this system). In fact, animals and humans need to quickly process sensory information relevant to their goals (e.g., routes, food, mates) in order to navigate the environment safely, survive, and reproduce. Individuals,

when confronted with unfamiliar, potentially threatening or rewarding stimuli, must also promptly shift their focus of attention and modulate their behavior accordingly. This intricate process of adapting to new and unforeseen stimuli has been defined as a *reorienting response* (Corbetta et al., 2008; Corbetta & Shulman, 2002). Reorientation happened, for example, when I shifted my attention from one environmental stimulus to another (different people on subway train), but also when I redirected my attention from my internal activity to the external environment, such as when the announcement of the next subway stop interrupted my crowded journey on my train of thought.

John Antrobus and Jerome Singer coined the term “*decoupling*” to describe the process of dividing attention between internal and external information when the mind wanders (Antrobus et al., 1966; Smallwood et al., 2003). When attention is directed towards an external goal, it prioritizes the processing of relevant sensory information, facilitating successful action (Posner & Petersen, 1990). Mind-wandering instead can be described as a state in which, rather than monitoring online sensory input, attention shifts inwards and focuses on one’s thoughts and feelings (e.g., my example on the subway train). This view conceptualizes mind-wandering as *attentional lapses* that lead to the formation of shallower representations of the surrounding stimuli (Smallwood & Schooler, 2006). The *perceptual decoupling* process was hypothesized to have two key consequences. First, it triggers a cognitive reorganization that prioritizes intrinsic, self-generated mental content over extrinsic sensory inputs. Second, it attenuates the processing of external stimuli. This attentional shift, thus, serves as a potential mechanism allowing for the persistence of self-generated states, ultimately contributing to performance lapses in demanding external tasks.

If the *perceptual decoupling* hypothesis holds true, mind-wandering episodes should correlate with measurable changes in an individual's access to environmental stimuli representations. Reading and encoding tasks - requiring the creation of online mental representations of the presented information - offered ideal contexts for examining this hypothesis. First, Grodsky & Giambra (1990) seminal work established that the likelihood of mind-wandering during reading was positively

associated with its likelihood during a simple signal detection task. This finding is noteworthy as it highlights the persistence of spontaneous thought across contrasting environments: one rich in stimuli (reading) and the other relatively impoverished (signal detection). However, they also revealed a crucial *context-dependent* aspect of mind wandering. While it was more frequent during easy blocks in the signal detection task, its frequency in reading remained unrelated to passage difficulty. Instead, passages perceived as uninteresting triggered more frequent mind-wandering episodes, indicating that, for semantically meaningful tasks like reading, engagement and intrinsic motivation (absorption) - rather than mere resource limitations - become primary drivers of mind-wandering.

If it is true that attentional shifting towards the inside prioritizes self-generated content over external stimuli, frequent mind-wandering is expected to negatively impact text comprehension. Schooler et al. (2005) investigated this hypothesis by having participants read passages from War and Peace while assessing both (self- and probe-caught) mind wandering and comprehension (measured immediately following probes). Periods of probe-caught mind wandering correlated with poorer comprehension compared to periods of focused attention, thus confirming that mind-wandering disrupts comprehension abilities. Similar observations have been reported when mind-wandering is induced through thought suppression tasks (Fishman et al., 2006) and during self-paced reading where text appears one item at a time (Schooler et al., 2005). Taken together, these empirical findings confirm that shallower representations emerge as attention diverts from task-relevant information.

What is the reason why our wandering minds decouple from the external environment? Some authors (Kam & Handy, 2013; Smallwood, 2013) argued that perceptual decoupling allows prioritization of self-generated thought by inhibiting the processing of information unrelated to the current train of thought, i.e., external task-related events. An alternative view posits that perceptual decoupling is not specifically aimed at insulating the internal stream of thought but is instead a consequence of limited attentional resources (Franklin, Mrazek, et al., 2013). In this view, perceptual

decoupling would indicate a lack of attention directed to external information but would not support the maintenance of the ongoing internal train of thought.

1.3. Self-generation and mental content

Let us return for a moment to the episode of myself on the subway of a crowded city. We have now understood how my attentional system was easily able to shift between different external sources of information (e.g., the multitude of people), but also between these same sources and the inside of my mental activity. Certainly fascinating, but a question at this point arises spontaneously: wouldn't it have been simpler for me to let myself be carried away by the multitude of external stimuli, or more banally to pay attention only to the announcement - otherwise indispensable - of the next subway stop? The question becomes even more intricate if we think that - besides me - any young adult spends on average one third of their entire waking life in these episodes of mind-wandering. The costs of attentional decoupling are partially offset by the critical nature of spontaneous thought *content*.

The content-based perspective on spontaneous thought has been adopted by a body of research that, in recent decades, has mainly focused on determining the “building blocks” of mind-wandering episodes. The earliest experience sampling approach was employed by Klinger & Cox (1987) to explore the properties of thought flow – in particular, *daydreaming*. The study identified three key independent dimensions characterizing daydreams: directedness (goal-oriented vs. spontaneous), stimulus independence (triggered by vs. independent from the external environment), and fancifulness/bizarreness (imaginative vs. realistic). Visual imagery emerged as the dominant modality for mental representations. Moreover, interior monologues (self-talk) were identified as a pervasive feature, independent of most other characteristics of human thought.

1.3.1. Self-reference

It is unsurprising to observe that human thought is largely centered around the *self*. After all, human introspection often focuses on what people know about themselves: personalities, music preferences, desired locations and/or habits. These facets of self-knowledge coalesce around the *self-schema* – a meticulously constructed set of beliefs about oneself, that is typically formed through repeated categorization and subsequent evaluation of behaviors and defines our identity, shaping the way humans process incoming information (Markus, 1977). Numerous empirical studies exploring the contents of mind-wandering corroborated the intuitions regarding the centrality of self-knowledge in human thought. For example, Baird et al., (2011) employed a Choice Reaction Time task, where participants reported the content of their thoughts at various intervals, and revealed that a substantial portion (66%) of task-unrelated thoughts was self-related. Cole & Berntsen (2016) also observed a high frequency of self-relevant memories spontaneously occurring during a vigilance task. Stawarczyk et al. (2013) utilized a multilevel factor analysis to examine participants’ ratings of various characteristics associated with task-unrelated thoughts, highlighting “personal significance” as a key factor explaining variations in thought phenomenology. These results align with other studies identifying self-relatedness as a central dimension of task-unrelated thought content (Ruby et al., 2013a; Ruby et al., 2013b). Further evidence for the self-referential nature of mind-wandering emerges from studies investigating thought characteristics in daily life. Song & Wang (2012) employed an experience sampling method to assess task-unrelated thought content, revealing that the majority of mind-wandering episodes were linked to the self and the individual’s personal life. Similarly, Andrews-Hanna et al. (2013) utilized a participant-driven approach, requiring subjects to report and assess a series of thoughts encountered throughout their daily life, and confirmed “self-relevance” as a defining feature of mind-wandering content.

What makes self-referential information crucial in shaping mind-wandering content? Among the various possible abstract representations of one’s personal characteristics, *personal goals* undoubtedly play a pivotal role. In fact, successful goal achievement hinges on a cognitive system

sensitive to environmental opportunities that facilitates goal-directed behavior (Gollwitzer, 1999; Klinger, 1999): in other words, these sensitivities enhance goal pursuit by increasing the accessibility of goal-relevant stimuli (Smallwood & Schooler, 2006). In fact, this sustained state of heightened sensitivity to goal-related stimuli and readiness to act upon them maximizes the opportunities to achieve the goal itself, even without explicitly thinking about it (Klinger & Cox, 2004). To facilitate efficient goal pursuit, this state of sensitization relies upon an implicit, underlying concept named “*current concerns*” (Klinger, 1978, 1999). The current concerns theory conceptualizes the individual’s state between two key moments: the initial commitment to a specific goal and either the successful achievement of the goal or its abandonment.

There is now substantial empirical evidence confirming that personal goals achievement is accompanied by a pervasive bias in cognitive processing – including attention, memory recall and – above all - the content of thought. For example, presenting stimuli related to an individual’s current concern in one channel of a dichotic listening task prompts a shift in attention toward that channel, subsequently increasing the number of thoughts related to that concern (Klinger, 1978). If this hypothesis is correct, mind-wandering might arise in direct opposition to the goal of task completion: this could occur due to the activation of a personal relevant goal, effectively competing for cognitive resources with the ongoing task (Smallwood & Schooler, 2006). However, individuals often fail to detect this automatic shift in attention from the primary task to a salient personal goal (Giambra, 1995; Schooler et al., 2005; see the next paragraph 1.4. for a more detailed discussion about this topic).

1.3.2. Temporal focus

Goal completion hinges significantly on our ability to orient mind-wandering towards the sole temporal perspective in which our personal goals reside: the *future*. What truly makes human spontaneous thought an indispensable survival tool is, in fact, its capacity to flexibly navigate through

time. It enables individuals to pre-experience potential future scenarios, facilitating the modification of subsequent behavior if necessary (e.g., Bar, 2007; D'Argembeau et al., 2011; Smallwood et al., 2011). Furthermore, the ability to accurately place autobiographical memories within their temporal framework is crucial for the development of a coherent and stable personal identity (Tulving, 1985). Starting from the seminal work by Tulving (2002) affirming the brain's ability to navigate through past and future experiences, several studies demonstrated distinct psychological correlates associated with mind-wandering depending on its temporal orientation. Smallwood et al. (2009) observed that most task-unrelated thoughts during undemanding tasks were predominantly future-oriented. This finding has been replicated in numerous laboratory studies (Baird et al., 2011; Ruby et al., 2013; Smallwood et al., 2011; Stawarczyk et al., 2011, 2013). Similarly, studies investigating the content of daily life thoughts confirmed the presence of a prospective bias (Andrews-Hanna et al., 2013; Song & Wang, 2012). Stawarczyk et al., (2011), for example, had participants write about either personal goals or a non-personal topic; with a subsequent assessment of mind-wandering content (temporal focus) during an unrelated task. Interestingly, participants who wrote about their personal goals displayed more-future oriented mind-wandering, corroborating the association between the saliency of current concerns (Klinger, 1999) and the temporal orientation of spontaneous thought. The study by Smallwood et al. (2011) found instead that reflecting on one's own personality traits increased future-oriented mind-wandering, revealing the relationship between self-knowledge and prospective thought.

At the end of this examination of the content of thought and its adaptive value, it is clearer why I - like every individual - have decided to engage my attentional resources in mind-wandering, without letting myself be carried away only by the crowded surrounding environment. The answer lies in the content of my thoughts: undoubtedly, my future and, in particular, my current concerns. In fact, any existential question - in the form of an abstract idea - as well as the imminent need to continue working on this PhD thesis, has probably captured a portion of my attentional resources. Once again,

as human beings, we renounce the processing of a part of the external environment to focus on the equally complex train of future-oriented thoughts that, if anything, promote our survival.

1.4. Coordination and regulation of thought: Intentionality and meta-awareness

The reason why I was able to maintain focus on my thoughts—while still detaching from my surroundings—and at the same time not missing the right stop on the subway - likely stems from my capacity to regulate/coordinate my attentional resources between my internal world—my mind—and the external environment.

What is the exact role of executive control in mind-wandering? In this regard, the *executive control hypothesis* (Smallwood & Schooler, 2006) posited that mind-wandering arises when the cognitive load required by a task exceeds an individual's capacity to maintain task-relevant information. This hypothesis does not explain, however, the evidence that high working memory capacity reduces mind-wandering during demanding tasks (McVay & Kane, 2009, 2010; Unsworth & McMillan, 2014). Hence, McVay & Kane (2010) integrated this perspective with theoretical insights from Watkins (2008) and Klinger, (1999), suggesting that mind-wandering occurrence is influenced not only by the executive control system's ability to prevent primary-task performance from these distractions, but also by the urgency of automatically generated, *goal-related thoughts* triggered by external and internal cues. The McVay & Kane's framework, however, fails to account for the positive correlation between working memory capacity and task-unrelated, self-generated thoughts in low-demand situations (Levinson et al., 2012; Rummel & Boywitt, 2014), nor does it allow to differentiate between external distractions and self-generated thoughts (Barron et al., 2011; Stawarczyk et al., 2014; Unsworth & McMillan, 2014).

The degree of executive control exerted over thought varies depending on the situation. In this regard, the *context regulation hypothesis* suggested that the role of executive control in mind-wandering varies with the demands of the external task (Smallwood & Schooler, 2015), highlighting the importance of considering situational context (Andrews-Hanna et al., 2014; Smallwood & Andrews-Hanna, 2013) in the study of spontaneous thought. Empirical evidence supported this view, demonstrating that, for example, individuals with remarkable executive control abilities tend to limit task-unrelated thoughts when external demands are high (Kane & McVay, 2012), while tend to generate more off-task thoughts in non-demanding environments (Levinson et al., 2012). This trend was also observed outside of laboratory settings (Kane et al., 2007). Moreover, it was shown that off-task thinking, and executive control abilities correlate negatively during complex span, sustained attention, and reading tasks (McVay & Kane, 2009, 2011; Mrazek et al., 2012a; Unsworth & McMillan, 2013).

In addition to executive control, another way to regulate thought lies in *metacognition*¹. The reason why I could write about my crowded mental experience on the equally crowded subway, in fact, is that I was aware of what was happening at that moment, both inside (in my mind) and outside (in the environment). Despite this awareness, however, I may not have intentionally decided to mind-wander. So, these abstract images - or thoughts related to my current concerns - could have simply *popped* into my mind without any intentional effort. This highlights the need to distinguish between two mental phenomena that - while seemingly overlapping - are distinct at both theoretical and empirical levels: *meta-awareness* and *intentionality*.

Although it seems that we are inherently aware of our conscious experience, evidence shows that this experience can occur with or without explicit meta-awareness (Reichle et al., 2010; Schooler,

¹ *Metacognition* encompasses various forms, all involving a "meta" level of cognitive processing that is distinct from the primary level of perception, decision-making, or attention (Fleming et al., 2012). This meta-level can involve evaluating the accuracy of one's perceptions, certainty about decisions or performance, assessing one's own ideas or theories, or being aware of the quality of one's attention (e.g., focused versus distracted; Fox & Christoff, 2014).

2002; Schooler et al., 2011; Zedelius et al., 2015). Understanding the distinction between the experience itself (experiential consciousness) and our explicit awareness of it (meta-awareness) is crucial for uncovering the nature of mind-wandering. In this regard, Schooler, (2002) proposed a distinction between *basic consciousness* and *meta-consciousness* of thought. Basic consciousness, encompassing “*perceptions, feelings, and non-reflective cognitions*”, was defined as a continuous process throughout wakefulness; meta-consciousness, on the other hand, as a monitoring system that intermittently evaluates the contents of basic consciousness and their relation to individual goals. According to this framework, the meta-consciousness (or “*meta-awareness*”) state would enable us to become aware of the current mental experience – thus, mind-wandering episodes (Schooler, 2002). Subsequently, Schooler et al. (2004) empirically demonstrated that mind-wandering can occur even without awareness. In this study, participants read passages while monitoring their mental states and reporting any episodes of mind-wandering (i.e., self-catching their mind-wandering episodes while reading; see paragraph 1.1. for an overview of this experience-sampling method). Moreover, intermittent thought probes were presented, prompting participants to report if they were mind-wandering just before the appearance of each probe. Their results showed that – although participants often self-caught their wandering minds - there were instances where mind-wandering episodes were only detected by the probes. If - and only if - participants were constantly aware of their mental experience, they would have self-reported their thoughts in any case regardless of the probes, presumably refocusing on the reading task.

Building upon the distinction between different levels of consciousness, Smallwood et al., (2007) differentiated between two forms of mind-wandering based on the degree of meta-awareness engagement. They termed these states “*tune-outs*” and “*zone-outs*” - reflecting aware and unaware mind-wandering, respectively - which have since been distinguished both behaviorally and neurally. For example, (Smallwood et al., 2007, 2008) demonstrated that mind-wandering without awareness was associated with more frequent response-inhibition failures and reading comprehension deficits

compared to mind-wandering with awareness. Furthermore, Christoff et al., (2009) revealed distinct brain activity patterns for tuned-out (aware) and zoned-out (unaware) mind-wandering. Collectively, these findings demonstrate tune-outs and zone-outs have different implications for task performance and neural activity, likely reflecting distinct cognitive processes (Seli, Ralph, Risko, et al., 2017).

To delve into the other side of the coin – the concept of *intentionality* in spontaneous thought – it is necessary to take a step back. First, the pioneering study by Giambra (1995) differentiated between *controlled* and *uncontrolled* mind-wandering. It was suggested that task-unrelated imagery and thoughts can occupy awareness either through involuntary– uncontrolled – attentional capture or through deliberate– controlled - redirection of attention. While the matter of intentionality in mind-wandering remained largely unexplored for several decades, more recent studies have revisited this distinction, suggesting that intentional and unintentional mind-wandering are distinct cognitive experiences. For example, Seli et al. (2016) demonstrated that participants reported more intentional mind-wandering during an easy task compared to a more difficult one, and this finding was replicated more recently (Seli, Konishi, et al., 2018), showing more unintentional mind-wandering during a difficult vs. easy task.

Aware and unaware, intentional and unintentional: these concepts - albeit theoretically distinct - might be considered redundant. It would be reasonable, in fact, to assume that intentional mind-wandering inherently involves meta-awareness of its occurrence whereas unintentional mind-wandering naturally lacks such awareness (Seli et al., 2017). Nonetheless, Smallwood (2013) recently introduced a theoretical framework that differentiates between the *ignition* and *continuation* phases of a mind-wandering episode. This view suggests that the overlap between meta-awareness and intentionality may only be necessary at the ignition phase of a mind-wandering episode. As the episode progresses, however, intentionality and meta-awareness could theoretically diverge. For example, an individual might intentionally initiate mind-wandering and be aware of its onset, but then become so absorbed that they lose awareness of its unfolding over time. On the other hand, one might

unintentionally engage in mind-wandering but then become aware of it as the episode unfolds. The distinction between intentionality and awareness in mind-wandering was confirmed empirically by Seli et al. (2017). Across two studies, they revealed *a)* opposite patterns in the relative rates of zone-out to tuned-out and unintentional to intentional mind-wandering; *b)* a share of mind-wandering episodes were intentionally initiated but lacked meta-awareness as well as another share were unintentionally initiated but became aware at some point.

At this point, the reader might have understood the possibility of exerting control on —thus regulating—our thought at different levels and the potential dynamism of this process. The extent to which we can regulate our thinking will likely determine the impact it will have on our lives. Keeping this in mind, we now proceed to describe the main costs and/or benefits that a wandering mind can entail.

1.5. Costs and benefits of the mind-wandering state

Our crowded journey through the meanderings of our mind can be as fruitful and generative as it can be harmful and catastrophic. What determines the outcome of this journey? Surely, at least in part, it depends on our ability to regulate and coordinate it. It is plausible to hypothesize that, for example, if I had not been able to exert some cognitive control over those abstract images – or those thoughts related to my work - they would have lost their charm, transforming into something disconcerting. At this point in the narrative, therefore, I will review all the possible - positive and negative - outcomes of mind-wandering, keeping in mind how much they depend on the human ability to correctly regulate the flow of thought.

The traditional view of spontaneous thought (e.g., Giambra, 1995; Smallwood et al., 2003; see also paragraph 1.1) conceptualizes thought as *task-unrelated* and, thus, detrimental to ongoing performance. In other words, this perspective focuses on the evidence that mind-wandering occurs with a significant cost. Along with its ubiquity, the costs of mind-wandering have led to characterize

it as a lapse in cognitive control (McVay & Kane, 2010). The investigation into the negative impact of mind-wandering on task performance has been extensively documented within the context of reading (see above; but also [Bonifacci et al., 2023](#); [M. Franklin et al., 2011](#); [M. S. Franklin et al., 2013](#); [Grodsky & Giambra, 1990](#); [Schooler et al., 2005](#)), revealing consistently that individuals who exhibit higher frequencies of mind-wandering reports during reading tend to perform worse on subsequent text comprehension assessments (Bonifacci et al., 2023). This comprehension deficit - extending beyond the immediate information presented prior to mind-wandering episodes - manifests as a broader impairment in the construction of *mental models* (Mooneyham & Schooler, 2013). For instance, studies have demonstrated that errors in detecting incongruities within the text are associated with mind-wandering episodes, suggesting a failure in constructing propositional models of the text (Smallwood et al., 2007). These model-building errors persist even when information is preserved over prolonged intervals (Smallwood et al., 2008). The robust relationship between mind-wandering frequency and reading comprehension is supported by additional evidence linking mind-wandering to superficial encoding and less regulated motor/verbal output (Franklin et al., 2013; Smilek et al., 2010). Research on this field has shown that the typical relationship between lexical properties of words and processing time is attenuated during periods of mind-wandering (Reichle et al., 2010). Similarly, vocal prosody during reading is subtly altered during mind-wandering episodes, indicating a broader impact on reading-related behavior (Franklin et al., 2013).

The Sustained Attention to Response Task (SART) has been extensively utilized for assessing mind-wandering costs (Robertson et al., 1997). This task entails a GO/NO-GO paradigm where participants are required to promptly respond (via key pressing) to frequent stimuli while refraining from responding to infrequent target stimuli. Mind-wandering during the SART is discernible through several performance indices: errors (failure to withhold responses to target), reaction time variability (coefficient of variation), omissions (failure to respond to non-targets), and anticipations (rapid, automatic responses to non-targets indicative of task disengagement). Each of these measures

correlates positively with self-reported mind-wandering rates (Allan Cheyne et al., 2009), making SART-related performance measures a widely used proxy for identifying mind-wandering episodes. Errors are often interpreted as pronounced task disengagement, while increased reaction time variability represents a less disruptive form of disengagement (Allan Cheyne et al., 2009; Mrazek et al., 2012; Smallwood, Davies, et al., 2004). Overall, this conception suggests that mind-wandering can yield deficits in sustained attention, such as failure to detect infrequent targets or engagement in automatic rather than focused attention.

While there is controversy regarding the exact contribution of executive control in mind-wandering (see the paragraph 1.4.), the reverse question – i.e., the impact of mind-wandering on measures of executive control– is supported by empirical evidence. Mrazek et al., (2012) administered automated versions of three common working memory tasks (the operation span task, the reading span task and the symmetry span task) with embedded thought-probes. They found that self-reported mind-wandering scores during these probes were negatively correlated with working memory ability scores. Additionally, there was a significant effect of mind-wandering on working memory performance on a trial-by-trial basis (Mrazek et al., 2012), even for the “easiest” set sizes within the task. This finding suggests that mind-wandering disrupts performance in working memory, rather than being merely a result of poor performance. Furthermore, the detrimental impact of mind-wandering on these measures convincingly explains why working memory ability has been used to predict mind-wandering in other contexts.

One possible explanation of engaging in mind-wandering could be that – as in my case on the subway – we perceive it as a pleasurable activity that provides an alternative to the boredom generated by the ongoing task. However, experimental evidence suggests that individuals are less happy when mind-wandering than when task-focused (Mooneyham & Schooler, 2013). In a study examining real-world mind-wandering episodes, for example, Killingsworth & Gilbert (2010) administered random probes via a web-based cell phone application. They found that people reported to be less happy when

their minds wandered, regardless of the activity they were engaged in, even the least enjoyable ones. Moreover, while people tended to mind-wander about pleasant topics more than unpleasant or neutral ones, there was no difference in happiness ratings between activity-related thoughts and positive mind-wandering. Mind-wandering also accounted for more than twice the variance in happiness ratings compared to the actual activities people were doing. More precisely, time-lag analyses² suggested that mind-wandering preceded negative mood and not the other way around, strengthening the conception of a causal relationship between mind-wandering and mood. Subsequent studies corroborated these findings, also highlighting a relation between past-oriented mind-wandering and unhappy mood (e.g., Plimpton et al., 2015; Smallwood & O'Connor, 2011). In this regard, the *content regulation hypothesis* suggests that the costs associated with mind-wandering can only be fully understood by considering the specific content of thought. In fact, all the variations in mind-wandering contents (i.e., temporal focus, affective state, levels of interest) can affect the functional outcomes of spontaneous thought (Smallwood & Schooler, 2015).

Given the significant adverse effects of mind-wandering reported so far, my experience on the subway would seem rather nonsensical. However, there must have been a valid reason for my mind to wander instead of focusing on listening for the next subway stop. From an evolutionary perspective, even if mind-wandering did not hinder reproductive success - thereby allowing it to evolve somehow—it is plausible to hypothesize that it offers some benefits to humanity. This idea was proposed early in the literature, but has only recently gained attention. In their seminal work on daydreaming features, in fact, Singer & Antrobus, (1963) identified a “*clearly problem-solving, objective, nonpersonal type*” of daydreaming, which contrasts with the “*more fantastic, emotional, variegated, anxious, and pleasant*” factors typically driving mind-wandering episodes. This “controlled” type of

^{**} The authors performed multilevel regression analyses to explore the relationship between happiness at a specific time point (T) and mind-wandering at preceding (T-1) and subsequent (T+1) time points. The findings demonstrated a significant negative correlation between mind-wandering at T-1 and happiness at T (Model 1), while no significant relationship was observed between mind-wandering at T+1 and happiness at T (Model 2). These results support the hypothesis that mind-wandering may cause unhappiness rather than being merely a consequence of it.

daydreaming – that, more recently, we would define as *intentional* (see the paragraph 1.4.) – likely yields important benefits to human beings and thus deserves scientific investigation (Mooneyham & Schooler, 2013).

The reader can now easily infer the conditions that maximize the likelihood of adaptive mind-wandering: intentionality and, of course, the future orientation of thought. As we have seen in the previous section (see the paragraph 1.3.2.), in fact, a significant portion of thoughts during mind-wandering is *prospective* (D’Argembeau et al., 2011; Smallwood et al., 2009). This future-orientation of mind-wandering - along with the close connection between spontaneous thought and individuals’ *current concerns* (Klinger, 1999; Smallwood & Schooler, 2006) - allows some benefits: for instance, anticipating and planning personal relevant future goals, also known as *autobiographical planning*. As reported in the previous section, Baird et al., (2011) examined the temporal focus and referents of participants’ thoughts during a low demanding task (CRT; see also Smallwood et al., 2009). Several findings from this study support the notion that mind-wandering fosters future planning. For example, thoughts were predominantly future-oriented, self-related and personally relevant, and individuals with higher working memory scores were more likely to mind-wander about the future rather than the past or the present, combining self-related and goal-directed content. Collectively, these results corroborate that, when sufficient working memory resources are available, the prospective nature of mind-wandering serves a functional purpose: it facilitates planning and thinking about future goals.

As functional as it may be, future orientation alone would not be sufficient to characterize the uniqueness of my crowded mental journey on the subway: if I were to summarize my mental experience in one more word, it would be “*creativity*”. In fact, perhaps the most intriguing aspect of mind-wandering emerges when the mind diverges from the conventional trajectories to generate new ways of interpreting reality. Anecdotes of creative insights occurring during periods of spontaneous thought are prevalent throughout the history of scientific discovery. Instances such as Archimedes’ contemplation in his bath or Poincaré’s musings while stepping onto a bus are well-known, albeit not

scientifically documented (Mooneyham & Schooler, 2013). Another recurring aspect of these narratives is the notion that solutions emerge only after previous attempts to resolve the problem have failed; in contemporary terms, this phenomenon is described as *incubation*. A meta-analysis by Sio & Ormerod (2009) revealed that, across various studies, incubation intervals proved most effective when individuals engaged in an undemanding task compared to either no task or a demanding task. Intriguingly, undemanding tasks are also associated with heightened occurrence of mind-wandering (Smallwood & Schooler, 2006). Thus, it seems that mind-wandering may contribute to successful incubation, facilitating the emergence of innovative solutions to previously encountered problems after the incubation period. To test this hypothesis, Baird et al. (2012) investigated whether performance on validated creativity problems (i.e., the Unusual Uses Task) varied depending on whether participants engaged in a demanding task, an undemanding task (promoting mind-wandering), a rest period, or no break between creativity problems. Their findings indicated that, relative to the demanding task, rest, and no break conditions, engaging in an undemanding task (specifically, the CRT) during an incubation period significantly increased creative solutions to the target problems. Despite the high incidence of mind-wandering in this undemanding task condition, it did not yield a higher occurrence of explicit thoughts about the creativity problems themselves. Hence, it was apparent that conditions maximizing mind-wandering can also be the most conducive to creative problem-solving. Nonetheless, it should be noted that this undemanding task condition did not confer additional benefits for new problems (presented for the first time after the incubation period), suggesting that mind-wandering may not universally enhance creativity.

Contemplating the nature of human daily activities, Mooneyham & Schooler (2013) suggested additional potential beneficial functions associated with mind-wandering:

- *Attentional Cycling*: it is adaptive for an individual with multiple goal states to be able to cycle through different streams of information (e.g., current sensory environment, prospective planning information, remembered experiences, etc.). Mind-wandering may provide us with

the opportunity to frequently switch between streams of thought, thus enabling us to maintain goal-appropriate behaviors for multiple goals at a time (Mooneyham & Schooler, 2013);

- *Dishabituation*: Learning may be enhanced with distributed practice relative to massed practice (Underwood & Ekstrand, 1967). The advantage of distributed practice may stem from the benefits in processing that are afforded by dishabituation, and as such, it is possible that mind-wandering during learning tasks in particular may allow for (albeit brief) periods of dishabituation from the task, thus providing the mind with an opportunity to return to the task with a refreshed capacity for attentive processing.
- *Relief from boredom*: When faced with a boring task or situation, our minds tend to wander, sometimes intentionally. This may be adaptive; the ability for our minds to disengage from the current external environment and to engage in an alternative train of thought may have evolved in part to allow us to overcome tedium and disinterest without overtly abandoning a necessary task. Mind-wandering may also reduce boredom by helping the time to pass. While boring tasks are typically estimated to last longer than they actually do, in fact, mind-wandering episodes have been observed to be accompanied by temporal estimations that are shorter than their on-task counterparts (Mooneyham & Schooler, 2013). As such, mind-wandering may act to “speed up” the perceived flow of time during tedious or boring activities.

The picture that emerges from the discussion so far is ambivalent: the ubiquity of mind-wandering in our lives can be both problematic and potentially beneficial. It becomes even more crucial, then, to study its phenomenology, identify the circumstances that maximize its occurrence, and develop strategies to manage thought flow efficiently. This is partly the aim of this PhD thesis, which was also among the multitude of thoughts that characterized the crowded mental journey on the subway of a crowded city. If anything, my experience might have been one of those instances in which I successfully regulated mind-wandering, bringing order and generating new ideas.

1.6. *The dynamic framework: from spontaneous to deliberate constraints*

As the puzzle of the various dimensions of spontaneous thought phenomenology becomes increasingly rich, it is perhaps worth considering another fascinating aspect: its *dynamism*. To grasp this concept, we need only think of the spontaneous *fluctuations* between my thoughts - which I mentioned at the beginning of this chapter - that allowed me to move agilely between the abstract images and concrete goals that crowded my mind. Indeed, it is precisely the dynamism of spontaneous thought that truly distinguishes it from other types of more "deliberate" thought (see the paragraph 2 for a more in-depth discussion of deliberate thought).

Despite its recent surge in popularity, research on mind-wandering carries a historical legacy rooted in the past task-centric perspectives, conceiving it as the antithesis of task-related or stimulus-oriented thought (Callard et al., 2013). For example, a prominent review (Smallwood & Schooler, 2015) conceives mind-wandering as a “*shift in the contents of thought away from an ongoing task and/or from events in the external environment*”. This approach defining mind-wandering through the lens of its content – akin to William James’s metaphor of the bird’s perchings rather than its flights - has been implicitly or explicitly endorsed by much of the existing empirical research on spontaneous thought (Christoff, 2012; Irving, 2016).

Building from these assumptions, Christoff et al. (2016) introduced a new theoretical framework, defining instead spontaneous thought as a mental state, or consequence of mental states, characterized by the absence of strong constraints on their content and on the transitions between mental states. One type of constraint is flexible and *intentional*, implemented through deliberate cognitive control mechanisms (Miller & Cohen, 2001; Miller, 2000). For example, we may consciously maintain focus on a dull lecture, by actively redirecting our attention back to the speaker whenever our thoughts begin to wander. Conversely, the other type of constraint is entirely *automatic* in nature, acting outside of the conscious control and holding our attentional focus to a specific set of

information (Irving, 2016). Affective and sensory salience (Jonides & Yantis, 1988; Todd et al., 2012; see also the paragraph 3.4.3.) are examples of such automatic constraints. Despite our best effort, in fact, we may find ourselves fixated on a buzzing fly in a quiet library or overwhelmed by a worrying emotional concern.

In sum, Christoff et al.'s framework conceptualizes mind-wandering as a particular case within the broader spectrum of spontaneous thought (see Figure 2). Compared to day-dreaming, mind-wandering exhibits more deliberate constraint, though it does not reach the level of cognitive control required in creative thinking or goal-directed thought. At the same time, it also differs from rumination and other thought patterns characterized by a high degree of automatic constraints, such as obsessive thought (Christoff et al., 2016).

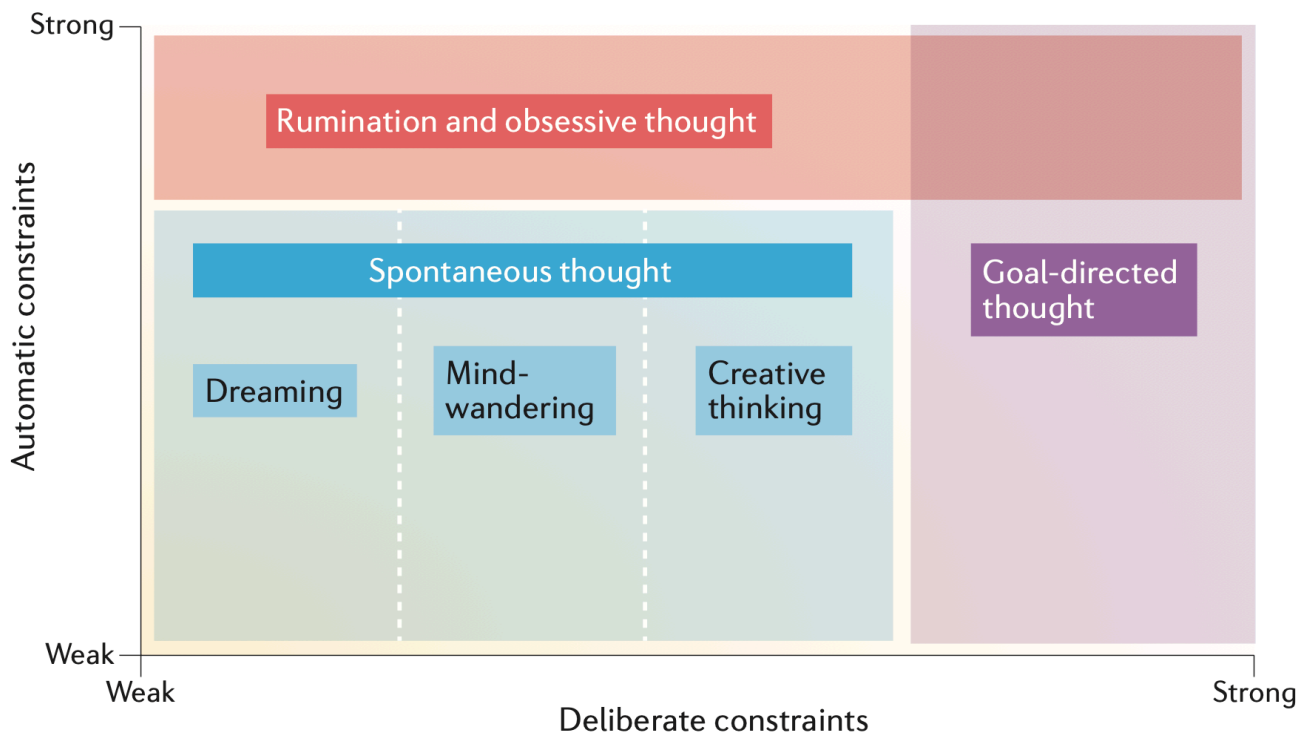


Figure 2. *The conceptual space of different types of thought.* Deliberate and automatic constraints can limit the content and evolution of thought over time. Deliberate constraints are exerted through cognitive control, while automatic constraints operate outside of it, encompassing mechanisms such as sensory or affective salience. Deliberate constraints are minimal during *dreaming*, increase somewhat during *mind-wandering*, rise further in *creative thinking*, and are strongest during *goal-directed thought*. Automatic constraints range from low to medium during *dreaming*, *mind-*

wandering, and creative thinking, but thought becomes non-spontaneous at higher levels of automatic constraint, such as in rumination or obsessive thinking (Christoff et al., 2016).

In contrast to the *family-resemblance view* (Seli et al., 2018; see also the paragraph 1.1.), this approach aims to define mind-wandering by delineating its essential features, thereby establishing clear boundaries for this area of investigation. Following Christoff's emphasis on the dynamic nature of thought— such as its "perchings" and the temporal unfolding of a mind-wandering episode— numerous research lines (e.g. [Cnudde et al., 2023](#); [Mills et al., 2021](#); [Pelagatti et al., 2020](#); [Zukosky & Wang, 2021](#)) have explored various phenomenological aspects related to it, including the transitions between mental states.

In the context of the present work, the concept of *deliberate* constraint becomes particularly relevant. The degree of executive control exerted over thought, in fact, determines the transition from spontaneous forms of thinking—such as mind-wandering, described in this paragraph—to more deliberate, goal-oriented forms of thought. These deliberate forms of thought will be the focus of the next paragraph.

2. Phenomenology of deliberate thought

As captivating as it is to be swept away by the crowd of thoughts, it is often necessary to bring them into order. It happens like when we take refuge from the chaotic metropolitan crowd that, in the long run, makes us feel disoriented. In these cases, based on our general knowledge of the world, we can take the helm of our mental journey and head to the most disparate places: re-immersing ourselves in experiences from long ago, as well as imagining hypothetical scenarios. As human beings, in fact, we are able to place the life events on a *mental timeline*, positioning them in relation to one another. Starting from this mental map - of which we have already learnt the coordinates - we can orient

ourselves with relative ease, making our journey more controlled. Another way of creating order is to mentally represent an intention that needs to be carried out in the future, and to keep it in memory for a certain period of time, before it is executed.

The reader might now wonder about the established criteria for defining this type of thought as *deliberate*. In the previous paragraph, in fact, we have shown how task-unrelated, stimulus-independent thoughts can emerge spontaneously and unexpectedly while we are engaged in other habitual activities or in response to irrelevant environmental stimuli. They differ from their deliberate counterparts in systematic ways: they tend to be more specific and distinctive and are often accompanied by identifiable impacts on mood and behavioral or physiological reactions at the time of recall (Berntsen, 1998; Berntsen & Hall, 2004). On the contrary, the content of this paragraph will focus on the ability to deliberately recall past events and/or simulate hypothetical future scenarios. This mode of thinking emphasizes the *slow* and *effortful* constructive nature of thinking, stemming from an individual's *intentional* decision (Kvavilashvili & Rummel, 2020). Using the words of Christoff et al. (2016), I am referring to those forms of thought upon which we exert deliberate constraints, shifting from mind-wandering/creative thought towards goal-directed thought (see Figure 2).

Building on these premises, this paragraph will explore various forms of deliberate— rather than spontaneous³ thought. First, I will begin with an in-depth focus on Mental Time Travel, aiming to detail some key theoretical models as well as the primary mental representations that characterize its phenomenology. Subsequently, along the spontaneous-to-deliberate axis, I will concentrate on

³ *Spontaneous (or involuntary) future thinking* involves mental representations about the future that arise unexpectedly while one is engaged in other habitual activities, often triggered by irrelevant environmental stimuli (Kvavilashvili & Rummel, 2020). These thoughts can pertain to planned tasks or events (e.g., buying a flight ticket tomorrow, attending a social event next week), plausible future events (e.g., envisioning a trip to Edinburgh or having children), or hypothetical scenarios and wishful thinking (e.g., winning the lottery, marrying a celebrity).

Prospective Memory, defining some of the high-level executive processes involved in this ability as well as the related theoretical frameworks.

2.1. Mental Time Travel

While physical time travel remains in the realm of science fiction, humans are able to mentally project themselves backward in time to relive past experiences - *episodic memory* – or forward to pre-experience potential future events – *episodic future thinking* (Suddendorf & Corballis, 1997).

The term Mental Time Travel (MTT) was first introduced by Tulving (1985). This seminal work suggested that MTT expands to both the past and the future and illustrated the concept with the case of the amnesic patient N.N., who was incapable of imagining future events as he was of recalling past experiences. Drawing on early 20th-century phenomenologists, Tulving (1985) also distinguished between two fundamental modes of consciousness in MTT: *autonoetic* and *noetic*. Autonoetic consciousness offers the unique ability to re-experience past or to anticipate future events in the present moment – a phenomenon that transcends the temporal and spatial contexts of their occurrence (Tulving, 1993). In contrast, noetic consciousness allows one to engage cognitively with abstract concepts, facts, and relationships among objects and events, irrespective of their immediate presence. Thus, individuals with noetic consciousness do not experience the subjective feeling of mentally traveling back in time to relive the content of the events that are currently in their awareness.

MTT should be distinguished from other seemingly related concepts. One such concept is *daydreaming* (see above, Christoff et al., 2016), that – as discussed previously – became the subject of scientific study through the pioneering work by Antrobus et al. (1966). Crucially, daydreaming does *not* necessarily involve the self as character; it may feature pure simulations of fictitious characters, such as superheroes. Thus, while daydreaming may sometimes involve MTT – in either a

spontaneous or deliberate form – it does not directly correspond to the concept (Berntsen & Jacobsen, 2008). Similarly, mind-wandering refers to “*a situation in which executive control shifts away from a primary task to the processing of personal goals*” (Smallwood & Schooler, 2006; see also paragraph 1.3.1.). Although related, none of these concepts fully captures the essence of MTT (Berntsen & Jacobsen, 2008).

The concept of MTT was further developed by Suddendorf & Corballis (1997), highlighting its generative nature. Episodic memory is, in fact, a *constructive* process rather than a literal replay of past events and this also extends to the creation of fictional scenarios, allowing us to construct narratives with little or no basis in reality. A decade later, Suddendorf & Corballis (2007) elaborated on this idea, which became a subject of considerable scientific debate.

Given that the ability to MTT can impact an individual’s future survival chances, it is reasonable to expect many species to have evolved prediction abilities. In such a dynamic world, in fact, organisms that can detect significant regularities (e.g., fluctuations in food availability) and act accordingly (e.g., being in the right place at the right time) gain an advantage over those that cannot. These organisms can actively influence their own futures by creating environments that meet their needs (see Odling-Smee et al., 2003), by adopting individual fine-tuning mechanisms – e.g., *imprinting* and other forms of learning - that provide greater flexibility. Learning and memory in general can be regarded as future-oriented adaptations, enabling individuals, rather than populations, to adjust to local changes and track short-term regularities. Building from these assumptions, Suddendorf & Corballis (2007) proposed a taxonomy of human memory systems – classified depending on their levels of flexibility. This taxonomy was also adapted to the prospective component (Miyashita, 2004; Squire, 1992; Suddendorf & Corballis, 2007), to distinguish how different memory systems contribute to future-oriented behaviors. MTT is conceived as the most flexible and recently evolved of these memory-based systems (see Figure 3). Beginning from the downside, we can find:

- *Non-declarative* or *implicit* memory systems, in humans, are so called because their content cannot be declared or verbalized (Tulving, 1985), and enable stimulus-driven prediction of regularities. For instance, through association, a conditioned stimulus (e.g., a light) signals the impending arrival of an unconditioned stimulus (e.g., an electric shock) and elicits a future-oriented response (e.g., avoidance behavior). Similarly, in operant conditioning, a specific behavioral action (e.g., pressing a lever) predicts a particular outcome (e.g., receiving a treat), thus reinforcing the behavior. Non-associative behavioral changes, such as habituation, can also be interpreted in terms of expectations (e.g., anticipating that the situation will not change). All these non-declarative memory systems collectively allow experience to modulate behavior, granting the organism a future advantage. Nonetheless, the resulting future-directed mechanisms – to which we can refer as *procedural* - still are limited to learning responses to current indicators of upcoming events: this behavior, in other words, remains bound to the perceptual tracking of stimuli.
- *Declarative*, or *explicit* memories offer instead greater flexibility: they can be voluntarily triggered (in a top-down manner) from the related brain structures, rather than solely through bottom-up processing driven by perception (Miyashita, 2004). These memories, in fact, function as decoupled representations, no longer directly tied to the perceptual system. In humans, they occur with awareness and are at least partially verbalizable (Tulving, 1985, 2005). Declarative memory can be divided into semantic memory and episodic components. The *semantic* component stores general knowledge (both in the past and the future), enabling the transfer of learning from one context to another and building the basis of inferential and analogical reasoning. However, it is limited by its reliance on a knowledge base that is insensitive to the specific details of the event itself. The *episodic* component, instead, is what truly refers to the concept of MTT.

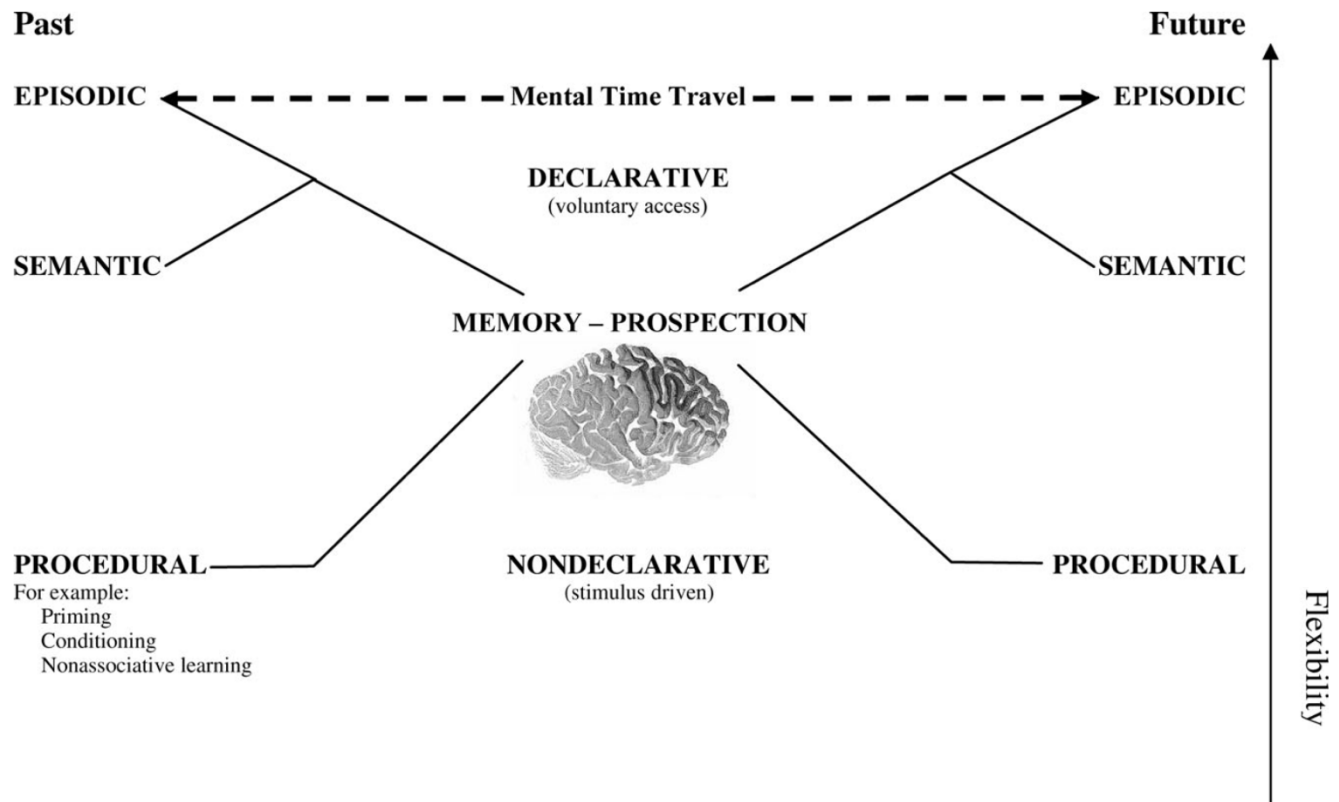


Figure 3. *Memory and Prospection systems.* On the left, the traditional taxonomy of memory systems proposed by Squire (1992), alongside its proposed counterpart for prospection (Suddendorf & Corballis, 2007)

2.1.1 *Mental representations of the past*

2.1.1.1. *Episodic memory*

Suppose we wish to take control of our MTT and deliberately immerse ourselves in our past. We would not only be capable of recalling specific past events, but also of identifying patterns in our experiences (Barsalou, 1988), organizing them into coherent *clusters* and sequences (Brown & Schopflocher, 1998), and ultimately crafting an overarching personal narrative that provides meaning and purpose to our lives (McAdams, 2001). A substantial body of evidence, in fact, highlights that our personal past is encoded in memory across various timescales and levels of specificity and generality (Burt et al., 2003; Conway & Bekerian, 1987; Dijkstra & Kaup, 2005; Mace & Clevinger,

2013; Piolino et al., 2010; Skowronski et al., 2007; D. Thomsen, 2009). This diversity in memory representations is substantially explained by two principal representational systems that keep track of past experiences and organize knowledge about the content and the structures of our lives: *episodic memory* and *autobiographical knowledge*. A close examination of both will enable us to fully understand the cognitive mechanisms involved in our mental journey into the past.

What is the most exhaustive definition for *episodic memory*? A repository for past experiences, encompassing perceptions, actions, thoughts, and emotions associated with events that typically unfold over minutes or hours (Conway, 2009; Tulving, 2002) – for example, a lunch with colleagues, a particular daily trip in the subway of a crowded city, a conversation with our partner. These experiences are not stored as monolithic entities, but rather as a multifaceted tapestry woven from threads of individual components. Notably, research has shed light on their temporal structures: memories of real-world experiences, in fact, are typically represented as a series of interconnected moments or “slices” organized chronologically (Anderson & Conway, 1993; D’Argembeau, 2020; Jeunehomme et al., 2018). Cognitive and neural evidence suggests these memory units are formed through a segmentation process that partitions experience into discrete events and subevents (Brunec et al., 2018; Clewett et al., 2019; Radvansky & Zacks, 2017). Dynamic changes in various aspects of the ongoing experience, such as location, characters, objects, and goals, guide the perception of event boundaries (Zacks & Swallow, 2007). These boundaries, in turn, would frame the integration and separation of information into meaningful memory components (Clewett et al., 2019; Radvansky & Zacks, 2017).

It is important to recognize that episodic memories are not verbatim reproductions of the past, but rather summary representations constructed from fragments of prior experiences (Conway, 2009; Schacter et al., 1998). This notion is further emphasized by recent studies revealing a temporal compression phenomenon occurring during recollection: events are mentally replayed at a faster rate than their actual duration (Faber & Gennari, 2015; Jeunehomme & D’Argembeau, 2019; Michelmann

et al., 2019). To investigate this compression mechanism, for example, Jeunehomme et al., (2018) employed wearable camera technology to compare the temporal structure of episodic memories with the actual content and duration of past events. Their findings revealed that memories often included temporal discontinuities in how events unfolded; certain portions were simply not represented during the mental replay process (see also Jeunehomme & D'Argembeau, 2019). A recent magnetoencephalography study that tracked memory replay for video clips provided further evidence for this time-compressed mechanism. Some video fragments were replayed at the same speed as perception, while others were skipped entirely, leading to an overall faster mental replay compared to the original viewing (Michelmann et al., 2019). The extent to which episodic memory compresses time is not constant; it varies across different events and is partly influenced by the granularity of event segmentation (Jeunehomme et al., 2020). These considerations revised the original episodic memory concept as originally proposed by Tulving (1985) and further elaborated developed in subsequent research.

Episodic memories are primarily *sensory-perceptual* in nature: this type of experience-proximal knowledge, when accessed, facilitates recollection (Conway, 2001). As a result, episodic memory aligns with *recollective experience*, i.e., a form of self-awareness in the past that is triggered by images, emotions, and other memory details that arise during the recollection process. This memory awareness informs the individual that the mental representation in question is indeed a memory of an actual experience, as opposed to a fantasy, dream, plan, or another – experience-distant – mental construct. It is important to note that recollective experience does not invariably denote a true memory – in the sense that the recalled experience actually occurred – but when recollection is present, the likelihood that the remembered event was genuinely experienced is high (Conway et al., 1996; Roediger & McDermott, 1995).

While the distinction between episodic and semantic memory is conceptually valuable, it is now clear that these systems are inextricably intertwined. The content of episodic memories, in fact,

typically includes a blend of event-specific information (e.g., perceptual details, context) and conceptual processing (Binder & Desai, 2011; Greenberg & Verfaellie, 2010; Irish & Piguet, 2013; Renoult et al., 2019; Strikwerda-Brown et al., 2019). Although episodic memories encapsulate knowledge about specific actions, as well as their outcomes, derived from moment-by-moment experiences, they do not persist in memory unless integrated into more enduring memory structures. The arrangement of several episodic memories, along with the abstractions drawn from them and the working self's attitudes and beliefs, forms higher-level memory representations, such as *autobiographical knowledge*.

2.1.1.2. Autobiographical knowledge

Autobiographical memory pertains to an individual's personal history. This encompasses a variety of self-related memories, like one's 5th-grade experiences, learning how to ride a bicycle, interactions with significant people, but also my mental experience on the subway of a crowded city. Recollections of past episodes, encapsulating sensory-perceptual details which we previously identified as episodic (see the previous paragraph), in fact, are also part of autobiographical memory (Conway, 2001).

Autobiographical knowledge encompasses more abstract, conceptual representations of the events and periods that constitute our lives (Conway, 2005; Renoult et al., 2012; D. K. Thomsen, 2015). It provides an organized set of representations containing factual knowledge about single life events (e.g., "*I know that I was in London for my 28th birthday*"), as well as knowledge of regularities in experience (e.g., *I know that I lived in London for a year*). Although the organization of autobiographical memory is still debated (see e.g., Mace & Unlu, 2019; Schulkind et al., 2012;

Brown, 2016), an influential view suggests that different layers of autobiographical knowledge are structured in partonomic hierarchies (Barsalou, 1988; Conway & Pleydell-Pearce, 2000). Conway & Pleydell-Pearce (2000), in particular, distinguished three main domains of knowledge representation that vary in specificity and temporal scope: *lifetime periods*, general events and event-specific knowledge. Lifetime periods encompass features (people, places, objects, goals, and activities) characteristic of specific spans of time in our lives, typically ranging from months to years (e.g., “*when I lived in Padua*”, Thomsen, 2015). General events include instead knowledge about repeated experiences (e.g., “*multiple tennis matches played during the childhood*”), single extended events (e.g., “*a trip to Lisbon last summer*”), and sets of events organized in sequences (e.g., “*learning to drive*”; Barsalou, 1988; Brown & Schopflocher, 1998). Lastly, event-specific knowledge pertains to experiences that occurred at a particular time and place (e.g., “*my crowded journey on the subway, on that particular afternoon*”). It is also important to distinguish between the experiential content of specific events (episodic memory) and conceptual knowledge about the occurrence of events – representations of the essential content or theme of events, referred to as their *gist* (Brainerd & Reyna, 2002) or *conceptual frame* (Conway, 2009). Nonetheless, autobiographical representations may involve a continuum of abstraction/concreteness rather than strict categories (Renoult et al., 2012). The hierarchical structure of autobiographical knowledge has been demonstrated in experiments showing that memories of specific events are often embedded in overarching memory structures, referred to as “*event clusters*”, which organize information about a set of causally or thematically related events (Brown, 2005; Brown & Schopflocher, 1998; Burt et al., 2003).

Why is it necessary to employ such complexity in memory structures, enabling the retention of episodic memories in a durable form (Conway, 2001, 2005)? We are aware of the multitude of memories formed each day, yet they quickly become difficult to access unless they are linked to high-level goals and event structures. Once this integration process is initiated, event retrieval will not only involve accessing event-specific details—stored in episodic memory—but also autobiographical

knowledge, which situates these events within a broader life context. For instance, my mental image of a crowded metro ride in a metropolitan city—an episodic memory— can be contextualized by knowing that this event occurred during one of my many weekday travels home from the university office in February or -even better - during the period abroad as part of my PhD program.

2.1.2. Mental representations of the future

Prospection occupies the majority of our waking life (Anderson et al., 2019; D'Argembeau et al., 2011). This capacity allows us to envision potential scenarios: we can evaluate opportunities and threats, consider different courses of action, and anticipate their consequences. It guides various aspect of human behavior and cognition, including decision-making (Bulley et al., 2016), planning (Bulley & Irish, 2018), emotion regulation (Jing et al., 2016), creativity (Addis et al., 2016), and empathy (Gaesser & Schacter, 2014). The concept of *prospection* encompasses a broad spectrum of future-oriented cognitive abilities (Gilbert & Wilson, 2007; Seligman et al., 2013), each of which serves distinct functions in adaptive behavior (Schacter, 2012a).

In this regard, the organizational framework proposed by Szpunar et al., (2014) has distinguished four modes of future-oriented thinking that support *prospection*, from the initial conception of a possible future event to the attainment of a goal. *Prediction* is defined as the ability to estimate the likelihood of future occurrences, and may be related both to expected short-term rewards (essential for learning) and longer-term estimates regarding specific or more abstract future states (Bar, 2007; Schultz et al., 1997). *Intention* involves instead mentally setting a goal (Ajzen, 1991; Locke & Latham, 2002; Ryan, 1970) that might be related to a specific autobiographical event (episodic) or a general/more abstract (semantic) forms of knowledge. For intended behaviors to be executed effectively, *planning* is often necessary: it involves deliberately identifying and organizing the steps

required to reach a specific autobiographical event/outcome (episodic) or a more general/abstract state in the future. The fourth mode is *simulation*, which constitutes the main focus of this paragraph.

2.1.2.1. *Episodic future thinking*

Simulation allows constructing a detailed mental representation of a specific event or more general state of the world. Its episodic component – also known as *episodic future thinking* or foresight - has gathered recent attention in the literature. It refers to the ability to imagine specific events unfolding in our personal future (Atance & O'Neill, 2001; Schacter & Addis, 2007; Suddendorf & Corballis, 2007; Szpunar, 2010). While not without limitations (Gilbert & Wilson, 2007), episodic future thinking allows us to mentally pre-experience future events: we can picture the setting, objects, people, actions, and emotions associated with a given situation, simulating it in our mind's eye (D'Argembeau & Van der Linden, 2004a).

What mechanisms drive the human ability for episodic future thinking? Multiple lines of evidence point to the relevance of episodic and semantic memory representations, serving as sources of information for imagining future events (Schacter et al., 2017). A prominent formulation of this view, known as the *constructive episodic simulation hypothesis* (Addis & Schacter, 2008), posits that episodic memory supports future simulation by enabling the flexible retrieval and recombination of elements from past experiences (e.g., details about locations, people, objects) into novel representations of potential future events (Schacter & Addis, 2007; Suddendorf & Corballis, 2007). While these flexible retrieval and recombination abilities are adaptive for constructing episodic simulations, they may also introduce memory errors, such as source misattribution and false recognition, by mistakenly combining elements from different past experiences. Key cognitive evidence for the role of episodic memory in future thinking comes from studies employing the Autobiographical Interview (AI; Levine et al., 2002; see also paragraph 2.1.4.). This procedure involves individuals recalling past and imagining future personal experiences, with the details they

produce categorized as either *internal* (episodic details such as specific events) or *external* (semantic details and commentary).

2.1.2.2. *Autobiographical knowledge*

Semantic knowledge contributes to the imagination of future events by providing the conceptual framework required to construct meaningful scenarios (Irish & Piguet, 2013). Notably, the temporal organization of event segments may be supported by semantic knowledge of typical relationships among various entities (e.g., people, objects) during events (e.g., knowledge about action sequences and causal relations; (Radvansky & Zacks, 2011; Sheldon et al., 2019). Neuropsychological research indicates, for example, that individuals with deficits in either episodic or semantic memory are impaired at constructing future scenarios (e.g., Irish et al., 2012.; De Luca et al., 2018; Grilli et al., 2023). Cognitive studies further indicate that imagined events are more detailed when their contextual settings are associated with richer memory traces (Schacter et al., 1998; Schacter & Addis, 2007). D'Argembeau & Mathy (2011) revealed that constructing episodic future thoughts – as well as the retrieving autobiographical memories (see Haque & Conway, 2001)- is predominantly a *generative* process, where general personal knowledge (i.e., personal semantic information and/or general events) is accessed prior to episodic details, and plays a crucial role in constructing episodic future thoughts. Interestingly, the authors observed a substantial proportion of personal goals (approximately 40%) reported by participants in this study aligned with culturally-shared expectations regarding significant – transitional - life events (*cultural life-scripts*, but also Berntsen & Jacobsen, 2008; Berntsen & Rubin, 2004). Moreover, cueing participants with culturally-shared vs. more idiosyncratic goals produced similar effects on future events fluency and access to episodic details. This suggests that mental representations of the future are largely influenced by cultural life scripts rather than solely by individual goals. Nonetheless, the specific ways in which cultural life scripts manifest in episodic future thoughts may still be unique to each individual (e.g. two people might envision their graduation day differently, despite following a similar general script). In other

words, D'Argembeau & Mathy (2011) theorized the importance of *personal goals* – be they culturally-transmitted or more idiosyncratic – in guiding and motivating the construction of future scenarios.

Research on autobiographical memory (e.g., Aizpurua & Koutstaal, 2015; Gaesser et al., 2011; Spencer & Raz, 1995) has also consistently shown that healthy older adults produce fewer internal/episodic details and more external/semantic details compared to younger adults, for both remembered past events and imagined future events. This pattern suggests a common role of episodic memory in both types of events (Madore & Schacter, 2014; Schacter, 2012). Although the temporal structure of episodic future thoughts awaits further investigation, the existing literature suggests that the representation of unfolding experiences is similar for both past and future events. Event segments are, in fact, organized chronologically when remembering past events and imagining future scenarios (Anderson et al., 2015). Like episodic memories, episodic simulations represent the dynamic unfolding of events in a compressed form; for example, mentally simulating a route takes less time than physically navigating it (Arnold et al., 2016; Bonasia et al., 2015).

Taken together, these findings indicate that episodic future thoughts are constructed from similar informational content – drawn from episodic and semantic memory – and share a comparable temporal structure with episodic memories: the unfolding of events is represented as a sequence of event segments organized chronologically. The ability to adapt temporal compression rates, in episodic simulations, may confer an advantage for prospection by facilitating the mental exploration of events in varying degrees of detail (Arnold et al., 2016).

2.1.3. Cognitive architecture underlying Mental Time Travel

How the reader might have understood from the previous sections, MTT encompasses a broad spectrum of – past and future - mental representations that vary in specificity and temporal scope. To navigate this vast array of representations, a coordinate system is required to establish how they are interconnected, thereby facilitating mental navigation between the past and the future. The proposal by Conway et al. (2019) followed this approach, assuming a hierarchical model of autobiographical memory organization (Conway, 2001, 2005) and a similar representational structure underpinning future-oriented cognition (D’Argembeau, 2015).

More recently, MTT has been conceived as the “*capacity to flexibly navigate hierarchical layers of autobiographical representations*” (D’Argembeau, 2020). In line with other theories (Hassabis & Maguire, 2007; Rubin & Umanath, 2015; Schacter & Addis, 2007), in fact, D’Argembeau (2020)’s theoretical framework conceptualizes mental simulations of past and future events as relying on common *constructive* processes. This framework posits that simulations of specific events, be they past or future, are constructed recombining details from prior experiences (drawn from episodic memory; Schacter & Addis, 2007) and semantic knowledge (Irish & Piguet, 2013), in various proportions depending on the type of event (e.g., memories of past events typically include more episodic details than imagined future events; Addis et al., 2008; Berntsen & Bohn, 2010; D’Argembeau, Ortoleva, et al., 2010). The function of event simulations is to provide a representation of the experiential content of events from an egocentric perspective – depicting what it is like to experience these events. These simulations depend on mental imagery (i.e., depictive representations, Pearson & Kosslyn, 2015) and utilize modality-systems for perception, action, emotion, and introspection (Barsalou, 2009). Both past recollection and future thinking involve *simulation* processes (Michaelian, 2016). However, event simulations may be atemporal in nature – meaning they lack a broader temporal context that locates events in the past, present or future – yet they possess an internal structure that represents the unfolding of events. Neuropsychological evidence suggests

that the subjective temporality of events (i.e., the sense that represented contexts refer to the personal past or future) is not an intrinsic property of simulations. Some patients, in fact, can form vivid representations of events corresponding to actual past experiences without experiencing these as events that occurred in their personal past (Race et al., 2011; Schacter et al., 2007; Tulving, 2002). D'Argembeau (2020), in his framework, expands this view, conceptualizing that simulation processes can mentally represent any kind of events, not only past and future ones but also fictitious scenes (Hassabis, Kumaran, Vann, et al., 2007), events involving others (de Vito et al., 2012), and simulations during literary reading (Tamir et al., 2016), among others (Addis, 2018).

The central proposition of D'Argembeau (2020)'s framework is that autobiographical knowledge provides the personal temporal context of event simulations, forming a cognitive *representational system* – a personal timeline – onto which remembered and imagined events can be mapped (Conway et al., 2019; D'Argembeau, 2015, 2016; Fivush, 2011). Although event simulations rely on mental imagery, in fact, autobiographical knowledge involves conceptual/propositional (language-based) representations, allowing us to link, sequence, and organize life experiences (Paivio, 1991). The autobiographical knowledge base organizes information about the content and structure of one's past, present and future life in hierarchical layers referring to different temporal scopes (see Figure 4).

At the apex of the hierarchy, *lifetime periods* represent knowledge about extensive spans of time – typically years. Moving down the hierarchy, representations of *general events* encompasses progressively shorter time spans – e.g., months, weeks, days. The lowest level of the hierarchy includes instead conceptual knowledge about the occurrence of specific events – representations of the essential content or theme of unique events, referred to as their *conceptual frame* (Conway, 2009) or *gist* (Brainerd & Reyna, 2002; Robin & Moscovitch, 2017). This layer accounts for the ability to think about unique events in the past or the future without necessarily constructing mental simulations of these events (e.g., knowing that I attended a social event in London last weekend or plan to visit Edinburgh next Sunday without mentally representing the experiential content of these events).

Hence, the subjective temporality of memories and future thoughts emerges from the synergy between event simulations and autobiographical knowledge. The sense of remembering the past or foreseeing the future arises when simulated contents are situated on a personal timeline through their connection with higher-order knowledge of the content and structure of one's life. (D'Argembeau, 2020). For example, the mental image of my trip to Edinburgh can – of course – generate a mental simulation, but I will not experience this simulation as a past or future event unless related to my personal life (see also Ernst & D'Argembeau, 2017; Ernst et al., 2019). Instead, a sense of future occurrence of this event may arise by considering that this event might happen, for example, during my last weekend in the UK next autumn.

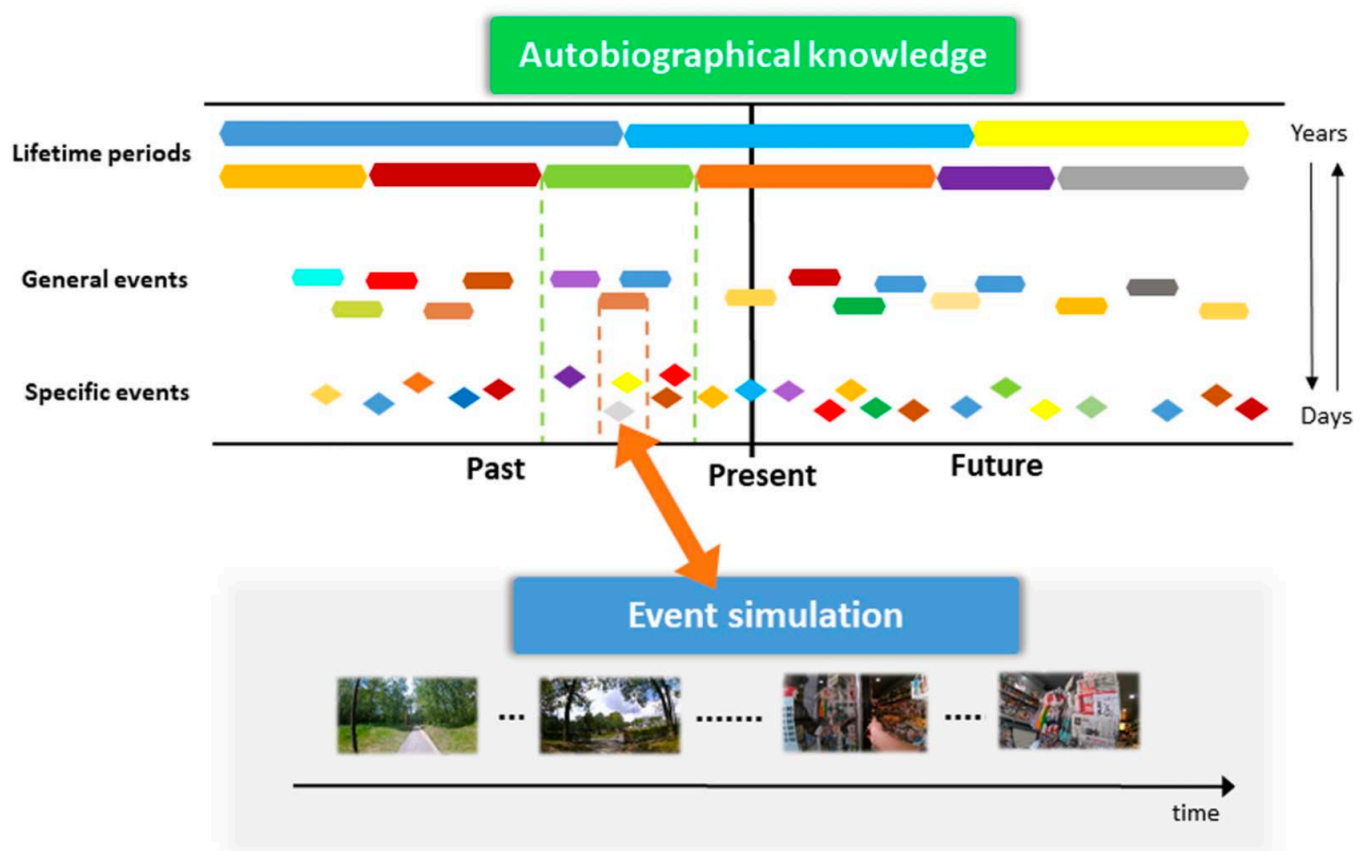


Figure 4. *Theoretical framework on the cognitive architecture underlying MTT.* Constructing simulations of past and future events requires both details from prior experiences and semantic knowledge. These simulations unfold through a sequence of experience units, typically organized chronologically. While simulations represent the experiential content of events, their subjective temporality is rooted in autobiographical knowledge, which instead provides a personal timeline. This timeline organizes life events into hierarchical layers—lifetime periods, general events, and specific

events—differing in specificity and temporal scope. The sense of remembering or anticipating arises when simulations are mapped onto this personal timeline, connecting specific events to broader life periods through autobiographical knowledge. The figure illustrates this process, showing how a specific event is nested within a general event and, in turn, a lifetime period (D’Argembeau, 2020).

Although event simulations are not intrinsically located in time, they have a typical internal temporal structure (see Figure 4). Some simulations may be like snapshots capturing slices of experience, but most represent events unfolding over time—usually minutes or hours. The dynamic unfolding of events is represented by sequences of experience units—event segments—organized in chronological order (Anderson et al., 2015; Anderson & Conway, 1993; Jeunehomme et al., 2018). These experience units are cohesive representations encompassing elements such as people, objects, locations, actions, emotions, and thoughts, which define specific moments or segments of experience (Jeunehomme et al., 2018, 2020). While event segments can be processed across multiple timescales, the primary units of event simulations generally span seconds, structured to capture psychologically meaningful changes in various dimensions of experience over time (e.g., changes in entities, contextual settings, goals, actions; Clewett et al., 2019; Radvansky & Zacks, 2017). This representational structure facilitates the compressed depiction of unfolding events, allowing for the reproduction or simulation of experiential contents with reduced temporal demands (Arnold et al., 2016; Jeunehomme & D’Argembeau, 2019; Michelmann et al., 2019).

It is important to note that MTT requires *meta-representational insight* into the relation between a represented event and the present. The remembered or imagined event needs to be represented “as a past or future event” (Redshaw, 2014); otherwise, one is entirely immersed in the event without a temporal marker (as in most dreams). This perspectival aspect of MTT (McCormack & Hoerl, 1999) may partly emerge from the organization of autobiographical knowledge. In the autobiographical knowledge base, in fact, lifetime periods, general events, and specific events are situated in relation

to the present, giving autobiographical representations their past or future temporality. Notably, what we commonly refer to as the “present” can vary in temporal scope, and this is reflected in the hierarchical structure of the autobiographical knowledge base, where the present spans current specific events, general events, and lifetime periods (D’Argembeau, 2020; see Figure 4).

2.1.4. *How to track Mental Time Travel pathways?*

The present work focuses on the *deliberate* - rather than spontaneous**⁴ act of remembering the past and/or imagining the future. Past research on this field has largely focused on this voluntary form of MTT (Berntsen & Jacobsen, 2008), where participants are asked to deliberately recall past events or imagine hypothetical future scenarios. Recognizing the importance of these methodological aspects in shaping this mode of thinking, I will review here some of the most frequently adopted methodologies for studying MTT, highlighting their advantages and/or potential limitations.

Past research on autobiographical memory in amnesic patients to date employed the *Crovitz technique*, a method derived from Galton’s pioneering studies (Crovitz & Schiffman, 1974; Galton, 1879; Robinson, 1976). In this procedure, subjects are provided with a list of cue words (e.g., “river”, “restaurant”, “happy”) and are required to describe an episode from their autobiographical memory related to each cue word, specifying the date and place of each recalled memory. The responses are scored based on the descriptive richness and specificity in time and place of each memory produced (Kopelman et al., 1989). This technique allowed, for example, Zola-Morgan et al. (1983) to find that Korsakoff patients⁵, when prompted, were able to recall past episodes from their autobiographical

⁴ *Spontaneous (or involuntary) future thinking* involves mental representations about the future that arise unexpectedly while one is engaged in other habitual activities, often triggered by irrelevant environmental stimuli (Kvavilashvili & Rummel, 2020). These thoughts can pertain to planned tasks or events (e.g., buying a flight ticket tomorrow, attending a social event next week), plausible future events (e.g., envisioning a trip to Edinburgh or having children), or hypothetical scenarios and wishful thinking (e.g., winning the lottery, marrying a celebrity).

⁵ *Korsakoff syndrome* is characterized by a pronounced memory impairment that is disproportionate to other cognitive functions, stemming from a nutritional deficiency in thiamine. The initial symptoms of the disorder can vary, and although

memory, but they had to delve much further into their remote past to do so compared to non-Korsakoff alcoholics and healthy controls. As well, the Crovitz technique has been proved effective in facilitating the construction of future events in MTT (Anderson et al., 2012; Rasmussen & Berntsen, 2014b).

The downside of the Crovitz technique was that somewhat artificial demands of the task (producing a personal memory related to a particular cue word) may distort the pattern of results obtained. Additionally, the subject's temporal gradient may reflect his bias to recollect from particular time periods rather than their overall capacity to do so (Congleton & Berntsen, 2018). Building from these assumptions, Kopelman et al. (1989) developed a semi-structured interview (the *Autobiographical Memory Interview*) to assess the recall of both autobiographical episodic and semantic memory across three broad lifetime periods: *childhood*, *early adulthood* and *recent* past. More recently, Levine et al. (2002) introduced the *Autobiographical Interview* (later adapted by Addis et al., 2008), that involves participants recalling memories from five lifetime periods, followed by probing to elicit more details in their description. These memories can be categorized into internal (episodic) and external (semantic) details, making this method effective for assessing the specificity – and eventual differences – in memory content. Subsequent research (Rasmussen & Berntsen, 2014a, 2018) has adapted an alternative version of this Interview to assess the level of episodic specificity in future thinking.

Additional methods have been employed to study memory retrieval. For instance, the *diary method* has required participants to record daily events to be used later as retrieval cues (Linton, 1975; Wagenaar, 1986), allowing for more accurate memory verification arising from the comparison between the memory and its recording (Berry et al., 2007; see also McGuigan & Salmon, 2004). The *questionnaire method* (Rubin, 2006) instead assessed autobiographical memory more subjectively,

persistent memory impairment can arise from non-alcoholic causes, this has become less common in recent times, likely due to improved overall nutritional standards (Kopelman, 1995).

making it a useful tool for analyzing individual differences and the phenomenological aspects of memory recall.

An effective way to investigate the structure of autobiographical knowledge is by examining the content of individuals' thoughts as they attempt to recall a past event. In this regard, significant insights have been gained from studies that use methods such as asking participants to *think aloud* (Barsalou, 1988; Burgess & Shallice, 1996; Haque & Conway, 2001; Reiser et al., 1986). This procedure, for example, was adapted by D'Argembeau & Mathy (2011) to track the exact temporal progression of memory structures while constructing future events (see the paragraph 2.1.4. and Study 2 to get more insights about this methodology).

In this section, I characterized the phenomenology of MTT as a form of deliberate thought (as opposed to spontaneous thought, discussed in the previous paragraph), examining the main theoretical models from the literature and outlining its cognitive architecture. Starting from the next paragraph, instead, we will focus on another form of deliberate thought characterized by the formulation of a future *intention*.

2.2. *Prospective Memory*

Let us suppose that we have simulated a hypothetical future autobiographical scenario (using the processes described in the previous paragraph) and have also managed to predict the possible consequences of this scenario. Following the taxonomy proposed by Szpunar et al. (2014), at this point, we should be able to set a goal in relation to it: this refers to the concept of *intention*. My musing on the subway about structuring this thesis project, for instance, was possible because the completion of the PhD thesis is an intention that travels with me - and within my thoughts - until its subsequent realization. While our previous focus has been on the future-oriented nature of mind-

wandering (1.2. *Self-generation and mental content*) and the possibility of deliberate⁶, future-directed MTT (2.1.2. *Episodic future thinking*), this section instead will delve into the most common example of goal setting related to fulfilling future intentions: prospective memory (PM).

PM refers to a complex interplay of higher-order cognitive processes that enables us to remember and execute intended actions in the future – e.g., paying a bill, sending a birthday card, attending a scheduled appointment (Einstein et al., 2005). It is straightforward to consider how this capacity is essential for successful daily functioning (Hering et al., 2018; Kvavilashvili & Rummel, 2020; Rummel & Kvavilashvili, 2023). PM does not necessarily require mentally projecting oneself into a possible future event or pre-living the action to be remembered. Thus, although oriented towards the future, PM does not involve MTT (Atance & O’Neill, 2001; Berntsen & Jacobsen, 2008).

Figure 5 provides an overview of the several distinct phases involved in a PM process (Ellis, 1996; Kliegel et al., 2002). The initial stage of PM, *intention formation*, involves planning an action and defining the future context for its execution (Ellis, 1996; Kvavilashvili & Ellis, 1996). This initial phase is followed by a delay period, known as the *retention* phase, which is essentially a storage phase during which the individual engages in unrelated activities while monitoring for the subsequent intention to be executed. Hence, the intended action may be periodically retrieved in this stage through incidental cues in the environment, deliberate mental revisions of one’s plans, or spontaneous memory pops (Kvavilashvili & Fisher, 2007). The *retrieval* phase represents the opportune moment for executing the intention. Encountering the appropriate context (e.g., “*lunchtime with a friend*”) typically triggers retrieval and potential execution if the intention is recalled promptly. Some

⁶ Future thoughts can be either *deliberate*—arising from a voluntary intention to engage in future thinking—or *spontaneous*, emerging without a conscious decision while a person is engaged in unrelated activities. Such spontaneous thoughts often occur in response to incidental environmental triggers (e.g., seeing a library on TV may prompt a thought about visiting a library tomorrow). Thus, spontaneity does not imply the absence of a trigger, but rather the lack of intention to think about it at the time. Across various fields (e.g., mind-wandering, spontaneous future thinking, prospective memory), terms like “spontaneous” and “involuntary” are often used interchangeably to indicate the absence of deliberate decision-making in generating thoughts about future events or tasks (Kvavilashvili & Rummel, 2020). In the present work, I refer to PM as a conscious/deliberate decision to perform a specific task in the future (i.e., forming an intention or plan) and remembering to execute the intended action after a delay.

researchers also propose a fourth, *execution* phase, encompassing the actual enactment of the intended action (Ellis, 1996; Kliegel et al., 2002). While much PM research focuses on investigating the cognitive processes involved in the retrieval phase (Cohen et al., 2008; McDaniel & Einstein, 2007), the recent review by Kvavilashvili & Rummel, (2020) prioritized the earlier stages - intention formation and maintenance – in relation to future thinking. The prospective nature of thought, in fact, plays a crucial role in both encoding and retention phases of PM tasks. In particular, while encoding involves deliberate intention formation (Kvavilashvili & Ellis, 1996), retention requires thinking about the PM instructions and this process can be deliberate (e.g., mental task revision) or spontaneous (e.g., thought popping into mind) (Ellis & Nimmo-Smith, 1993; Szarras & Niedźwieńska, 2011).

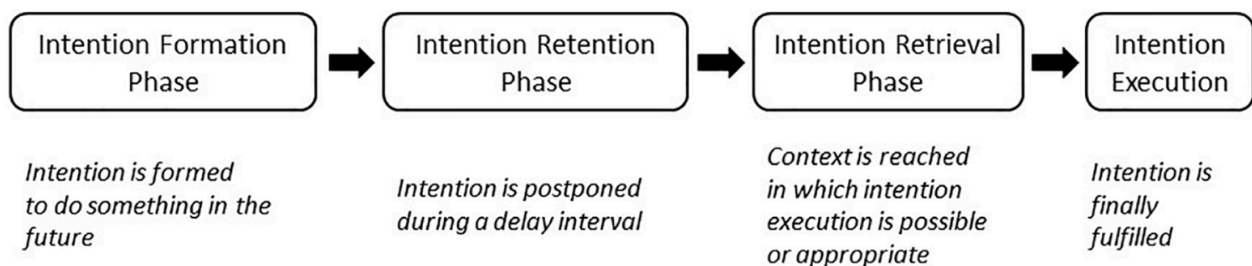


Figure 5. Schematic illustration of the four phases of Prospective Memory (PM), as adapted from Ellis, (1996) and Kliegel et al. (2002).

Similar to other cognitive psychology domains, most PM research utilizes laboratory paradigms resembling the phases depicted in Figure 5 (Einstein & McDaniel, 1990). Participants typically perform a primary ongoing (ONG) task plus an additional PM task, that involves remembering to perform an intended action when a specific target is presented (event-based PM; Marsh & Hicks, 1998; Strickland et al., 2018) or at a specific time or time interval (time-based PM; Einstein & McDaniel, 1990; Park et al., 1997). Naturalistic tasks are also employed to measures PM processes, requiring participants to simply carry out simple future intentions in their daily lives (e.g.,

remembering future phone calls) with timing and/or accuracy data collected (e.g., Leirer et al., 1994; Rendell & Thomson, 1999; Rummel & Kvavilashvili, 2019).

PM instructions typically interfere with the performance on a continuous ONG task. Behaviorally, this leads to slower reaction times and/or lower accuracy compared to baseline conditions – i.e., when participants perform the ONG task without monitoring for a PM target (Brandimonte et al., 2001). These behavioral findings suggest that performing the ONG task and monitoring for the PM target share common cognitive resources, although the underlying mechanisms are not yet fully understood (cf. the “*PM cost*” debate; Einstein et al., 2005; Einstein & McDaniel, 2010; Smith, 2003; Smith et al., 2007; Strickland et al., 2017).

Distinct theoretical approaches have been adopted by the literature to explain the PM cost. For instance, the *Preparatory Attentional and Memory* (PAM; Smith, 2003) theory has proposed that individuals must engage in preparatory processes before the moment when the prospective target occurs. Failure to do so would result, in fact, in missing the appropriate moment to execute the intention. According to PAM theory, this preparation process involves reallocating attentional resources away from the ONG task to the PM task to keep the intention active in working memory. Given the limited capacity of working memory (Cowan et al., 2005), however, maintaining the intention is expected to interfere with ONG task performance, especially if the ONG task also relies on the same pool of working memory resources. Supporting this capacity-sharing concept, some studies have shown how PM performance correlates with working memory abilities (Arnold et al., 2015; Smith et al., 2011). Accordingly, the PM cost has been interpreted as direct evidence of the assumption that both the ONG and the PM task draw on the same limited working memory capacity.

Another influential theory that seeks to explain the interplay between ONG and PM performance is the *multiprocess framework* (e.g., see Einstein et al., 2005; McDaniel & Einstein, 2000). This theory posits that different processes underpin complex everyday PM behavior.

Specifically, the recruitment of one or another mechanisms (e.g. deliberate monitoring vs. spontaneous reflexive-associative processes) depends on various factors, such as the specific characteristics of the PM task, the relative emphasis placed on PM vs. ONG performance, and individual differences (Einstein et al., 2005; McDaniel et al., 2015a; McDaniel & Einstein, 2000). In this regard, the PM cost effect can be viewed as the result of an effortful monitoring process for the PM target - alternating with a target-checking process - occurring during the retrieval phase (Guynn, 2003, 2021). Alternatively, PM retrieval can occur spontaneously – i.e., without the need for these monitoring processes to be engaged - if PM targets are easily detectable within the ONG task and if there is a strong associative link between the targets and the intended action (McDaniel et al., 2015b).

A key factor impacting the level of interference between the ONG and the PM task is *PM load* – i.e., the number of potential PM targets – or intentions – that need to be monitored to perform the PM task. High-load conditions, in fact, require the allocation of extra cognitive resources to strategically monitor for additional PM targets (Meier & Zimmerman, 2015). This supports the notion of common cognitive resources underlying both PM target monitoring and ONG task execution (see also Barban et al., 2014).

2.2.1. *Intention Offloading*

Directing attention outward should not always be considered a distraction (see paragraphs 1.2. and 1.5.), as it does not necessarily impede thought processes. Contrarily, at times it may even be considered an advantage. It is crucial to not forget, in fact, that human beings, as agents, actively – and continuously - engage with their external environment, which in turn *shapes* their thinking. If anything, the act of writing these pages – creating an external trace of my ideas – has certainly influenced the way I have thought about the content of this work in subsequent instances. This concept – also referred to as *distributed cognition* – has been recognized within many fields of psychology (Clark & Chalmers, 1998; Kirsh, 2010) and cognitive neuroscience (Gilson et al., 2020; Wang, 2022).

What does it mean to be a *cognitive* agent in a complex environment? Our mental capacities are inherently limited: for instance, we can only accurately perceive a reduced portion of the visual field (Pylyshyn & Storm, 1988; Simons & Levin, 1997; Treisman & Gelade, 1980) and can maintain only a limited amount of information in working memory (Eriksson et al., 2015). Nonetheless, to overcome these limitations, human beings often engage in thinking through interactions with their bodies and objects in the physical environment. An example of this triple interaction between mind, body and environment is *cognitive offloading*, i.e., the use of physical actions to modify the information processing demands of a task. Cognitive offloading reduces computational effort, allowing humans to accomplish cognitive tasks that would otherwise be unattainable. Accordingly, research has shown that cognitive offloading enhances performance across various domains, including perception (Risko et al., 2014), memory (Gilbert, 2015), arithmetic (Goldin-Meadow, Nusbaum, Kelly & Wagner, 2001), counting (Carlson, Avraamides, Cary & Strasberg, 2007), and spatial reasoning (Chu & Kita, 2011).

Remembering delayed intentions – i.e., PM (see paragraph 2.2.) – can be particularly challenging because, in many cases, intentions are not effectively cued by the external environment and necessitate instead self-initiated actions. Thus, it is not surprising that people often rely on external tools to create perceptual cues that can trigger intended actions in the future. Common examples include tying knots in handkerchiefs, placing reminders in the environment - such as post-it notes or task-relevant objects - or more recently, using smartphones or wearable devices that can deliver time-, location-, or person-based reminders. This form of cognitive offloading is referred to as *intention offloading* (Gilbert et al., 2023; Risko & Gilbert, 2016).

Traditionally, laboratory studies on PM (see paragraph 2.2.) have prevented participants from setting external reminders: the outsourcing of intentions to external tools was conceived as external *noise* that obscures the underlying processes of “real” PM (e.g., Uttl & Kibreab, 2011). However, in line with the view of humans as cognitive agents in the environments - i.e., distributed cognition –

intention offloading plays an integral role in our ability to retain delayed intentions in real-world contexts. To fully understand the processes by which intentions are fulfilled, thus, it is essential to consider intention offloading alongside brain-based mechanisms, rather than dismissing it as an irrelevant factor. These premises gave rise to a new area of investigation that was carried out during the last 5-10 years (for a recent review, see Gilbert et al., 2023).

How can intention offloading be measured in an experimental setting? In this regard, Gilbert (2015) developed a novel paradigm that can be administered as an online web-based experiment. The task requires participants to drag ten numbered circles in sequential order to the bottom of the box displayed on the screen. Delayed intentions are embedded within the task by presenting specific instructions at the beginning of each trial (e.g., “*please drag number 7 to the top instead*”). Participants, thus, must produce a nonstandard, delayed response when encountering a particular target in the box. This design closely mirrors traditional laboratory PM paradigms (see the previous paragraph, but also (Brandimonte et al., 2001; Smith, 2003) but with a much shorter retention interval – seconds, rather than minutes or longer. To perform the intention offloading task, participants can rely on two different strategies to remember their intentions: *internal*, brain-based memory processes to maintain and then recall the instructions or *external*, i.e., setting reminders by immediately placing target circles near their instructed location at the beginning of the trial (e.g., “placing the “7” circle near to the top of the border). Participants are typically informed about this strategy and given the freedom to choose whether to use external reminders or rely solely on their memory. Alternatively, they can be forced to use either one option or the other (internal memory and external reminders; to get more insights about this experimental procedure, see [Gilbert \(2015\)](#)). More recently, this paradigm has been revisited (Gilbert et al., 2020) to examine whether individuals optimally weigh the costs and benefits of using reminders or exhibit a systematic bias either in favor of or against using them.

Several factors concur to the decision to offload intentions. For instance, both behavioral (Gilbert, 2015) and neuroimaging (Landsiedel & Gilbert, 2015) studies have shown that individuals are more

inclined to offload intentions as *memory load* of the PM task increases or when faced with interruptions; both of which degrade performance in the absence of offloading. This confirms that intention offloading is influenced by the internal cognitive demands that would otherwise be required to perform a task. Apart from objective need, however, intention offloading is also driven by *metacognitive beliefs* about its effectiveness or one's own memory abilities. Boldt & Gilbert (2019), in fact, revealed that individuals with lower confidence in their memory are more likely to set reminders, even after controlling for objective memory abilities, and that this pattern extends to other cognitive domains. When this belief is accurate, the decision to offload intentions offers several benefits, including the creation of more durable and precise external representations, which increase the likelihood of fulfilling the intended intentions. However, various factors—such as undetected performance benefits, cognitive effort biases, or erroneous beliefs about the effectiveness of offloading—can lead individuals to set reminders even in situations where it does not improve accuracy. Confirming this, Sachdeva & Gilbert (2020) showed that participants often overestimate the benefits of offloading (*reminder bias*), even when their performance would be at ceiling without it: even overconfident participants who received positive feedback, in fact, still showed a positive reminder bias.

The metacognitive account alone, however, cannot fully explain the reminder bias observed in intention offloading. This suggests the involvement of additional factors: one such factor was identified as *cognitive effort avoidance*. Cognitive effort is considered aversive, and individuals tend to avoid tasks that require it, preferring instead reliance on external reminders – such as smartphone alerts - which reduce the cognitive load of remembering intentions. This tendency to avoid mental effort was tested experimentally by offering financial rewards to participants (Sachdeva & Gilbert, 2020a): it was shown that financial incentives encouraged them to exert more cognitive effort, thereby reducing, but not eliminating, the reminder bias. If their performance depended on metacognitive

beliefs only, instead, these incentives would not have influenced participants' strategies, as they would have stuck to their preferred approach (reminder bias).

It is clear, therefore, that reminder setting - as a form of the broader cognitive offloading process - can represent a *deliberate* - or automatic - strategy adopted to efficiently manage cognitive resources. As cognitive agents, we are capable of interacting with the external environment to *offload* at least part of the cognitive load required of us, thereby *freeing up* precious cognitive resources for other aspects of our lives.

3. Neural and physiological correlates of thought

Let's go back to the concept of *complexity*. In the previous paragraphs, we have explored how the phenomenology of the human - spontaneous and deliberate - thought has evolved to adapt to the complex and rapidly changing external environment, resulting in the same degree of complexity. We can take this argument one step further by considering that this phenomenological complexity itself is the result of an astonishingly large number of neural connections in our brain allowing for the mental processes we experience as *consciousness*. If nothing else, this aspect contributes to what makes us truly *human*.

The complexity of the human mind relies on the “*physical scaffolding of the brain*” (Bassett & Gazzaniga, 2011). The human brain – in fact - is estimated to contain around 86 billion neurons (Zimmer, 2011; Lent et al., 2012). This complex structure operates across multiple temporal and spatial scales, giving rise to intricate molecular, cellular, and neuronal processes that collectively support cognition.

In this chapter, we will review some of the most significant neuroscientific evidence concerning the neural and physiological bases of spontaneous and deliberate thought. The decision to present the

phenomenology of these two processes separately in the first two paragraphs and then consider them jointly in this context is not casual. It reflects my attempt – that aligns with more recent literature about the field (e.g., see Christoff et al., 2016; Kvavilashvili & Rummel, 2020) - to assume an integrated perspective that conceptualizes these forms of thought as an unified class of phenomena belonging to a spontaneity-deliberation continuum.

Given the complexity of our neural and physiological systems, I will adopt a *bottom-up* approach, moving from the particular to the general. First, I will focus on the ventromedial prefrontal cortex (vmPFC), starting with describing its anatomy and connectivity, and then examining its prominent role in spontaneous and deliberate thought, in cooperation with other brain regions - such as the hippocampus. Second, I will present a review of more extensive brain networks—some of which include the hippocampus and the vmPFC – that have emerged in the neuroscientific literature as key candidates supporting spontaneous, deliberate thought, as well as their cooperation. Finally, I will address some physiological components of spontaneous and deliberate thought, with particular emphasis on pupil diameter as a marker to detect them.

3.1. The pivotal role of the vmPFC

The frontal lobes constitute approximately one-third of the entire human cerebral cortex (Clark et al., 2010), largely supporting higher-level cognition (Badre, 2008; P. W. Burgess & Shallice, 1996; Miller & Wallis, 2009). A key region within the frontal lobes is the ventromedial prefrontal cortex (vmPFC). Since the vmPFC stands out as one of the largest brain areas in the human cortex, unraveling its functions has posed a significant challenge to neuroscience (Delgado et al., 2016; Hiser & Koenigs, 2018; Myers-Schulz & Koenigs, 2011). In this section, we will examine some historical key findings that have helped clarify its role, before delving deeper into its relationship with more specific thought-related cognitive processes.

The clinical case of Phineas Gage offers a compelling historical window into the functional significance of the vmPFC. Prior to his injury, in fact, Gage was lauded for his well-balanced mind and astute business acumen. However, a stark picture of a transformed personality was provided following his accident. Gage's behavior became characterized by impulsivity, difficulties in decision-making and emotional regulation, lacking social restraint and incapable of maintaining long-term plans. Following the landmark case of Phineas Gage (for a detailed review, see Damasio et al., 1994), numerous reports have documented striking personality changes and deviant social behavior in individuals with vmPFC damage, previously exhibiting normal behavior (Bechara et al., 1997; Damasio et al., 1982). These observations strongly align with contemporary understanding of vmPFC function, underscoring its central role in shaping human behavior.

While the description of Phineas Gage's personality provides invaluable historical context, it becomes necessary to acknowledge the inherent limitations of a single-case study. Modern research methodologies, including neuroimaging and lesion studies, are instrumental in refining our understanding of the specific contribution of the vmPFC to various cognitive components. This region, in fact, is now recognized as a critical hub for integrating emotional information with decision making processes, thereby guiding appropriate social behavior (Hiser & Koenigs, 2018).

Although a comprehensive theoretical framework that integrates the different tasks and domains involving the mPFC is still forthcoming, several perspectives converge on the idea that the mPFC plays a crucial role in integrating multiple sources of information to compute the broader (e.g., contextual, affective, causal, evaluative, social) meanings of stimuli or events (Brod et al., 2013; Krueger et al., 2009; Lieberman et al., 2019; Preston & Eichenbaum, 2013; Roy et al., 2012). Moreover, influential theories emphasize the role of the vmPFC in *schema processing* and the integration of new information with existing knowledge structures (for reviews, see Brod et al., 2013; Gilboa & Marlatte, 2017; Robin & Moscovitch, 2017; van Kesteren et al., 2012). This relation between the vmPFC and schematic knowledge will constitute the focus of the next paragraph.

3.1.1. vmPFC and schematic knowledge

Before delving deeper into the involvement of the vmPFC in schema processing, we will now define the concept of *schema*: it refers to “*adaptable associative networks of knowledge extracted over multiple similar experiences*” (Ghosh et al., 2014; Ghosh & Gilboa, 2014). Why should humans have developed this function? The literature consistently identifies three key functions of schemata: guiding behavior (Cooper & Shallice, 2006; Head & Holmes, 1911; Rumelhart, 1980), facilitating the encoding of new information, including inferential elaboration (R. C. Anderson, 2018; Bransford & Johnson, 1972; Preston & Eichenbaum, 2013), and initiating retrieval processes during memory search and reconstruction (Anderson, 2018; Anderson & Pichert, 1978; Arkes & Freedman, 1984; Nuthall, 2000; Rumelhart, 2017).

Based on recent advancements in neuroscience, Ghosh & Gilboa (2014) identified four fundamental attributes that characterize schematic structures: they are *associative*, based on multiple episodes, lack unit details, and are *adaptable*. First, schemata⁷ are associative networks comprising interconnected units – elements, events, variables, schema *nodes*, features, or paired-associates (Halford & Busby, 2007; Schank & Abelson, 1977; Tse et al., 2007, 2011; Wang et al., 2012): the relationships between these units are often more critical than the units themselves, as they combine in an associative network essential for interpreting new information and modifying sensory perceptions (Ghosh & Gilboa, 2014). Second, the structure of schemata is derived from multiple experiences sharing a basic framework. They represent high-level constructs that incorporate shared features among events, rather than focusing on unique details (Bartlett, 1932). For example, knowing the sequence of actions that typically occur during a concert requires having attended more than a single concert. Robin & Moscovitch (2017) referred to this broad representation as the *gist* of an

⁷ The terms “*schemas*” and “*schemata*” are used interchangeably, as both are accepted plural forms of “*schema*” (Corcoran, 2006; Berlucchi & Aglioti, 2010).

event, as opposed to a specific schema. Third, schemas lack unit details due to their foundation in multiple experiences with inherent variability. For example, rather than specifying that Professor X gives a lecture, an event schema for a lecture would generalize that a professor gives a lecture, based on attending multiple lectures. Fourth and last feature is *adaptability*, that enables schemata to generalize across experiences and guide behavior. Without this flexibility, in fact, a schema would be limited to specific information - about *that* specific event that happened on *that* particular moment - rather than extracted commonalities, hindering their role in facilitating encoding and shaping behavior (for a broader review about the essential features of schemata, see [Cooper & Shallice, 2006](#); [Ghosh & Gilboa, 2014](#); [Gilboa & Marlatte, 2017](#); [Rumelhart, 1980](#)).

The contribution of the vmPFC in schema processing has been documented in several neuroimaging studies (see e.g., [Gilboa & Marlatte, 2017](#); [Masís-Obando et al., 2022](#); [McCormick et al., 2020](#); [Schlichting & Preston, 2014](#); [Sekeres et al., 2018](#); [Wagner et al., 2015](#)). Of particular interest, here, are lesion studies confirming this neural evidence. Early neuropsychological studies on schematic processing, in fact, primarily focused on individuals with frontal lobe lesions, revealing impairments in event-schema (script) knowledge, such as sequencing errors or difficulties categorizing actions (Godbout & Doyon, 1995; Sirigu et al., 1995). More recently, damage to the vmPFC has been shown to disrupt the ability to reinstate and instantiate⁸ schemas, leading to difficulties in associating new information with relevant schemata (Ghosh et al., 2014; Giuliano et al., 2021). For example, vmPFC patients display impaired schema-based memory benefits and are less influenced by schematic congruency during encoding and retrieval tasks (Spalding et al., 2015). Interestingly, in tasks like the Deese-Roediger-McDermott (DRM) paradigm⁹, vmPFC lesions can reduce false memory errors, suggesting weakened schema-related processing (Warren et al., 2014).

⁸ Once acquired, schematic knowledge needs to be *reinstated* (i.e., activated from memory to become relevant to the current context) and then *instantiated* (i.e., maintained and applied to the ongoing cognitive process) in order to influence perception and learning (e.g., [Gilboa & Marlatte, 2017](#); [Hebscher et al., 2019](#)).

⁹ The Deese-Roediger-McDermott paradigm (Deese, 1959; Roediger & McDermott, 1995) is a widely used experimental procedure in cognitive psychology to study false memory formation. In this paradigm, participants are presented with a

Among the various typologies of schemata, *self-schema* holds a privileged role, shaping the way individuals interpret their own behavior and make attributions about others. Neuroimaging studies showed that the vmPFC is particularly active during tasks requiring the evaluation of self-related information, further supporting its critical role in self-schema processing (Denny et al., 2012; Lieberman et al., 2019). Lesion studies (e.g., Stendardi et al., 2021; Philippi et al., 2012; Verfaellie et al., 2019) further supported this role, showing that vmPFC damage impaired the ability to distinguish between self and other-related information and disrupted future self-predictions. Combined with neuroimaging evidence, these findings underscore the critical role of the vmPFC in maintaining and updating self-schemas, essential for a coherent sense of self over time. Damage to this region would impair the integration of personality-related information into schemas, affecting how people interpret personal traits and social behavior (see also Wagner et al., 2012; Stendardi et al., 2023; Lockwood et al., 2024)

Additionally, vmPFC damage disrupts schema-supported associations between previously learned pairs, thus impairing complex inferential processes (e.g., *transitive inference*; Kosciak & Tranel, 2012; Spalding et al., 2018). In this regard, Giuliano et al. (2021) examined network-level oscillatory dynamics in vmPFC patients while classifying words according to a given schema/semantic category. They revealed that the vmPFC plays a crucial role in coordinating the reinstatement and instantiation (*see note 8*) of schemas, interacting with regions like the lateral temporal cortex and posterior parietal cortex to support schema and category processing. These findings underscore the pivotal role of the vmPFC in integrating and utilizing prior knowledge, as well as its broader impact on the cognitive functions dependent on schematic processing.

list of words that are semantically related to a non-presented "critical lure"—a word that would logically fit within the list but is not actually included. For instance, a list might contain the words "*bed, rest, awake, dream, snooze*" but the critical lure "*sleep*" is not presented. However, many participants later falsely recall or recognize "*sleep*" as having been part of the list.

In one of the following paragraphs (3.4.), we will explore how the selective vmPFC-related schema impairments can contribute to deficits in both spontaneous and deliberate thought. For now, the next section will focus on neuroscientific studies that have overall implicated the vmPFC in both spontaneous and deliberate thought.

3.1.2. The role of the vmPFC in spontaneous and deliberate thought

A variety of theoretical accounts have been proposed to elucidate the roles of the vmPFC in episodic recollection (Clewett et al., 2019; Moscovitch et al., 2016; Ranganath & Ritchey, 2012; Rugg & Vilberg, 2013), episodic future thinking (Gilmore et al., 2018; Mullally & Maguire, 2014; Schacter et al., 2017) and autobiographical memory (Cabeza & St Jacques, 2007; Grilli & Verfaellie, 2014; Palombo et al., 2018). Moreover, extensive evidence suggests its involvement in resolving conflicts and minimizing interference between memory representations (Guise & Shapiro, 2017; Preston & Eichenbaum, 2013).

What is the role of the vmPFC in autobiographical memory? Early lesion studies showed that vmPFC patients retrieve fewer autobiographical memories compared to healthy controls, and this impairment was strongly correlated with impairments in executive functions – such as planning and executing plans - rather than with performance on standard memory tests (Kopelman et al., 1999; Sala et al., 1993). These findings led to the hypothesis that vmPFC damage might impair retrieval strategies or the organization of autobiographical memory (Moscovitch, 1995; Moscovitch & Melo, 1997). This view remains influential, with several lines of research supporting it (Gilboa, 2010; Gilboa & Marlatt, 2017; Thaiss & Petrides, 2008; Tranel & Jones, 2006).

Evidence from the above-mentioned studies converges to a crucial role of the vmPFC in MTT processes. In this regard, it has been proposed that the mPFC¹⁰ serves as a central *information*

¹⁰ The literature often subdivide the medial prefrontal cortex (mPFC) into distinct sectors: the anterior-medial (amPFC), dorsal (dmPFC), and ventral (vmPFC) regions. DMN-related studies, however, often label the vmPFC as *mPFC*. Additionally, the amPFC—frequently identified as a central hub of the DMN—closely aligns with the area referred to here as vmPFC (see [Andrews-Hanna et al., 2014](#); [Andrews-Hanna, Reidler, Huang, et al., 2010](#); [Andrews-Hanna, Reidler,](#)

processing hub (see the paragraph 3.1., but also Andrews-Hanna, 2012) that integrates and organizes layers of autobiographical knowledge (D'Argembeau, 2020; see also Moscovitch et al., 2016). This potential role aligns with fMRI evidence showing that memories integrated into autobiographical clusters are associated with greater mPFC activity and increased functional connectivity (see paragraph 3.4.) between the mPFC and posterior regions supporting semantic and episodic memory representations (Demblon et al., 2016). Furthermore, a dorsal region of the mPFC has been linked to reflective thinking on the importance and implications of autobiographical events (D'Argembeau et al., 2014). Using a Crovitz-based (see the paragraph 2.1.4.) autobiographical memory task, extended to include future events, for example, Bertossi, Aleo, et al. (2016) found that vmPFC patients were equally impaired in imagining both future and past events. Additionally, they showed that vmPFC patients struggled to describe both fictitious scenes and future events, indicating a broader impairment in generating non-experienced scenarios. Bertossi, Candela, et al. (2017) instead differentiated between the mental construction of future scenarios and the ability to describe visual scenes, finding that vmPFC patients were impaired in both tasks. Importantly, even after controlling for performance in basic description tasks (such as describing pictures), vmPFC patients still showed significant deficits when tasked with constructing future scenarios. This suggests that the impairment in vmPFC patients is specific to the mental simulation of future events and cannot be fully attributed to difficulties with general descriptive abilities. Such findings align with early studies suggesting that vmPFC damage impacts the ability to generate detailed autobiographical memories (Kopelman et al., 1999; Sala et al., 1993). Taken together, they confirm that the mPFC may act as a *central processing hub* (Andrews-Hanna, 2012), enabling the integration of different layers of autobiographical representations for both past- and future-oriented MTT. Notably, the mPFC may integrate specific

Sepulcre, et al., 2010; Bathelt & Geurts, 2021). Coordinates reported in numerous fMRI studies typically focus on Brodmann Area 10 (BA10) within MNI space (see Lieberman et al., 2019; Schmitz & Johnson, 2006; Wen et al., 2020), though some researchers extend the aMPFC definition to include parts of BA9 and BA11 (see Johnson et al., 2002; Longe et al., 2009; Goldberg et al., 2011; Zysset et al., 2003).

event representations with higher-order representations of the content and structure of one's life, thus providing a personal temporal context for remembered and imagined events (D'Argembeau, 2020).

As well, activity of the vmPFC has been associated with spontaneous thought. For example, Bertossi & Ciaramelli (2016) investigated mind-wandering in vmPFC patients employing an ES assessment during computer tasks varying in difficulty. Their results showed that these patients exhibited a reduced frequency of mind-wandering; moreover, when mind-wandering did occur, there was a notable shift towards present- rather than future-oriented thinking. This study provides the first formal evidence that vmPFC damage affects both the frequency and temporal focus of mind-wandering, findings that were further replicated using transcranial direct current stimulation (tDCS; Bertossi, Peccenini, et al., 2017).

Based on the evidence presented in this section, the vmPFC appears to support both spontaneous and deliberate thought. However, as we will explore later, this brain region is part of a broader neural network - that includes the hippocampus - whose activity sustains a common process underlying both types of thought: *event construction*. Before delving into this process, however, it is essential to first understand the neural connections that enable the vmPFC to interact with other areas as part of this extensive network.

3.1.3. *Anatomy and connectivity of the vmPFC*

After gaining a clearer understanding of the contribution of the vmPFC to a myriad of high-level cognitive processes—particularly in schematic knowledge (see also paragraph 3.1.1.)—we now focus on the anatomy and connectivity of this region. The rationale behind this choice lies in achieving a better comprehension of the complexity of the various connections involving the vmPFC, which positions it as a prime candidate for integration into a broader neural network supporting higher-level cognition.

The vmPFC has been extensively studied in terms of its cytoarchitecture and anatomical connectivity, thanks to the pioneering work by Helen Barbas (Barbas & Pandya, 1989) and Joel Price (e.g., Ongür & Price, 2000). This region is located along the inferior part of the medial wall of the frontal lobe, incorporating the medial segment of the orbital frontal cortex. Medially, its posterior boundary is defined by the subcortical septal region, extending anteriorly to the frontal pole; ventrally, the vmPFC stretches onto the orbital surface, reaching the medial orbital sulcus, and its posterior limit is adjacent to the primary olfactory cortex (Mackey & Petrides, 2014). Even if anatomical classification of the vmPFC vary significantly in the literature, with no clear consensus on its exact boundaries (Alexander et al., 2023; Hiser & Koenigs, 2018; Mackey & Petrides, 2014), measurable variations in the density of cortical layers IV and Va in post-mortem human brains have allowed for the identification of several sub-regions within the vmPFC (Bhanji et al., 2019; Delgado et al., 2016). Ongür & Price (2000) delineated, in particular, two networks within the human orbital and medial prefrontal cortex: the *orbitofrontal network*, encompassing Brodmann Areas (BA) 12 and 13, and the *medial frontal network*, which includes BAs 9, 10, 11, 24, 25, and 32 (see Figure 6; but also Nieuwenhuis & Takashima, 2011). This research indicates that the vmPFC is a crucial node within a network receiving sensory information from the external world and body (via the orbital frontal cortex) and relaying it to structures like the hypothalamus, amygdala, and midbrain periaqueductal gray. This anatomical circuitry alone hints at the potential role of the vmPFC as a sensory-visceromotor interface critical for social behavior, mood regulation, and motivational drive – all fundamental components of personality (Raichle, 2015).

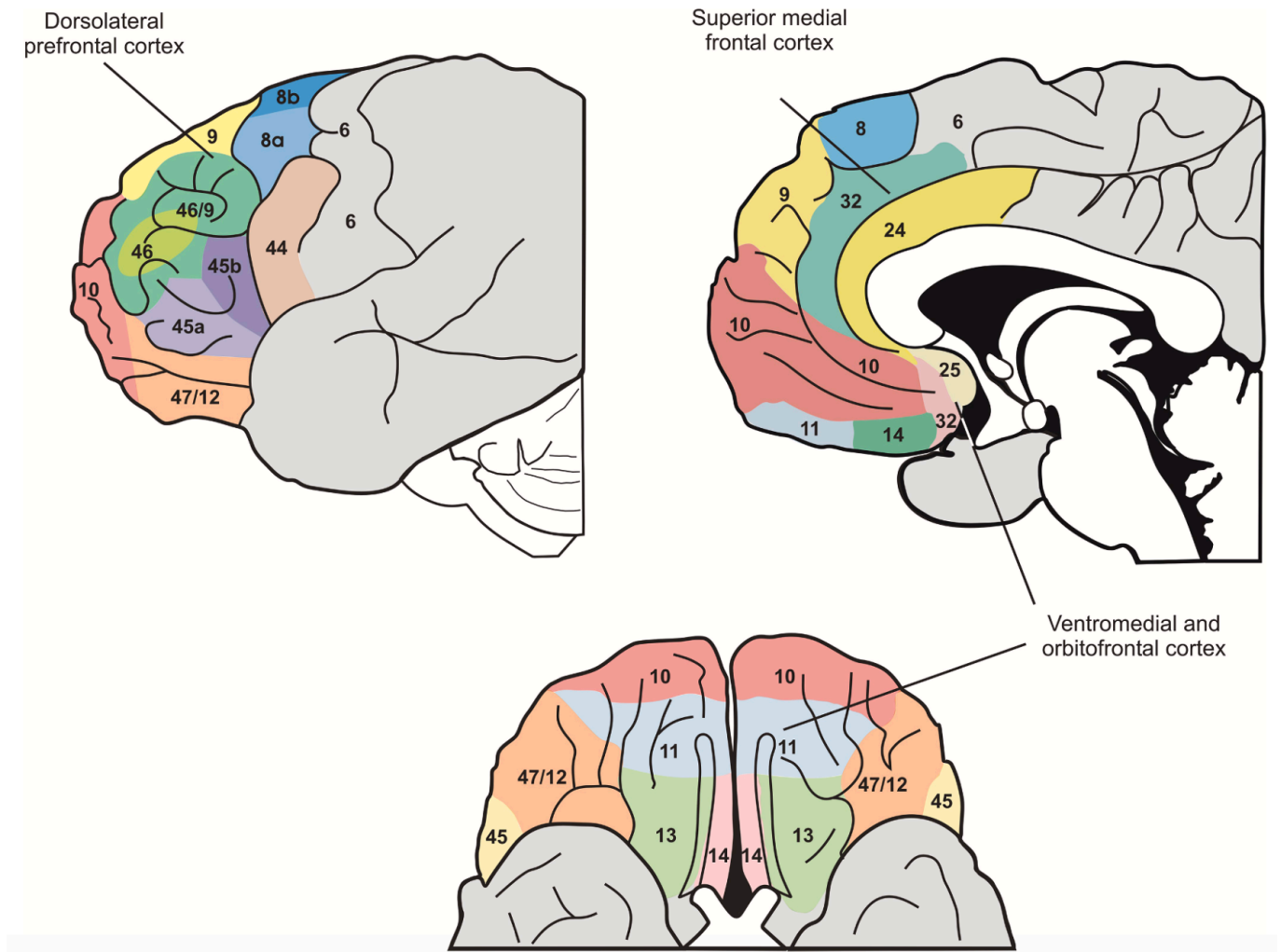


Figure 6. Cytoarchitectonic map and functional subdivisions of the prefrontal cortex (PFC; José et al., 2020). The PFC regions, corresponding to Brodmann Areas (BA), are labeled following the parcellation system developed by Petrides & Pandya (1994; 1999; 2002).

A detailed nomenclature of vmPFC structural connectivity originates from neuroanatomical tract-tracing studies on homologous regions in nonhuman primates. When these findings are compared to the human brain using non-invasive imaging methods, in fact, substantial evidence indicates broad similarities (Jbabdi et al., 2013; Mackey & Petrides, 2010; Ongür & Price, 2000; Schaeffer et al., 2020; Wallis, 2012). Thus, neuroanatomical tract-tracing techniques applied to homologous areas in nonhuman primate brains have allowed to construct a comprehensive nomenclature of the structural connectivity of the vmPFC (Barbas & Pandya, 1989; Croxson et al., 2005; Yeterian et al., 2012).

The vmPFC exhibits peculiarities in terms of connectivity: unlike the lateral sections of the orbitofrontal cortex, it receives minimal direct inputs from primary sensory regions and, in contrast to lateral prefrontal regions, shows weak connections with the motor cortex (Bhanji et al., 2019; Ongür & Price, 2000). Importantly, the vmPFC has major outputs to various brain regions, including the hypothalamus, periaqueductal gray, amygdala, hippocampus, nucleus accumbens, and superior temporal cortex (Gluth et al., 2015; Motzkin et al., 2015; Vianna & Brandão, 2003; Wallis, 2012; Zhang et al., 2018). Using the diffusion tensor imaging, Greicius et al. (2009) have also identified long-range connections between the vmPFC and the posterior cingulate cortex.

A clear pattern of connectivity has emerged, in particular, between the vmPFC and the hippocampi, through the identification of three primary reciprocal pathways connecting these two regions: the uncinate fasciculus, the fornix and the cingulum bundle (Catani et al., 2013; Concha et al., 2005; Malykhin et al., 2008). Additionally, a fourth indirect pathway connects the vmPFC to the hippocampi through the mammilo-thalamic tract and anterior thalamic projections (see Figure 7, but also McCormick, Ciaramelli, De Luca, et al., 2018).

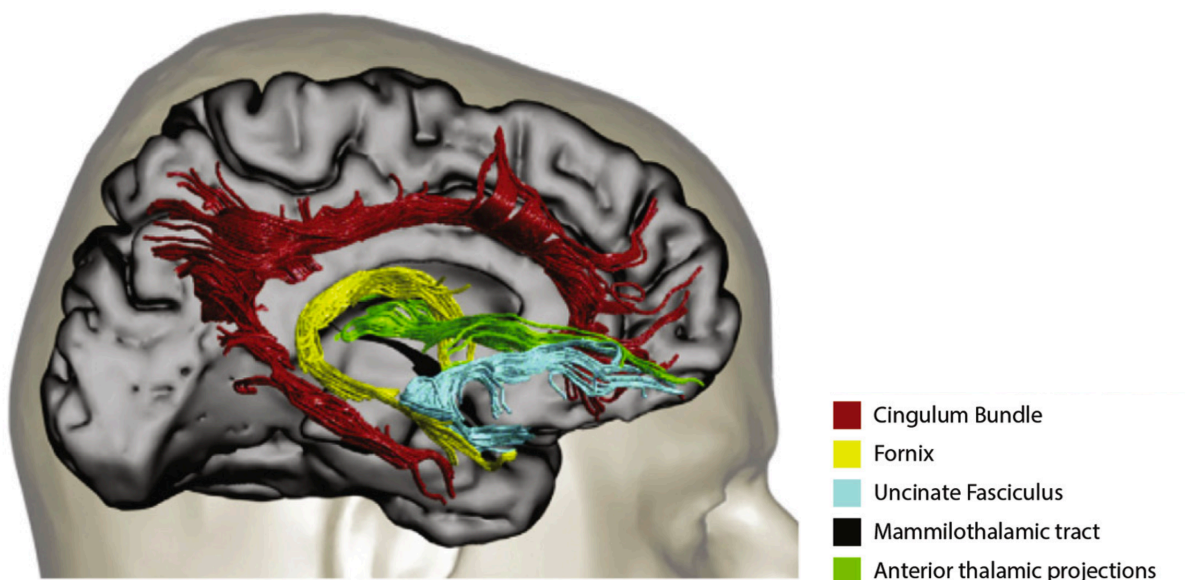


Figure 7. An overview of the primary anatomical connections between the hippocampi and the ventromedial prefrontal cortex (*vmPFC*) in humans, identified through diffusion-weighted imaging (adapted from Catani et al., 2012; McCormick et al., 2018).

These anatomical and connectivity findings reinforce the view that the vmPFC and the hippocampus are components of the same network. In the following sections, we will explore how this network has been identified and associated—albeit in different ways—with the emergence and maintenance of both spontaneous and deliberate thought processes over time.

3.2. *The pivotal role of the hippocampus*

At this point, the reader should have a clear understanding of how the vmPFC exhibits a high number of connections with other brain areas and how a privileged role is played by its interplay with the hippocampus. Located in the medial temporal lobe (MTL) of each hemisphere, the hippocampus has a peculiar, curved shape that has been compared to a seahorse ([Amaral & Witter, 1989](#); to get more insights about its neuroanatomy, see [Sloviter & Lomo, 2012](#); [Witter, 1993](#)). Recent advances in high-resolution fMRI have allowed for more precise delineation of specific hippocampal subregions, thus helping to clarify their functional roles (e.g., [Dalton et al., 2017](#); [Zeidman & Maguire, 2016](#)).

Activity of the hippocampus has been traditionally related to autobiographical memory (e.g., [Addis, Moscovitch, et al., 2007](#); [Svoboda et al., 2006](#)). Since the first clinical observations of the patient H.M., in fact, several studies defined the neuropsychological profile of hippocampal amnesia** ([Scoville & Milner, 1957](#); [Squire, 1992](#)). It has been then showed that patients with hippocampal damage fail to recall memories from their remote and recent past if a vivid and detailed retrieval is required ([Addis, Wong, et al., 2007](#); [Rosenbaum et al., 2008, 2009](#); [Steinvorth et al., 2005](#); [St-Laurent et al., 2009, 2014](#); [Viskontas et al., 2000](#)). Conversely, they remember facts about their lives such as their home address and the name of their school ([Nadel & Moscovitch, 1997](#); [Winocur & Moscovitch, 2011](#)), but lack episodic details, which are clear pictures in their mind's eye of a particular scene from a past event. This impairment was further confirmed by other studies ([Addis, Wong, et al., 2007](#); [Baddeley et al., 2001](#); [M. Berryhill et al., 2010](#); [St-Laurent et al., 2014](#)) that scanned patients with hippocampal damage using fMRI while attempting to recall autobiographical memories, finding decreased hippocampal activation compared to control groups. However, in cases

where patients had gist-like recollection lacking vividness, they observed up-regulation of neocortical structures – particularly the vmPFC. More recently, Kurczek et al. (2015) found that while patients with bilateral vmPFC damage could describe snapshots or scenes from autobiographical memories in as much detail as controls, patients with MTL damage could not describe single moments from events in vivid detail. In contrast, Bertossi et al. (2016) observed that vmPFC-damaged patients had significant difficulties recalling detailed extended events, regardless of whether the memories were recent or remote.

Hippocampal activity has also been associated with future thinking (Martin et al., 2011; Squire et al., 2010; Tulving, 2002). In fact, hippocampal patients struggle not only with recalling detailed autobiographical memories but also with vividly envisioning their future (Hassabis & Maguire, 2007; Klein et al., 2002; Kurczek et al., 2015; see also Squire et al., 2010; Dede et al., 2016 for alternative reviews). Given the importance of vivid visualizations in recalling the past and imagining the future, it was hypothesized - and then confirmed - that hippocampal patients struggle with imagining fictitious scenes without the need for temporal context (Hassabis et al., 2007; but see Squire et al., 2010). These findings led to the proposal of the *Scene Construction Theory* (Clark & Maguire, 2016; Hassabis & Maguire, 2009; Maguire et al., 2016; Maguire & Mullally, 2013; Zeidman & Maguire, 2016) which posits that the hippocampus constructs spatially coherent mental scenes essential for both memory and imagination. Evidence supporting the scene construction theory includes findings that patients with bilateral hippocampal damage show deficits in cognitive phenomena such as *boundary extension*, where healthy individuals extrapolate beyond the view of a scene (Intraub, Bender & Mangels, 1992; Intraub & Richardson, 1989). Patients with hippocampal damage exhibited attenuated boundary extension (Mullally et al., 2012; but see Kim et al., 2015). Additionally, these patients struggle with tasks requiring the mental construction of scenes from different viewpoints, unlike their performance with faces or objects (Lee et al., 2005). A recent study found that patients with selective bilateral hippocampal damage could detect semantic violations (e.g., an elephant with butterfly ears) but were impaired at detecting constructive violations (e.g., an endless staircase) in

scenes, which require internal scene representation (McCormick et al., 2017). Collectively, these findings demonstrate that the hippocampus is crucial for constructing coherent mental scenes (Clark & Maguire, 2016).

On the other hand, McCormick, Rosenthal, Miller, et al. (2018) tracked hippocampal patients over two days, asking them on twenty separate occasions to report the spontaneous thoughts they had immediately before each query. The results indicated that these patients reported mind-wandering as frequently as healthy controls. However, the nature and content of their thoughts were markedly different. While controls demonstrated flexible thinking about the past, present, or future using vivid, visual scenes, in fact, hippocampal patients' thoughts were primarily constrained to the present and consisted mainly of verbal descriptions about themselves or their immediate surroundings.

We have now established that both the hippocampus and vmPFC are involved in spontaneous and deliberate thought. However, their contributions differ: damage to the vmPFC appears to affect schematic (higher-level) knowledge that drives thought, while damage to the hippocampus impairs the composition of perceptual, contextual, and emotional details that "color" the scenes forming a mental event. In the following section, we will explore how these findings have informed new theoretical models describing the roles of the vmPFC-hippocampus neural dynamics in human thought.

3.3. Constructing mental events: The hippocampal-vmPFC neural dynamics

Although the performance of vmPFC and hippocampal patients appears similar, a closer inspection reveals distinct behavioral patterns between these patients' groups. In this regard, a recent review of lesion studies by McCormick et al. (2018) made direct comparisons between patients with hippocampal and vmPFC lesions across several studies to outline the selective contribution of these two brain regions to several cognitive functions. Their observations converged in a tentative *model*

that proposed the alignment of the vmPFC and the hippocampus in a hierarchical network supporting endogenous processes: the vmPFC would act as a *supervisor* - initiating scene construction - while the hippocampus would play a subordinate role. In particular, the vmPFC would cooperate with the hippocampus to initiate the event construction process, potentially coordinating the selection of relevant elements from the neocortical regions. These elements would then be integrated within the hippocampus, creating the “*building blocks*” of a coherent scene. In this process, the vmPFC would engage in iterative re-initiation through feedback loops with the neocortex and the hippocampus, thereby creating the dynamic flow of sequential scenes that, taken together, compose an extended mental event (McCormick et al. 2018).

Supporting this idea, studies in healthy individuals have shown that magnetoencephalography (MEG) phase coherence¹¹ between the vmPFC and hippocampus is significantly stronger during dynamic scene exploration compared to static scene exploration (Kaplan et al., 2017). Other research lines confirmed that the mPFC- hippocampal neural interplay (Campbell et al., 2018; McCormick et al., 2015; St Jacques et al., 2011) allows for the integration of event simulations with higher-order autobiographical knowledge (D’Argembeau, Stawarczyk, et al., 2010; Demblon et al., 2016; Stawarczyk & D’Argembeau, 2015). Moreover, during the construction of event simulations, the mPFC-hippocampal neural dynamics may help organize event segments into chronological sequences that represent event unfolding (Baldassano et al., 2018; McCormick, Ciaramelli, De Luca, et al., 2018). Recent MEG findings further support this view, showing that activity in the vmPFC precedes and likely drives hippocampal activity during voluntary scene construction and autobiographical memory retrieval (Barry et al., 2019; see also Monk et al., 2020, 2021). In summary, the vmPFC-

¹¹ *MEG phase coherence* refers to the synchronization of oscillatory brain activity between different regions as measured by magnetoencephalography (MEG). This technique detects the magnetic fields generated by neural electrical activity and is used to study the communication between brain regions (Gross, 2019). Phase coherence specifically quantifies the consistency of the phase relationship between signals from two brain regions over time, indicating functional connectivity (Engel & Singer, 2001).

hippocampal interplay would help organize event segments into chronological sequences that depict the unfolding of mental events (Baldassano et al., 2018; McCormick, Ciaramelli, Luca, et al., 2018).

Regarding spontaneous thought, Ciaramelli & Treves (2019) described the vmPFC-hippocampal neural dynamics supporting event construction, simulating the transitions between mental states following both vmPFC and hippocampal damage. This model suggests that – in mind-wandering - the vmPFC facilitates the congruent retrieval of sequential memories, while the hippocampus enhances the content of these memories. Specifically, vmPFC-mediated transitions^{**}
¹² between thought contents would be likely driven by the instantiation of particular local schemata (see the paragraph 3.1.1. and Gilboa & Marlatte, 2017 for a review). The hippocampus supports both voluntary and spontaneous cognition by providing rich, detailed mental scenes, whereas the vmPFC, along with other areas storing specific schemata, coordinates the proper linking of memory attractors to create coherent, extended events.

As summarized in Figure 8, thus, healthy individuals would experience attention shifts inward from an ongoing task to mentally constructed experiences, guided by relevant schemata and enriched by hippocampal memories. A lesion to the hippocampus is expected to reduce the episodic richness of thoughts, leaving the schema-driven transitions intact; this would result in thought flow that is primarily focused on context-poor items or moments. Conversely, a lesion to the vmPFC would likely disrupt mind-wandering, making it overly dependent on hippocampal input, resulting in fragmented and inconsequential mind-wandering triggered by infrequent hippocampal outputs without adequate schema-guided construction processes (see Figure 8, but also Ciaramelli & Treves, 2019).

¹² Schemas are associative networks made up of interconnected units, such as elements, events or variables. The connections between these units shift from one configuration to another, shaping the way information is structured and processed. These transition mechanisms have been defined as “*latching dynamics*” (Ciaramelli & Treves, 2019; Spalla et al., 2021; Viol et al., 2021).

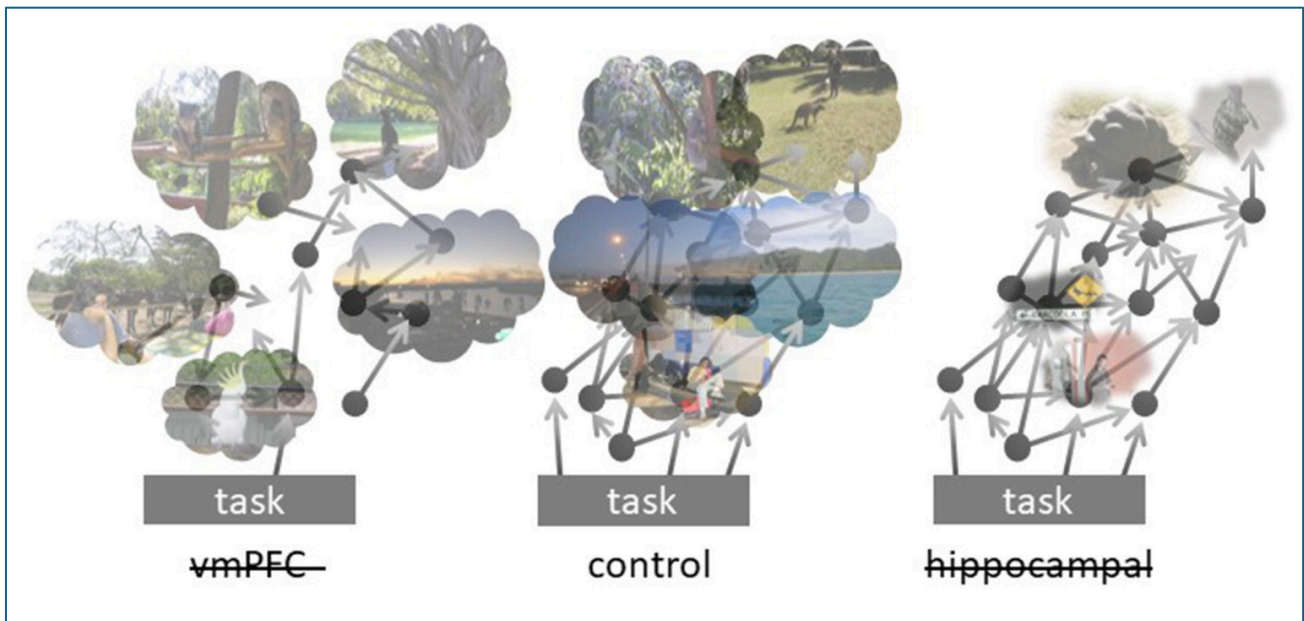


Figure 8. Schematic representation of the model by Ciaramelli & Treves (2019) simulating mind-wandering in vmPFC patients (*left*), control participants (*center*) and hippocampal patients (*right*). The black circles depict schemata, while the arrows represent the activation of other relevant schemata that - in a series of interactive sequences- support spontaneous thought. Ongoing cortical activity can trigger the activation of memories in the hippocampus (represented by clouds), which provides them with episodic details. In healthy controls, attention shifts from an ongoing task to endogenous activity, flowing smoothly and guided by relevant schemata, enhanced by context-rich hippocampal memories. A hippocampal lesion is expected to reduce episodic content enhancement while preserving schema-driven transitions, resulting in context-poor memories. In contrast, a vmPFC lesion disrupts mind-wandering, making it overly reliant on hippocampal content, leading to fleeting and inconsequential thoughts triggered by infrequent hippocampal output and poorly supported by schema guidance.

Event construction, however, likely involves dynamic interactions between the vmPFC, the hippocampus and *other* brain regions supporting thought processes. In this regard, D'Argembeau (2020) noted that variations in the levels of abstraction of autobiographical representations reflect distinctly in the brain activity. For example, several studies (Cabeza & St Jacques, 2007; Kim, 2012; McDermott et al., 2009; Spreng et al., 2009; Svoboda et al., 2006) had shown how retrieving autobiographical memories engages a wide array of brain regions, including not only the mPFC, but also medial and lateral temporal areas, posterior cingulate/retro splenial cortices and inferior parietal lobes. Within this network, different types of autobiographical representations correlated with specific neural signatures (Addis et al., 2004a; Holland et al., 2011; Levine et al., 2004; Renoult et al., 2016).

Crucially, a meta-analysis revealed a shift in brain activation from posterior to anterior structures as the abstraction level of the autobiographical content increased (Martinelli et al., 2013). Specific memory retrieval predominantly activated the MTL – including the hippocampus and parahippocampal gyrus – and posterior cortical structures – such as the precuneus and posterior cingulate/ retro splenial cortices – regions associated with the episodic recollection network (Rugg & Vilberg, 2013). In contrast, the retrieval of higher-order autobiographical knowledge - encompassing autobiographical facts, general events, and abstract self-representations - was mainly linked to frontal and lateral temporal regions. Intriguingly, the mPFC was the sole brain region consistently activated by various types of autobiographical representations (Martinelli et al., 2013).

Building on these assumptions, D'Argembeau (2020) argued that the construction of event simulations in deliberate thought (MTT) primarily relies on the interaction between the hippocampus and posterior cortical regions responsible for representing event segments and situation models (see Figure 8). These include sensory regions and higher-order posterior areas, such as the parahippocampal cortex, posterior cingulate cortex, retro splenial cortex, precuneus, and angular gyrus (Baldassano et al., 2017; Ranganath & Ritchey, 2012). The hippocampus would integrate multiple event features – objects, people, spatial context, and sequential information – represented across the cortical hierarchy to construct high-dimensional event representations (Clewett et al., 2019; Cowell et al., 2019; Horner & Doeller, 2017). This process would support mental simulation of specific events or scenes (Mullally & Maguire, 2014; Schacter, 2012b). Research in this field suggests, in fact, that the longitudinal axis of the hippocampus provides a gradient of representational granularity, with an anterior-to-posterior gradient from coarse- to fine-grained representations (Brunec et al., 2018; Collin et al., 2015; Grady, 2020). Studies in both rodents and humans indicate that the *posterior* hippocampus – in conjunction with posterior neocortical structures – mediates the representation of perceptual details of events, while the *anterior* hippocampus – in concert with anterior neocortical structures – represents the *gist* or general context of events (Sekeres et al., 2018). Thus, the mental simulation of specific events may primarily depend on the posterior hippocampus

and posterior cortical regions, whereas the representation of the essential content of events – their *gist* or conceptual framework – may rely on the anterior hippocampus (Moscovitch et al., 2016; Poppenk et al., 2013; Sekeres et al., 2018; Sheldon & Levine, 2016). Additionally, both the angular gyrus and posterior cingulate cortex seem to play a role in representing and integrating multimodal contextual details, such as sensory-perceptual information, that support event simulations (Ramanan et al., 2018; Stawarczyk et al., 2021).

Instead, higher-order autobiographical knowledge – encompassing lifetime periods and general events (see paragraphs 2.1.1.2. and 2.1.2.2.) was associated to the activity of anterior temporal lobe (Grilli et al., 2018; Martinelli et al., 2013; Jackson et al., 2018; see Figure 8). Although semantic knowledge is distributed widely across the cerebral cortex (Binder et al., 2009) and overlaps significantly with the episodic memory network (Renoult et al., 2019), in fact, functional parcellation of the temporal lobe using resting-state and task-state data suggests that the anterior temporal cortex is involved in higher-order multimodal semantic representations, while more posterior regions support modality-specific representations (Jackson et al., 2018). In other words, the anterior temporal lobe is thought to function as a trans-modal conceptual hub, extracting similarity structures and facilitating generalization across various types of representational contents (Ralph et al., 2017). This role would be crucial in representing the higher-order structure of autobiographical experiences. Importantly, this perspective does not contradict the idea that more posterior, modality-specific cortical regions contribute to MTT by providing the sensory-perceptual content of event simulations (Binder & Desai, 2011; Renoult et al., 2019).

In D'Argembeau (2020)'s framework, the mPFC is conceived as an *integration hub* within the entire MTT network (see Figure 8), that integrates various layers of autobiographical representations – i.e., combining event-related with superordinate autobiographical knowledge details - to support both past and future-oriented MTT. This view is reinforced by multiple evidence indicating connections between the mPFC and the hippocampus (Campbell et al., 2018; McCormick

et al., 2015; St Jacques et al., 2011; see also paragraph 3.1.3.) and the anterior temporal lobe (Jackson et al., 2018). Moreover, this perspective does not contradict previous theories, that assign the vmPFC the role of a supervisor in constructing the temporal unfolding of an extended mental event (McCormick et al., 2018).

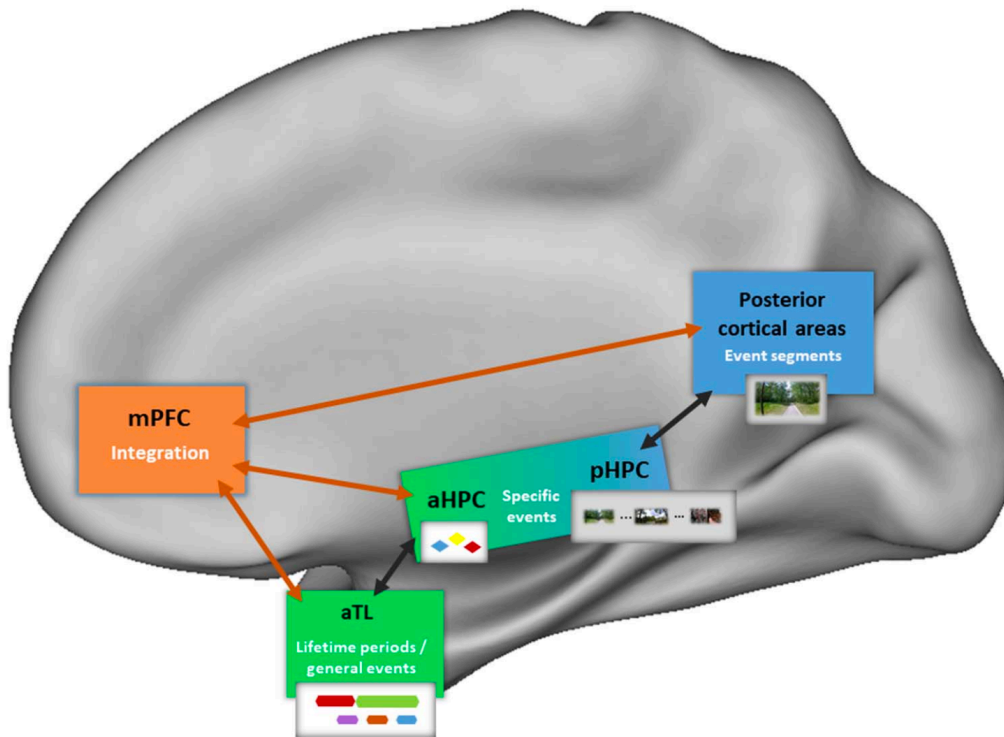


Figure 9. The neural network of brain regions supporting Mental Time Travel (MTT), as described by D’Argembeau (2020). *aHPC* = anterior hippocampus; *pHPC* = posterior hippocampus; *aTL* = anterior temporal lobe.

Taken together, these recent theoretical models suggest that *event construction* supports both spontaneous and deliberate thought. Thought processes would be supported in particular by large-scale dynamic interactions between brain regions responsible for representing event details – e.g. hippocampus – and conceptual knowledge – e.g. the mPFC. It should become increasingly evident to the reader that it is not sufficient to simply refer to *that* specific brain region as being involved in *that* particular cognitive process. Instead, it is necessary to introduce the concept of *neural networks*. Advances in neuroscience research, in fact, have led to the discovery of extensive neural networks

that play a critical role in the generation and maintenance of both spontaneous and deliberate thought. These neural networks will be the focus of discussion in the following section.

3.4. *Brain networks and their interactions*

The human brain exhibits a remarkable degree of functional specialization, with distinct regions demonstrating unique patterns of functional connectivity (see paragraph 3.5.). Regions with highly similar connectivity profiles can be conceptualized as forming a system or *network* (Vincent et al., 2008). At the advent of functional neuroimaging, researchers theorized about the processes performed by the human brain and consequently designed experimental paradigms to elicit such processes (e.g., [Friston, 1994](#); [Raichle, 1998](#)). As evidence accumulated, certain collections of brain regions were identified as sharing cognitive functions, thus defining *functional systems* (e.g., [Power et al., 2011](#); [Wig, 2017](#)). Prior to the investigation of spontaneous BOLD activity, however, the associations of regions within a functional system were largely inferred from task-based paradigms. More recently, this approach was suggested to represent transient and task-dependent brain activations, rather than fundamentally related networks within a broader brain-wide context (Smith et al., 2009). Building from these assumptions, extensive recent neuroimaging research has delineated multiple functional neural networks that have been broadly classified into two categories: *processing* and *control* networks. Processing networks are typically regarded as more modular and static, whereas control networks are posited to be dynamic and flexible, capable of adapting to a diverse array of tasks ([Dosenbach et al., 2008](#); [Posner & Petersen, 1990](#)).

In this section, I will extend the whole picture providing an overview of the principal neural networks identified in recent cognitive neuroscience research, connecting them to various cognitive processes—such as external attention and executive control—that support spontaneous and deliberate thought. This narrative strategy—though admittedly simplistic in attempting to compartmentalize processes or neural networks involved - is not meant to be exhaustive. The reader

should keep in mind that these processes, and consequently the neural mechanisms underpinning them, are interconnected in a continuous, inexorable, and—hopefully—flexible flow of thought. It is no coincidence, in fact, that I introduced this chapter by discussing the concept of *complexity*.

3.4.1. *The Default Mode Network*

In the late 19th century, some empirical observations revealed that the brain remains as active during rest as it does during cognitively demanding tasks, implying the presence of ongoing brain activity during unconstrained mental processes. This activity was also found to be concentrated in specific brain regions, such as the prefrontal cortex. Subsequently, the development of neuroimaging techniques – such as functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) – in the 1980s and 1990s, enhanced the researchers’ abilities to observe brain activity across different tasks, including activity in deeper brain structures.

Originally identified as a set of regions consistently deactivated during externally-oriented tasks (Raichle et al., 2001, Greicius et al., 2003), the DMN has been then linked to spontaneous mental processes (Christoff et al., 2009, Stawarczyk, Majerus, Maquet, et al., 2011). Other studies instead (Buckner et al., 2008; Ochsner et al., 2004; Spreng et al., 2009) suggested its recruitment extends beyond spontaneous cognition, being active during internally-oriented, goal-directed tasks such as episodic memory retrieval, future planning, and mentalizing.

Andrews-Hanna et al. (2010) examined the anatomy and function of the DMN across three different experiments to address conflicting hypotheses regarding its role. Results of this analysis – that combined functional connectivity with hierarchical clustering analysis – identified two distinct subsystems of the DMN that converge on a midline core. We now describe the neuroanatomy and the functions of these three subsystems in turn.

The *MTL subsystem* (Figure 10) includes the vmPFC, the hippocampal formation, parahippocampal cortex, retro splenial cortex and posterior inferior parietal lobule. This subsystem

exhibited increased activity specifically when participants engaged in episodic future thinking. This pattern is aligned with numerous functional imaging and neuropsychological studies that underscore the role of the DMN in both recalling the past and imagining the future (reviewed in Schacter et al., 2007). The activation of similar regions during both memory recall and future-oriented thought confirmed that these abilities share a common set of underlying processes. Andrews-Hanna et al. (2010)'s findings, based on strategy probes and item analysis, also revealed that participants often employed a mnemonic scene construction strategy—drawing on memories to build mental scenes—which accounted for 32% of the variance in activity within the MTL subsystem. This confirmed that mnemonic scene construction is a critical component of future-oriented thinking, a process distinctly supported by the MTL subsystem rather than by the entire DMN.

The *dorsomedial prefrontal cortex* (dmPFC) *subsystem* (Figure 10) comprises— apart from this latter region - temporo-parietal junction, lateral temporal cortex, and temporal pole. In contrast to the constructive role of the MTL subsystem, the dmPFC subsystem shows preferential activation when participants focus on their current mental states. 13% of its variance- in fact - was explained by the affective self-referential composite measure (i.e., a combination of personal significance, introspection about one's mental states and evoked emotions; see [Andrews-Hanna et al., 2010](#)). This finding aligns with previous research indicating that the dmPFC subsystem is activated when individuals process self-referential information, particularly affective content (e.g., Gusnard et al., 2001; Johnson et al., 2002; Lane et al., 1997; Lombardo et al., 2010; Ochsner et al., 2005; Saxe et al., 2006; Vanderwal et al., 2008). Interestingly, regions within the dmPFC subsystem are also engaged when participants infer the mental states of others (reviewed in Amodio & Frith, 2006; Frith & Frith, 2003; Ochsner et al., 2004). The potential neural overlap between affective, self-referential, and social cognitive processes suggests a broader role for this subsystem in metacognition (Ochsner et al., 2004), mental state inference (Frith and Frith, 2003; Olsson and Ochsner, 2008), social cognition (Mitchell, 2006), or using one's own mental states as a model for understanding the mental states of others

(Goldman, 1992). However, the exact interaction between emotion, self-knowledge, and the prediction of others' mental states remains unclear.

The *midline core* of the DMN, instead, is composed of the anterior anterior mPFC and the posterior cingulate cortex. Supporting their possible integrative role as hubs within the DMN, the anterior mPFC and PCC exhibited functional characteristics of both subsystems (Figure 10), showing preferential activation for self-related activities regardless of temporal context. These regions show higher activations for personal events that have actually occurred (Hassabis, Kumaran, & Maguire, 2007), are likely to occur (Szpunar et al., 2009), or align with personal future goals (D'Argembeau, Stawarczyk, et al., 2010). Moreover, the anterior portion of the mPFC (and often the PCC) is activated when participants make judgments or recall trait adjectives about themselves, as opposed to others (D'Argembeau et al., 2005; Heatherton et al., 2006; Kelley et al., 2002; Lou et al., 2004; Mitchell et al., 2006), and these regions correlate with self-referential thoughts (D'Argembeau et al., 2005) and perceived similarity or closeness to the self (Mitchell et al., 2006). Collectively, these observations suggest that the hubs of the DMN may play a crucial role in evaluating aspects of personal significance (see also D'Argembeau et al., 2009). These findings by Andrews-Hanna et al. (2010) converged with previous studies on functional connectivity (Margulies et al., 2007, 2009; see also paragraph 3.5.) and connectional anatomy (Barbas et al., 1999; Kondo et al., 2005)¹³.

¹³ *Connectional anatomy* refers to the study of how different regions of the brain are structurally connected. It focuses on the neural pathways that link various brain areas, emphasizing the role of these connections in enabling communication and coordination between different parts of the brain. Researchers use several techniques to study connectional anatomy, including diffusion tensor imaging (DTI), which visualizes white matter tracts, and tract tracing methods in animals.

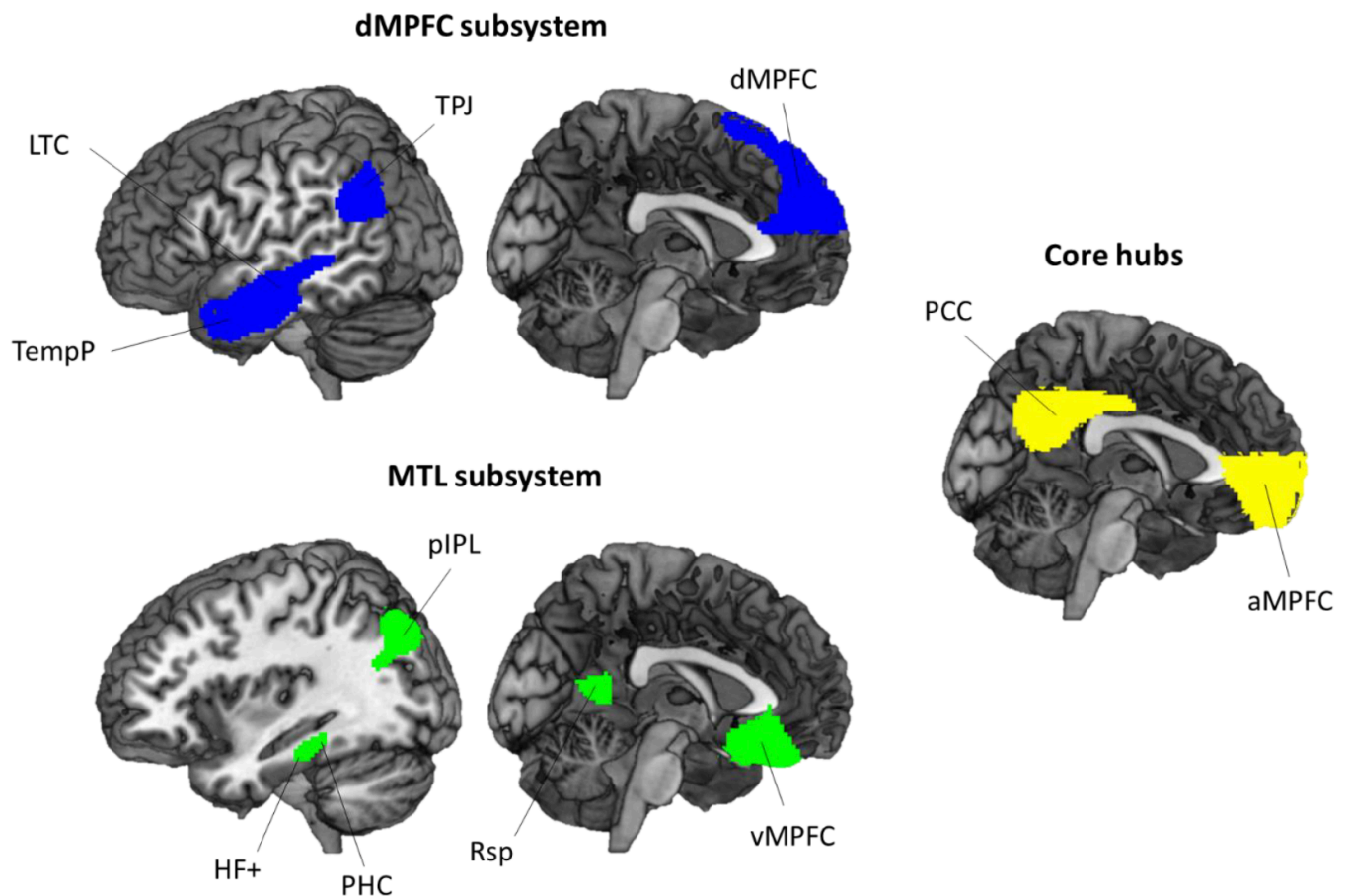


Figure 10. Representation of the three subsystems of the Default Mode Network (DMN), based on networks 10, 15, 16, and 17 outlined in the 17-network parcellation by Yeo et al. (2011) and further categorized according to the coordinates specified by Andrews-Hanna et al. (2010). The blue regions represent the dorsomedial prefrontal cortex (dmPFC) subsystem, which includes the midline dmPFC, as well as the bilateral temporoparietal junction (TPJ), lateral temporal cortex (LTC), and temporal pole (TempP). The green regions denote the medial temporal lobe (MTL) subsystem, comprising the midline ventromedial prefrontal cortex (vmPFC) and the bilateral posterior inferior parietal lobule (pIPL), retrosplenial cortex (Rsp), parahippocampal cortex (PHC), and hippocampus (HF+). The midline core system, highlighted in yellow, consists of the bilateral anterior medial prefrontal cortex (amPFC) and the posterior cingulate cortex (PCC). Image adapted from Wen, Mitchell, & Duncan (2020).

What is the exact role played by the DMN in cognition? The debate surrounding the role of the DMN during passive states has led to two primary hypotheses: the *sentinel hypothesis* and the *internal mentation hypothesis* (Andrews-Hanna, 2012). The sentinel hypothesis posits that the DMN is involved more broadly external attention, particularly in monitoring the environment for significant

or unpredictable stimuli. Evidence supporting this hypothesis includes observations that DMN activity increases during tasks requiring participants to anticipate unpredictable targets (Gilbert et al., 2007; Gusnard & Raichle, 2001; Raichle et al., 2001; Shulman et al., 1997), and that greater activity within the network is associated with faster response times during such tasks (Gilbert et al., 2006; Hahn et al., 2007). On the other hand, the internal mentation hypothesis suggests that the DMN is primarily engaged in internally-directed cognitive processes during passive states. These processes, often referred to as stimulus-independent thought, mind-wandering, or daydreaming, involve the generation and manipulation of mental images, reminiscence, and future planning. A growing body of neuroimaging studies (e.g., Mason et al., 2007; Wang et al., 2009) supports this hypothesis, demonstrating positive correlations between DMN activity and spontaneous internal mentation. For example, research has shown that elevated DMN activity precedes reports of mind-wandering during sustained attention tasks, particularly when participants are unaware that their minds have wandered (Christoff et al., 2009).

Functional balance between the DMN and other brain systems is essential to support human cognition adaptively. For example, a seminal paper on resting-state functional connectivity (Fox et al., 2005; see also paragraph 3.5.) identified anticorrelations between the DMN and the so-called “*task-positive network*” primarily comprising the Dorsal Attention Network (DAN) and elements of Fronto-Parietal Control Network (FPCN). This scientific discovery captured a compelling relationship: as novel, attention-demanding tasks activate the DAN, there is a corresponding decrease in DMN activity, encapsulated by the metaphor of “*losing oneself in one’s work*” (Raichle, 2015).

3.4.2. *The Dorsal and Ventral Attention Networks*

Human attentional focus constantly shifts between internal and external sources (Andrews-Hanna et al., 2010). In contrast to the well-established contribution of the DMN in internally-directed cognition, past research attributed the DAN a role for directing the attention outward.

When directing the attention outward, we might prioritize further processing of certain stimuli over others (i.e., *selective attention*; Treisman, 1969). This attentional bias can emerge in two different ways: through a *top-down* mechanism, where attention is voluntarily directed towards stimuli with specific features or in a *bottom-up* fashion, with stimuli automatically capturing attention without a conscious effort (e.g., Corbetta & Shulman, 2002; Mesulam, 1999; Posner & Petersen, 1990; Fox et al., 2006). These voluntary and/or automatic forms of attention are thought to be governed by two partially distinct but interacting neural systems centered around the superior (SPL) and inferior parietal lobule (IPL), respectively (Corbetta & Shulman, 2002; see Figure 11). These two systems are the Dorsal Attention Network (DAN) and the Ventral Attention Network (VAN).

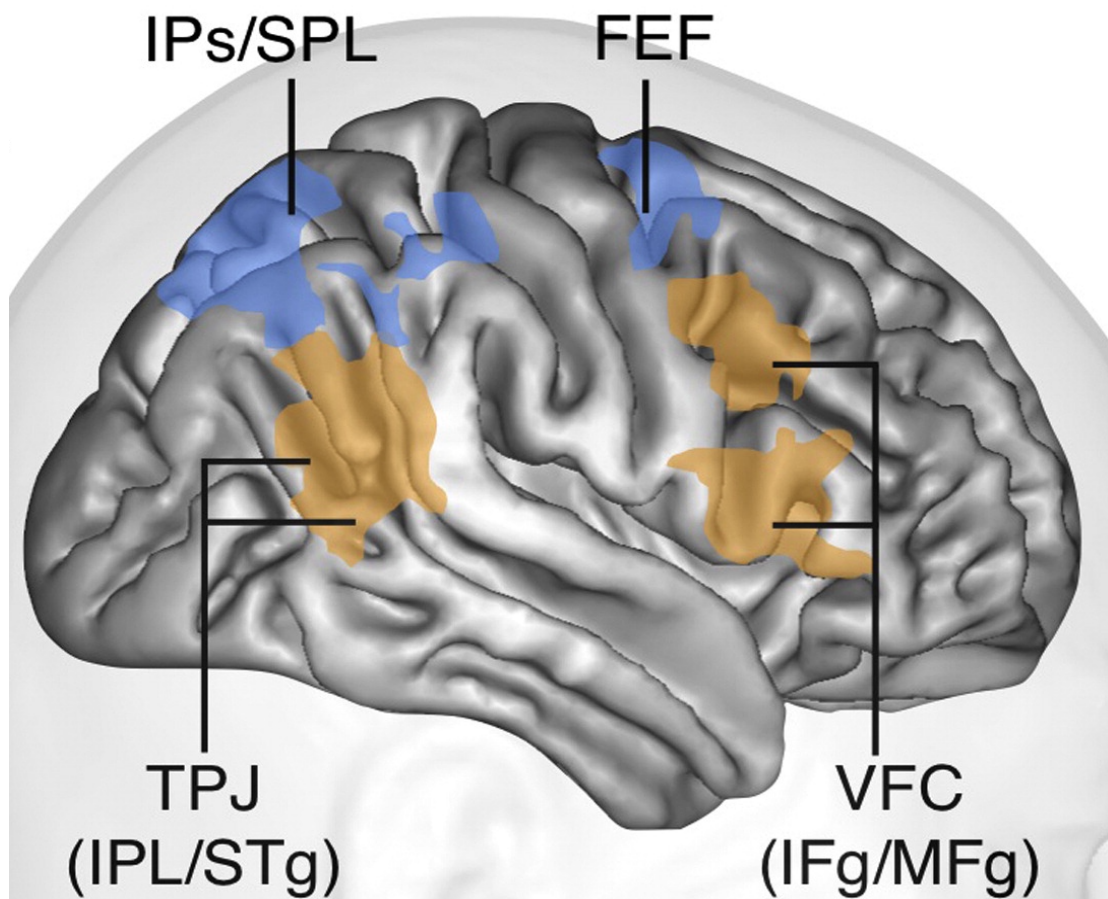


Figure 11. The Dorsal Attention Network (DAN) and the Ventral Attention Network (VAN) as described by Corbetta & Shulman (2002). The DAN (including frontal eye fields, FEF; the intraparietal sulcus, IPS; and the superior parietal lobe, SPL) is represented in blue. The VAN (consisting of the ventral frontal cortex, VFC; and the temporoparietal junction, TPJ) is depicted in

yellow (adapted from [Chica et al., 2013](#)). *STg* = superior temporal gyrus; *IFg* = inferior frontal gyrus; *MFg* = middle frontal gyrus.

Interestingly, the SPL and the IPL have also emerged as a neural correlate of attention inward, supporting episodic memory retrieval (i.e., Cabeza et al., 2008a; Ciaramelli et al., 2008a; Wagner et al., 2005; see also paragraph 2.1.1.1.). Building on the purported distinction between the roles of the dorsal and ventral parietal cortices in external attention, in fact, it was hypothesized that SPL supports indirect retrieval by allocating top-down attentional resources to strategic retrieval processes – in other words, directing top-down *Attention To Memory* (ATOM theory; Ciaramelli et al., 2008b; Ciaramelli & Moscovitch, 2020). The ventrolateral prefrontal cortex (vlPFC) would select cues to access the memory, whereas the dlPFC would indicate when a memory search is needed. If the retrieved information does not match the desired memory, further cue specification would be required, leading to additional cycles of memory search. Throughout this process, the SPL would allocate attention to the various components of strategic - *indirect* - retrieval, from cue specification to final memory verification. By contrast, the IPL would be implicated in *direct* retrieval, mediating the automatic capture of attention by memory contents retrieved via the MTL – i.e., bottom-up *Attention to Memory* (Ciaramelli et al., 2008). During direct retrieval, cues would interact automatically with information stored in memory systems via the MTL. Early post-retrieval monitoring, facilitated by the vmPFC, would ensure the task relevance of the retrieved memory, similar to processes observed in search and detection paradigms (Shulman et al., 2003). The temporoparietal junction would signal the detection of task-relevant memory content, bringing the memory into consciousness. If the memory conflicts with other information, more strategic monitoring processes, supported by the dorsolateral prefrontal cortex (dlPFC), may be triggered to assess its accuracy. If the memory passes this final prefrontal check, or if no conflict exists, retrieval attempts cease, and the memory would subsequently guide behavior (Schacter et al., 2007; Ciaramelli et al., 2008; see also Ciaramelli & Moscovitch, 2020).

In this section, we have seen how human thought can be triggered through a bottom-up capture of attention—whether from external or internal stimuli—and that this mechanism supported by the VAN. For a stimulus to capture attention, it must be *salient*. The focus of the next paragraph, therefore, will be on a neural system that largely overlaps with the VAN: the Salience Network.

3.4.3. *The Salience Network*

Internal and external stimuli continuously bombard the human nervous system. A crucial challenge, thus, lies in identifying the most relevant inputs for maintaining *homeostasis* *. This capacity necessitates a system capable of integrating highly processed sensory information with visceral, autonomic, and motivational signals (“*hedonic markers*”, see Damasio, 1999). The integrated picture arising from all these signals allows the organism to determine its course of action – for example, acting or not. Seeley et al. (2007) introduced that the activity of a Salience Network is well-suited for this critical function.

The Salience Network is built around paralimbic structures (to get more insights about the neuroanatomy and functions of the Salience Network, see Goulden et al., 2014; Uddin, 2016; Seeley, 2019; Seeley et al., 2007), with the dorsal Anterior Cingulate Cortex and the orbital fronto-insula playing a prominent role. These regions, in fact, are known to underlie interoceptive-autonomic processing (e.g., Craig, 2009; Critchley et al., 2004; Singer et al., 2004). Notably, these brain areas co-activate in response to diverse forms of salience, encompassing the emotional aspects of pain (Peyron et al., 2000), empathy for pain (Singer, Seymour, et al., 2004), metabolic stress, hunger, pleasurable touch (Craig, 2002), aesthetic chills to music (Blood & Zatorre, 2001), recognition of loved ones (Bartels & Zeki, 2004) or allies (Singer, Kiebel, et al., 2004), and social rejection (Eisenberger et al., 2003). Most remaining nodes within the Salience Network reside instead in subcortical areas responsible for emotion, homeostatic regulation, and reward (Menon & Levitin, 2005; Ongür & Price, 2000).

The role of the Salience Network in thought is rooted in *affective salience*: in fact, it is not only involved in autonomic processes but also plays a role in directing the train of thought toward a mentally relevant content (Andrews-Hanna et al., 2014; Andrews-Hanna, 2012; Christoff et al., 2016). Christoff et al. (2016) describes, for example, how the Salience Network can exert automatic constraints on thought, thus reducing its variability and imposing stability over time. This occurs especially when the MTL subsystem of the DMN (see the paragraph 3.4.1.) provides only minimal internal variability, and the Fronto-Parietal Control Network (FPCN) exerts weak deliberate constraints over thought. The focus of the next paragraph will be, in fact, the FPCN.

3.4.4. *The Fronto-Parietal Control Network*

Thinking is a complex activity. For example, planning for one's personal future necessitates both internally-focused cognition (e.g., simulating future experiences) and goal-directed cognition (e.g., problem solving to achieve personal goals; Verschure et al., 2014). Given the competitive nature of the DMN and DAN, how can goal-directed cognition with an internal and self-relevant focus be mediated by these two apparently anti-correlated networks? One possibility is the existence of a third network, the Fronto-Parietal Control Network (FPCN), that facilitates functional interplay between them.

Regions within the FPCN respond to cues indicating task onset and react differentially to performance feedback events (e.g., correct vs. incorrect trials). This network encompasses parts of the DAN (as proposed by Corbetta & Shulman, 2002) plus additional regions commonly associated with top-down control in cue-delay-trial paradigms¹⁴, such as the dorsolateral prefrontal cortex and

¹⁴ In cue-delay-trial paradigms, participants are given a cue (stimulus or signal) indicating the task they need to perform. After the cue, a delay period follows, requiring participants to retain the relevant information in memory without receiving any additional task-related input. The trial then begins, where participants either respond to a probe or carry out the task

the inferior parietal lobule. Components of the FPCN have been examined in the context of cognitive control (e.g., Nee, 2021) and have been anatomically characterized using resting-state functional connectivity analyses. In particular, the FPCN involves the rostro-lateral prefrontal cortex, middle frontal gyrus, anterior insula/ frontal operculum, dorsal anterior cingulate cortex, precuneus, and anterior inferior parietal lobule. It is positioned anatomically between the DMN and DAN (Vincent et al., 2008).

Spreng et al. (2010) tested the hypothesis that FPCN would flexibly engage with either the DMN or DAN to support goal-directed cognition. Using a data-driven approach – the multivariate Partial Least Squares analysis¹⁵ - the authors found that two planning- autobiographical and visuospatial - tasks engaged the FPCN. Task-related functional connectivity (see paragraph 3.5.) analyses further indicated that the FPCN coupled with the DMN during autobiographical planning and with the DAN during visuospatial planning. Moreover, research demonstrated that the FPCN interacts with the DMN during creative processes, specifically during the generation (DMN) and revision (FPCN) of creative ideas (Beaty et al., 2014; Bendetowicz et al., 2017). Bendetowicz et al. (2017) also found that damage to the right medial prefrontal regions of the DMN impaired the ability to generate remote ideas, while damage to the left rostrolateral prefrontal regions of the FPCN did not hinder idea generation but affected the ability to combine those ideas effectively. Taken together, these findings substantiate the view that the FPCN can flexibly couple with the DMN and the DAN to support goal-oriented cognition (Fox et al., 2015).

Using multi-modal functional Magnetic Resonance Imaging (fMRI), Golchert et al. (2017) investigated the cortical organization underlying individual differences in the intentional or unintentional mode of spontaneous thought. Individuals who reported higher levels of intentional

based on the cue held in memory during the delay. These paradigms allow researchers to assess how the brain maintains and manipulates information over short periods and how various cognitive control processes (such as attention and memory) operate during task performance (e.g., Curtis & D'Esposito, 2003; Goldman-Rakic, 1996)

¹⁵ **Partial Least Squares is a multivariate technique that identifies a set of orthogonal latent variables optimally correlating the blood-oxygen-level-dependent (BOLD) response with the experimental design. This technique has high sensitivity to distributed network activity (McIntosh et al., 2004).

mind-wandering exhibited greater cortical thickness and functional connectivity between the DMN and the FPCN. These findings suggest that the intentionality of mind-wandering is mediated by the integration between the DMN, and regions associated with cognitive control.

In Christoff et al.'s framework, the FPCN provides deliberate constraints over thought processes. In this context, the MTL subsystem of the DMN determines relatively weak internal variability, with the midline core of the DMN and the Salience Network imposing only minimal automatic constraints. As we have seen in paragraph 1.6, deliberate/intentional and flexible constraints relate to goal-directed thought. It is no coincidence, in fact, that the involvement of FPCN has also emerged as the neural correlate of other deliberate forms of thought, e.g., PM (Cona et al., 2015; McDaniel et al., 2013; Beck et al., 2014).

Having reviewed the functions of various thought-related brain networks, it becomes evident that certain complex – and common - mechanisms at the neural-network level are responsible both for internal and external attention, as well as both spontaneous and deliberate thought. For example, the engagement of the DAN supports the shift of attention between both external and internal stimuli, while functional connectivity between the DMN and the FPCN underlies several forms of thought, exerting different levels of constraint. To gradually approach an understanding of the complexity of the mechanisms underlying thought, however, it is necessary to add one final piece to the puzzle: the examination of some *physiological* mechanisms that support thought-related cognitive functions.

3.5. *Physiology of human thought*

The Autonomic Nervous System (ANS), also referred to as the visceral or involuntary nervous system, operates without conscious control. It innervates cardiac muscle, smooth muscle, and various endocrine and exocrine glands, thereby influencing the activity of most tissues and organ tissues in the body (Khonsary, 2017; McCorry, 2007). Consequently, the ANS plays a crucial role in regulating

homeostasis (Jänig, 2022; McCorry, 2007). It consists of two distinct divisions: the sympathetic and the parasympathetic systems. Both systems are continuously active, providing a baseline level of nervous input to tissues, which can either increase or decrease (Diamond & Cribbet, 2013; Ondicova & Mravec, 2010). This tonic activity, in fact, allows for precise regulation of tissue function, as the nervous input can be adjusted to either enhance or inhibit activity.

Each division of the ANS predominates under specific conditions. The parasympathetic system is dominant during calm, resting states: its primary role under these conditions is to conserve and store energy, as well as regulate fundamental bodily functions such as digestion and urination. In contrast, the sympathetic system is dominant during emergency “*fight-or-flight*” responses and exercise, where its overall effect - being involved in arousal and wakefulness - is to prepare the body for strenuous physical activity. Moreover, the sympathetic nervous system controls the iris dilator muscle, facilitating pupil dilation, which is associated with heightened arousal. This mechanism explains the increased pupil size observed during states of excitement or alertness (for more insights into ANS activity, see Scott-Solomon et al., 2021; Jansen et al., 1995; see also Mathôt, 2018; but also Szabadi, 2018 for the pupil size regulation by the sympathetic system).

Central to this arousal and alertness mechanism is the locus coeruleus (LC)¹⁶, which produces norepinephrine. The LC regulates an alerting system that is vital for maintaining optimal vigilance and performance (Smith & Nutt, 1996). The activity of the LC is marked by a balance between slow tonic fluctuations and rapid phasic responses to stimuli, following an inverted-U-shaped curve (Aston-Jones & Cohen, 2005; Sara, 2009). In this regard, the *exploration-exploitation trade-off hypothesis* (Aston-Jones & Cohen, 2005) posits that the LC-NE system orchestrates brain state shifts between seeking new information (exploration) and pursuing known goals (exploitation). Optimal information processing is thought to depend on intermediate tonic LC activity levels (Unsworth &

¹⁶ The *locus coeruleus* (LC) is a small nucleus located in the brainstem, specifically in the pons, and is the principal site of norepinephrine production in the brain. It plays a crucial role in regulating arousal, attention, stress responses, and wakefulness. The LC is involved in a range of cognitive and physiological processes, influencing behavior through its widespread projections to the cortex, limbic system, and spinal cord (Aston-Jones & Cohen, 2005; Sara & Bouret, 2012).

Robison, 2018). This level – in fact - promotes efficient task completion by selecting salient actions within a neural network through transient norepinephrine bursts (O'Donnell et al., 2012). Deviations from this optimal level- either decreased or increased tonic levels - can impair performance on primary tasks. Elevated tonic LC-NE levels - for example - induce an exploratory mode, triggering responses that would otherwise not surpass the activation threshold (Jepma & Nieuwenhuis, 2011).

Understanding the role of the LC-NE system in thought mechanisms necessitates comprehension of two more concepts: functional connectivity and *neural gain*. Functional connectivity refers to the functional cooperation between distinct brain regions with synchronized neural activity over time, even without direct anatomical connections (Fox & Raichle, 2007; Friston, 2011). Neural gain instead is modulated by the LC-NE system, dynamically adjusting communication across cortical and subcortical areas (Mittner et al., 2016). High neural gain strengthens well-established connections and blocks weaker ones, while low neural gain attenuates strong connections and activates weaker ones. Increased neural gain correlates with enhanced functional connectivity, which in turn coincides with larger pupil diameters —a proxy for neural gain. Research suggests that high neural gain facilitates exploration mode and causes network instability (Shine et al., 2018).

3.5.1. Pupillometry and spontaneous thought

The reader will have now grasped the crucial role of the regulatory activity driven by distinct neural networks (e.g., the DAN and the FPCN) supports spontaneous thought. This activity, however, necessitates the existence of an additional system capable of dynamically orchestrating the neural activity across these brain networks, ensuring adaptive responsiveness of human cognition to both internal and external demands. Here, the domain of physiology becomes central to our exploration, as the locus coeruleus-norepinephrine (LC-NE) system – which we have described in the previous paragraph - has emerged as a candidate neural modulator of spontaneous thought (Mittner et al., 2014; Smallwood, Brown, et al., 2011).

High neural gain states (see the previous paragraph) have been associated both with spontaneous thinking and task-engagement. In this regard, Mittner et al. (2016) proposed a model for mind-wandering, departing from the traditional view (e.g., Andrews-Hanna et al., 2010; Buckner et al., 2008; Raichle et al., 2001; Spreng et al., 2010) that core DMN nodes (PCC and mPFC) are direct neural substrates of spontaneous cognition. Instead, these nodes would act as integrative processing units, dynamically adjusting based on converging large-scale networks. The LC-NE system is posited as the *driving force* behind attentional focus, with norepinephrine fluctuations determining a global processing state influencing cognitive efficiency. This model distinguishes between *exploratory* off-focus states and *active* mind-wandering. As illustrated in Figure 12, initial high engagement and motivation in a task are reflected in intermediate LC-NE activity levels, leading to optimal neural gain (*on-task state*). This state prioritizes task-relevant networks (e.g., DAN) while deactivating task-unrelated networks (e.g., DMN). Over time, focused attention requires a system refresh, leading to the *off-focus state* with higher functional between-network connectivity and increased DMN activity. This state allows for the selection of new behavioral goals, such as returning to the main task or engaging in mind-wandering. Finally, *active mind-wandering*, driven by internal goals, would resemble the on-task state (and, again, an optimal neural gain), but with reduced functional connectivity due to the differential engagement of fewer networks (i.e., MTL subsystem and midline core of the DMN; Andrews-Hanna et al., 2010; Mittner et al., 2016; see Figure 11).

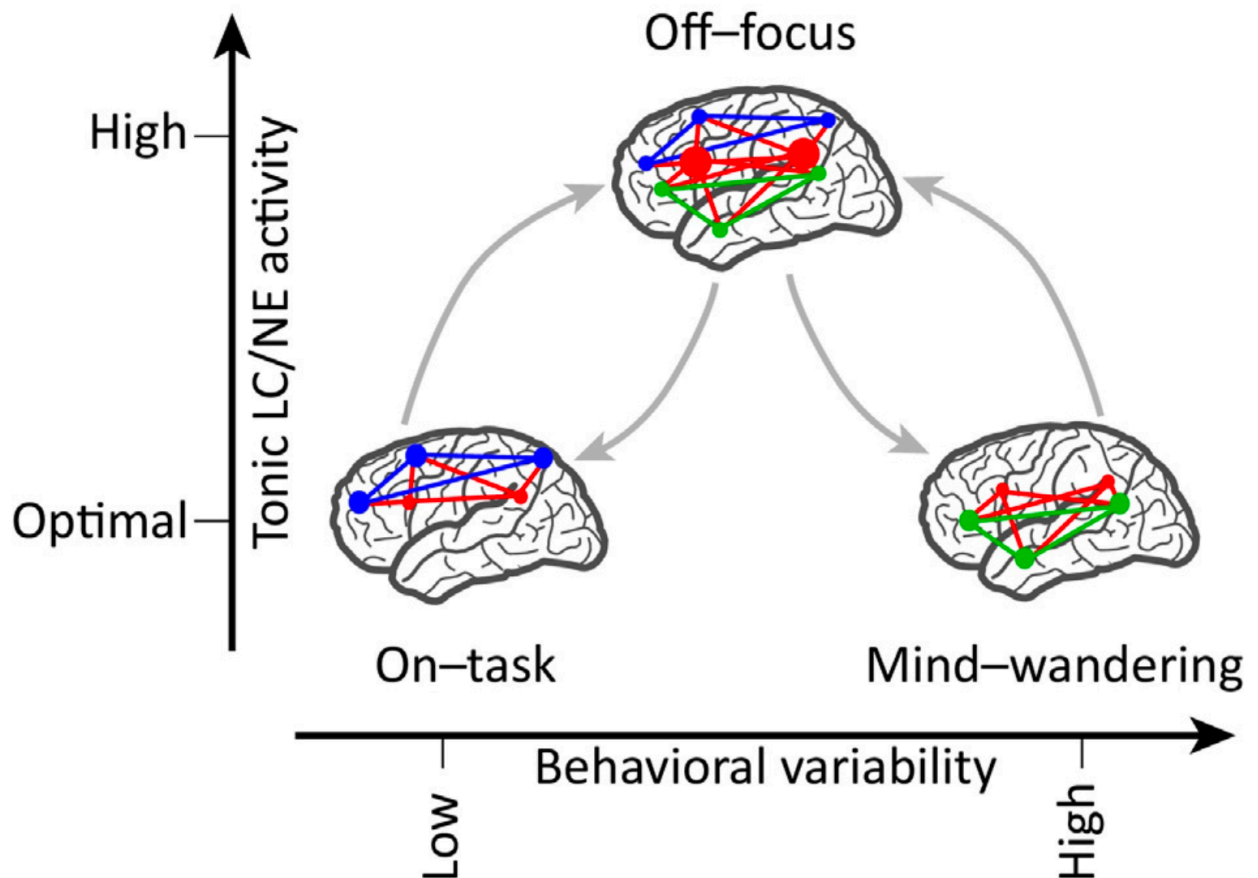


Figure 12. *Neural Model of Mind-Wandering* (Mittner et al., 2016). Optimal performance and deliberate internal focus, such as mind-wandering, occur when neural gain is moderate. In these states, the transmodal hub nodes of the default-mode network (DMN)—the posterior cingulate cortex (PCC) and medial prefrontal cortex (mPFC) (red)—are connected to a limited number of networks involved in task performance. For instance, during the on-task state, the PCC and mPFC interact with the dorsal attention network (DAN) (blue), while during mind-wandering, they connect with the medial temporal lobe (MTL) subsystem of the DMN (green). When neural gain increases, participants may subconsciously shift toward considering alternative activities, a state termed *exploration*. This state is characterized by higher activation and broader connectivity of the PCC and mPFC with multiple distinct brain networks, moving the participant *off-focus*. This state involves activations in the DAN (middle frontal gyrus, frontal eye field, superior parietal lobule in blue), the MTL subsystem (ventral mPFC, hippocampal formation, posterior inferior parietal lobule in green), and the DMN hubs (mPFC and PCC in red).

Expanding on the proposed connection between arousal states (regulated by the locus coeruleus-norepinephrine, or LC-NE, system) and spontaneous thought, several studies have explored whether biomarkers of sympathetic activity— e.g., pupil diameter – relate to self-reported mind-wandering during various cognitive tasks (Franklin et al., 2013; Grandchamp et al., 2014; Konishi et al., 2017; Mittner et al., 2014., 2018, 2020; Unsworth & Robison, 2016, see also Pelagatti, Blini & Vannucci

for a recent review on the use of pupillometry as a biomarker of mind-wandering). Mittner et al. (2016)'s model of mind-wandering, for instance, was tested by Unsworth & Robison (2018), who investigated – in a series of four experiments – the relationship between arousal and various mind-wandering states using pupillometry. The authors aimed to determine whether tonic – pretrial baseline – pupil diameter could be an indicator of arousal and cognitive load, by varying between on-task and mind-wandering states under different experimental conditions. Across all experiments, mind-wandering was consistently linked to poorer behavioral performance and smaller task-evoked pupillary responses¹⁷. In situations promoting external attention (e.g., *psychomotor vigilance task*), on-task reports correlated with larger tonic pupil diameters, while situations fostering internal attention showed no significant difference in tonic pupil diameters between on-task and mind-wandering states. These findings supported previous theories (Lenartowicz et al., 2013; Mittner et al., 2016), confirming the assumption that the internal/external orientation of attention significantly affects both mind-wandering and on-task states. Based on their findings, Unsworth & Robison (2018) hypothesized the existence of three distinct mind-wandering states, each of them associated with different arousal levels (see Figure 13). The promotion of an external focus of attention would generate more frequent internal thoughts due to either low arousal (*non-alert mind wandering*) or high arousal (*exploratory mind wandering*). Conversely, in situations that encourage an internal focus of attention, such as prompting personal concerns or tasks allowing intermittent breaks, *active mind wandering* would be more frequent, characterized by optimal – intermediate - arousal levels and attention focused internally rather than on-task.

¹⁷ *Task-evoked pupillary response* refers to the transient dilation/contraction of the pupil in response to cognitive or sensory events. It occurs briefly, often aligning with the onset of a specific task or stimulus, and is linked to activation in the locus coeruleus-norepinephrine (LC-NE) system (Granholm & Steinhauer, 2004; Murphy et al., 2011). In contrast, a *tonic/sustained* pupil dilation/contraction refers to longer-lasting changes in pupil size that occur over extended periods of engagement with a task/activity (Laeng, Sirois, & Gredebäck, 2012).

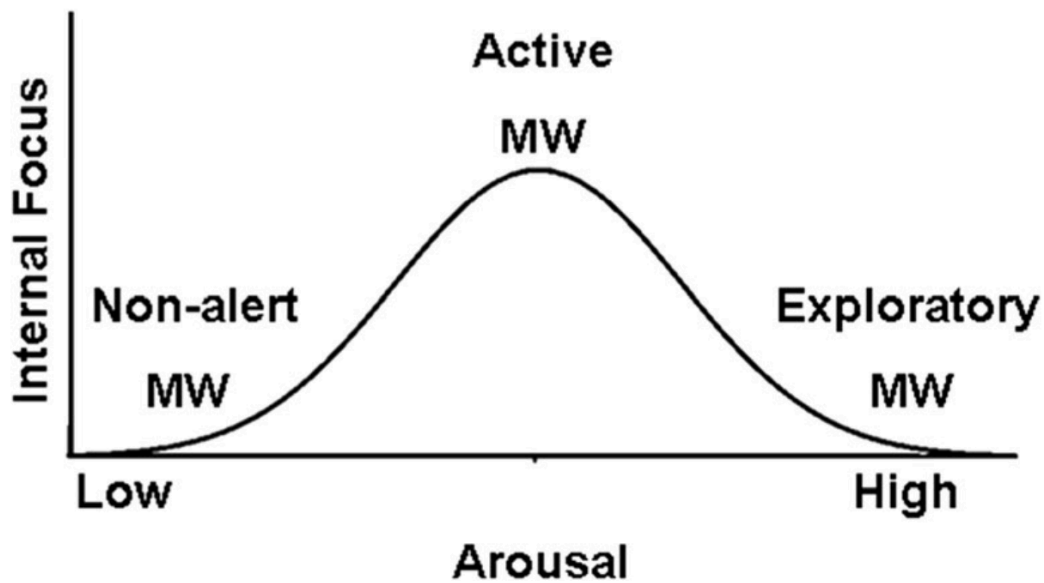


Figure 13. Unsworth & Robison (2018)'s model, displaying changes in mind-wandering states as function of arousal levels.

3.5.2. Pupillometry and deliberate thought

Finally, we will explore how the LC-NE system has also been associated with the mechanisms underlying deliberate - goal-directed and/or task-related - thought. Based on the same principle, in fact, extensive research, has implicated pupil size as a key measure of attention, arousal and general task engagement (Clewett et al., 2020; Eldar et al., 2021; Gilzenrat et al., 2010; Joshi et al., 2016; Kahneman & Beatty, 1966). In particular, differences in pupil size have been implicated in sustained attention (Brink et al., 2016; Decker et al., 2020; Unsworth & Robison, 2016) and working memory tasks (Robison & Brewer, 2020; Unsworth & Robison, 2015, 2018; Zokaei et al., 2019).

Research has established that pupil diameter can serve as an indicator of cognitive load. For instance, Hess & Polt (1964) observed that pupil diameter increased with the difficulty of mental arithmetic tasks, and Kahneman & Beatty (1966) found that pupil size expanded in response to each additional item in a digit string maintained in working memory. More recent studies (Alnæs et al., 2014; Cabestrero et al., 2009; Granholm et al., 1996; Peavler, 1974; Wahn et al., 2016) have

corroborated these findings, showing that pupil diameter is associated with cognitive load across various memory and cognitive control paradigms (see van der Wel & van Steenbergen, 2018 for a review). This phenomenon, where pupil diameter changes in response to a stimulus during an experimental trial, is known as the task-evoked pupillary response (TEPR). TEPRs typically begin approximately 0.4 seconds after stimulus onset, peak around 1 second, and return to baseline within 2–3 seconds after stimulus onset (Goldinger & Papesh, 2012).

Pupil diameter has also been associated with autobiographical memory retrieval. El Haj et al., (2019) investigated this by measuring pupil dilation during memory retrieval compared to a control task where participants were instructed to count aloud. The results revealed higher pupil dilation during memory retrieval, suggesting that an increase in pupil diameter is a reliable index of the cognitive load exerted while reconstructing memories. Building on these findings, El Haj & Moustafa (2021) investigated whether imagining future events would similarly elicit pupil dilation. They measured pupil dilation in participants under two conditions: recalling past personal events and imagining future events. Pupil diameter was significantly higher during future rather than past thinking and future event retrieval took longer, indicating a higher cognitive load compared to past events. Moreover, a positive correlation was found between retrieval time and pupil size, suggesting that pupil dilation might also reflect the increased cognitive demands associated with future thinking.

Moyes et al. (2019) investigated the potential of pupillometry to measure cognitive load in event-based PM (see the paragraph 2.2.). Their study addressed this gap by employing a lexical decision task under three conditions: a baseline ongoing task, (2) a single-item PM condition, and (3) a category PM condition¹⁸. To examine the cognitive processes involved in monitoring for PM targets, they focused on pupillometry data from trials before any targets were presented to isolate the

¹⁸ In *category* PM tasks, participants are instructed to monitor for target items that fall within a predefined category (e.g., animals, colors, or types of food). In the study by Moyes et al. (2019), participants performed a lexical decision (ONG) task, where they classified a sequence of letter strings as words or nonwords. When a target word that belonged to the category “*animal*” was presented, participants were required to press a specific button to indicate that they had detected the target.

monitoring processes without the influence of target detection. The authors also made key assumptions about the temporal profiles underlying a PM performance, distinguishing between *sustained monitoring* and *transient checking* processes. This allowed them to see whether the pupillometry effect, if any, was time-locked to stimulus presentation or sustained throughout the trial. Their results showed that pupil size increased significantly in the category but not in the single-item PM condition. This increase in pupil size was sustained throughout the task, rather than occurring transiently after stimulus presentation. No transient pupillary response was detected instead with non-target checking, though a strong transient response was observed when targets appeared in PM conditions. These findings suggest the presence of a *sustained* PM monitoring process that persists even during inter-trial intervals and is detectable with pupillometry (Moyes et al., 2019).

Chapter 1.

Distracted from the here and now:

Neural bases of internal and external distraction

In the Introduction, we highlighted that, according to the traditional view of spontaneous thought, when our minds begin to wander, attention drifts away from the external environment (i.e., *perceptual decoupling*; Kam & Handy, 2013; Schooler et al., 2011; Smallwood et al., 2007). When focusing on the neural bases of thought, instead, we understood the compelling relationship (i.e., *functional antagonism*) between the DMN and DAN: as novel, attention-demanding tasks *activate* the DAN, DMN activity correspondingly *decreases*. This suggests that, under certain circumstances, internal and external stimuli compete for attentional resources.

Building from these assumptions, Chapter 1 will explore the neural bases of inward and outward attention, focusing on two key brain regions of the DMN and the DAN: respectively, the mPFC and PPC. In other words, what effect does selective inhibition of the mPFC or PPC activity exert on internal and external attention?

Study 1.

**The role of posterior parietal cortex and medial prefrontal
cortex in distraction and mind-wandering ***

Luca Giacometti Giordani¹, Andrea Crisafulli¹, Giovanni Cantarella^{1,2}, Alessio Avenanti^{1,2}, and
Elisa Ciaramelli^{1,2,*}

1. Centre for studies and research in Cognitive Neuroscience, Cesena, Italy

2. Department of Psychology ‘Renzo Canestrari’, University of Bologna, Bologna, Italy

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Abstract

Distraction reflects a drift of attention away from the task at hand towards task-irrelevant external or internal information (mind-wandering). The right posterior parietal cortex (PPC) and the medial prefrontal cortex (mPFC) are known to mediate attention to external information and mind-wandering, respectively, but it is not clear whether they support each process selectively or rather they play similar roles in supporting both. In this study, participants performed a visual search task including salient color singleton distractors before and after receiving cathodal (inhibitory) transcranial direct current stimulation (tDCS) to the right PPC, the mPFC, or sham tDCS. Thought probes assessed the intensity and contents of mind-wandering during visual search. The results show that tDCS to the right PPC but not mPFC reduced the attentional capture by the singleton distractor during visual search. tDCS to both mPFC and PPC reduced mind-wandering, but only tDCS to the mPFC specifically reduced future-oriented mind-wandering. These results suggest that the right PPC and mPFC play a different role in directing attention towards task-irrelevant information. The PPC is involved in both external and internal distraction, possibly by mediating the disengagement of attention from the current task and its reorienting to salient information, be this a percept or a mental content (mind-wandering). By contrast, the mPFC uniquely supports mind-wandering, possibly by mediating the endogenous generation of future-oriented thoughts capable to draw attention inward, away from ongoing activities.

1. Introduction

Distraction, a common experience of human mental life, reflects a drift of attention away from an ongoing task and towards task-irrelevant yet salient information. There are multiple sources of distraction. Attention can be diverted from its original focus by stimuli in the sensorial world, such as a sudden sound of church bells ringing, the voice of a friend calling, a headache. Our mind, however, can also wander off-task to focus on our inner world, a phenomenon known as mind-wandering (Antrobus et al., 1966; Christoff et al., 2016; Fox et al., 2015; Smallwood & Schooler, 2015; Stawarczyk, Majerus, Maquet, et al., 2011). The most paradigmatic form of mind-wandering is both stimulus-independent (internally generated) and task-unrelated (Stawarczyk, Majerus, Maquet, et al., 2011). An example is fantasizing about attending an upcoming concert while swimming.

The neural bases of attention to the external world have long been investigated, while those of mind-wandering have been addressed only more recently, in the last decade (see, for reviews, Christoff et al., 2016; Seli et al., 2018). For the most, these two lines of research have run parallel. This is surprising considering that internal and external sources of information compete for attention, and that our mental life consists in fact of a blend of mental states that are in part goal-directed, and in part reflecting the straying of attention towards internal or external task-irrelevant stimuli. What are the neural bases of our ability to direct attention to internal and external information?

It has long been known that when attention is allocated to the external environment, two different brain networks are engaged, in which the posterior parietal cortex (PPC) figures prominently (Corbetta & Shulman, 2002; Theeuwes, 1991). The dorsal PPC is engaged during the voluntary orienting of attention towards relevant stimuli, whereas the ventral PPC responds to the reorienting of attention towards relevant yet unexpected stimuli (Corbetta et al., 2008). For example, enhanced responses in the ventral PPC, especially in the right hemisphere, are observed when subjects are cued to expect a target at one location, but it unexpectedly appears at another (Corbetta et al., 2000; Indovina & Macaluso, 2007; Posner, 1980), or when individuals monitor the environment for

infrequent targets (oddballs; e.g., [Bledowski et al., 2004](#); [Downar et al., 2000](#); [Stevens et al., 2005](#)). The capture of attention by salient external stimuli may interfere with performance. In a functional neuroimaging (fMRI) study, [de Fockert et al. \(2004\)](#) had participants search for a circle among diamonds (see also [Theeuwes, 1991](#)). In 25% of trials, the target (circle) or a distractor (diamond) was a color singleton. The presence of a color singleton distractor interfered with search performance, leading to an increase in reaction times (RTs) to the target ([Theeuwes, 1991](#); [Jonides & Yantis, 1988](#)), which was accompanied by activity in the dorsal PPC bilaterally. The role of right PPC in mediating the capture of attention by a perceptually salient distractor singleton is corroborated by causal evidence. [Hodsoll et al. \(2009\)](#) had participants undergo a similar visual search task following the inhibition of the right or left PPC through transcranial magnetic stimulation (TMS). TMS of the right – but not left – PPC reduced the RT cost associated with singleton distractor trials, supporting the view that the right PPC plays a crucial role in mediating shifts of attention towards (distraction from) external sources of information ([Mevorach et al., 2006](#)). As well, in a target discrimination task ([Heinen et al., 2011](#)), TMS over the right angular gyrus of PPC interfered with bottom-up reorienting of attention. Moreover, patients with lesions to the right PPC may show neglect, a deficit in detecting contra-lesional stimuli, especially if invalidly cued ([Friedrich et al., 1998](#)).

Attention can be captured by internal information as well. Germane to this is the ubiquitous experience of mind-wandering, whereby attention is diverted away from the external environment and current goals towards task-unrelated and stimulus-independent thoughts, such as memories, future plans, and current concerns ([Christoff et al., 2016](#); [Stawarczyk, Majerus, Maquet, et al., 2011](#)). Like external distraction, mind-wandering is not costless: it interferes with processing of external events ([Barron et al., 2011](#)) and performance in the task at hand ([Franklin et al., 2011](#); [McVay & Kane, 2010](#); [Smallwood et al., 2007](#)). fMRI evidence indicates that mind-wandering is associated with activity in the ‘default network’, a set of interconnected brain regions that includes the medial prefrontal cortex (mPFC), the MTL, the posterior cingulate cortex, and the lateral temporal and parietal cortex, whose activity is enhanced during relatively passive (as compared with goal-directed)

and internally focused states (Buckner et al., 2008; Christoff et al., 2009; Mason et al., 2007). The default network is more engaged during mind-wandering (stimulus-independent and task-unrelated thought) compared to other types of off-task thoughts that are less removed from the current experience, such as external distractions (which are triggered by an external stimulus; e.g., ‘was that a thunder?’) and task-related thoughts (which are related to the ongoing activity; e.g., ‘this task is boring’), though different subregions of the default network respond preferentially to different forms of off-task experience (Stawarczyk, Majerus, Maquet, et al., 2011). In particular, the mPFC, in both its ventral (vmPFC) and dorsal aspects, seems to be crucially implicated in mind-wandering (J. R. Andrews-Hanna, Reidler, Sepulcre, et al., 2010). Bernhardt et al. (2014) found that the thickness of mPFC regions is positively related to individuals’ tendency to mind-wander. Further, patients with lesion to the vmPFC show a reduced frequency of mind-wandering compared to healthy and brain-damaged controls. Moreover, their off-task thoughts are mostly present-oriented, and never about the future (Bertossi & Ciaramelli, 2016).

Although previous studies have associated the right PPC and the mPFC with the ability to direct attention to external and internal information, respectively, no study has tested empirically whether these regions support each process selectively, or rather they support both processes (Stawarczyk et al., 2014). Mind-wandering shares cognitive components with external distraction, in that in both cases a task-irrelevant stimulus, be it internal (during mind-wandering) or external, diverts attention from its original focus (Unsworth & McMillan, 2014). According to recent models of attention, the PPC mediates the re-orienting of attention to internal (e.g., memory) in addition to external sources of information (Cabeza et al., 2008b; Ciaramelli et al., 2008b; Ciaramelli & Moscovitch, 2020; A. D. Wagner et al., 2005). The right PPC may act as a convergence node regulating the interaction between the ventral attention network, implicated in detecting salient information (Ciaramelli et al., 2008b; Corbetta et al., 2008), and the default network, implicated in generating thought contents (Christoff et al., 2016; Ciaramelli & Treves, 2019; Stawarczyk, Majerus, Maquet, et al., 2011), allowing the flexible switching of attention between external and internal

stimuli, possibly via interactions with the the locus coeruleus-norepinephrine system (Mittner et al., 2016). On this view, the right PPC should be related to mind-wandering, in addition to external attention. On the other hand, there is evidence that mPFC may also support attention towards the external environment under some conditions. Gilbert et al. (2006), for example, found that activity in BA 10 of mPFC was associated with shorter reaction times to external stimuli (see also Gilbert et al., 2005), and lesions to the mPFC can result in poor performance in simple RT tasks (Stuss et al., 2002, 2005). Whether or not mPFC is causally and uniquely implicated in mind-wandering, therefore, awaits empirical confirmation.

Here we investigate the causal involvement of the right PPC and mPFC in directing attention towards task-irrelevant external and internal information using a task that allows the concomitant assessment of both. In a task modified by (Hodsoll et al., 2009), participants searched target circles among distracting diamonds, while the presence of color singleton distractors enabled the assessment of attentional capture by salient external information. The visual search task was occasionally interrupted by thought probes assessing the frequency and contents of off-task thoughts. The effect of singleton distractors on visual search performance served as an index of external attention, whereas the tendency towards mind-wandering served as an index of internal attention. The task was executed both before and after cathodal (inhibitory) tDCS of the right PCC, mPFC, or sham tDCS (see Figure 1).

If the right PPC is primarily implicated in directing attention to the external environment (Corbetta & Shulman, 2002), then cathodal tDCS of the right PPC should reduce the detrimental effect of singleton distractors on visual search (as in Hodsoll et al., 2008), but not mind-wandering. The few studies of mind-wandering following tDCS of right PPC appear consistent with this prediction, though they do not speak to our question directly. Kajimura & Nomura (2015;2016) have repeatedly shown that applying anodal (excitatory) tDCS to right PPC and concomitant cathodal (inhibitory) tDCS to the lateral prefrontal cortex decreases mind-wandering, indicating that, if anything, the PPC contributes to down-regulating mind-wandering (see also Filmer et al., 2021;

Hasenkamp et al., 2011). It is not clear, however, whether the same results would be obtained targeting right PPC alone, or inhibiting (as opposed to enhancing) activity in PPC, as we plan to do. Indeed, in a recent study targeting right PPC with anodal tDCS, Kajimura et al. (2019) found a reduction of mind-wandering, but Coulborn et al. (2020) found no effect. A limit of previous studies is that mind-wandering was not distinguished by externally-triggered forms of off-task thought, such as external distractions and task-related thoughts (Stawarczyk, Majerus, Maquet, et al., 2011), which may have complicated the detection of a link between the right PPC and internal distraction. Indeed, if the right PPC mediates shifts of attention to the external environment (Corbetta & Shulman, 2002), tDCS-induced inhibition of PPC might have an impact on off-task thoughts triggered by external stimuli, even though it is not expected to reduce mind-wandering. On the other hand, if PPC is implicated in directing attention to both external and internal information (Cabeza et al., 2008a; Ciaramelli & Moscovitch, 2020), then tDCS of the PPC should reduce both the distractor effect on visual search and mind-wandering.

Considering that mPFC is a crucial node of the brain default network (Buckner et al., 2008; Christoff et al., 2009; Mason et al., 2007; Stawarczyk, Majerus, Maquet, et al., 2011), we predict that cathodal tDCS to mPFC would reduce mind-wandering, but not the capture of attention by external (distractors) stimuli in the visual search task. These predictions are supported by previous evidence that patients with lesion to the ventral mPFC have reduced mind-wandering (Bertossi & Ciaramelli, 2016), but are, if anything, even more distractable than healthy controls by task-irrelevant external information, for example during flanker or Stroop tasks (Di Pellegrino et al., 2007; Ziaei et al., 2018).

A final question pertains to the temporality of mind-wandering. (Bertossi & Ciaramelli, 2016) found a selective reduction of future-oriented mind-wandering in vmPFC patients, consistent with the role of vmPFC in future thinking and future-oriented cognition (Ciaramelli, Anelli, et al., 2021; Ciaramelli, De Luca, et al., 2021; Schacter et al., 2012; Stawarczyk & D'Argembeau, 2015). However, a tDCS study by the same group did not show a selective role of mPFC in future-oriented mind-wandering (Bertossi, Peccenini, et al., 2017), possibly because in that study mind-wandering

was not distinguished by external distractions and task-related thoughts, which are typically present-oriented. Therefore, here we re-examine the temporality of mind-wandering, with the prediction that cathodal tDCS to mPFC (but not PPC) would reduce future- more than past-oriented mind-wandering.

2. Materials and Methods

2.1. Participants

Sixty-one right-handed young adults with no self-reported history of neurological or psychiatric disease were recruited from among the students of an introductory psychology course at the University of Bologna for course credits. Participants were randomly allocated to one of three stimulation groups: the PPC group (N = 22, 8 males, to receive cathodal tDCS over the right PPC, see below; mean age = 21.82, SD = 1.59), the mPFC group (N = 21, 8 males, to receive cathodal tDCS over mPFC, see below; mean age = 23.19, SD = 2.44), and the sham group (N = 22, 8 males, to receive sham tDCS, see below; mean age = 22.41, SD = 2.04) (see Table 1). Age ($F = 2.42$, $p = 0.10$) and gender ($\chi^2 = 0.02$, $p = 0.99$) did not differ across stimulation groups. The sample size was determined based on previous studies using tDCS (Axelrod et al., 2015; Bertossi, Peccenini, et al., 2017; Kajimura et al., 2019; Kajimura & Nomura, 2015). Participant groups were matched for working memory performance ($p > 0.27$, $\eta^2 < 0.041$ both for accuracy and RTs) and baseline propensity to mind-wander at the Mind Wandering questionnaire (MWQ; $p = 0.36$; $\eta^2 = 0.03$) (Table 1; see Supplementary Materials for more detail on the task/questionnaire; Appendix A). Participants were blind to the type of stimulation they were going to receive, and reported similar (low) levels of discomfort following (PPC, mPFC, or sham) tDCS ($p = 0.2$; $\eta_p^2 = 0.05$). Participants gave informed consent to participate to the study, which was approved by the Bioethical Committee of the University of Bologna and carried out in agreement with international norms (Declaration of Helsinki 1964).

	Age	Working memory	MWQ	Discomfort from tDCS
Sham group	22.41 (2.04)	0.71 (0.18)	16.41 (4.35)	2.00 (1.63)
PPC group	21.82 (1.59)	0.64 (0.21)	16.45 (3.02)	2.64 (2.24)
mPFC group	23.19 (2.44)	0.72 (0.21)	17.90 (4.02)	2.95 (1.24)

Table 1. Mean values (and SD) for age, working memory accuracy, mind wandering questionnaire (MWQ) scores, and rating of discomfort following tDCS by participant group. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

2.2. Procedure

2.2.1. tDCS

tDCS was delivered using a battery-driven Eldith constant direct current stimulator (neuroConnGmbH, Ilmenau, Germany). A pair of surface sponge electrodes was soaked in a standard saline solution (NaCl 0.9%) and held in place with elastic rubber bands. In all participants, a monopolar tDCS montage was used, with the cathodal (5x5 cm) and anodal (5x7 cm) electrodes placed over a scalp region and the right deltoid, respectively. We targeted PPC and mPFC using an extracephalic montage, delivering anodal current over the right deltoid, to avoid the confounding effect of a cephalic reference electrode (see also Avenanti et al., 2018; Bertossi, Peccenini, et al., 2017; Im et al., 2012; Monti et al., 2007). Participants were randomly assigned to receive either active cathodal stimulation over the right PPC (PPC group), active cathodal stimulation over the mPFC (mPFC group), or sham stimulation (sham group) (see Figure 1). Active tDCS was delivered with a constant current of 2 mA (current density ~ 0.08 mA/cm²), complying with current safety guidelines

(Nitsche et al., 2003). Active stimulation lasted for 15 min, plus 15 sec of ramp-up and ramp-down at the beginning and end of the stimulation. Impedance was constantly controlled and kept below 8 kOhm, with the addition of saline solution whenever needed. There is evidence that this stimulation protocol can affect cortical excitability for up to 30 min after the end of the stimulation, thus covering the entire duration of the visual search test (Nitsche et al., 2008).

In the PPC group, the electrode was positioned in a site corresponding to P4 (right parietal) point of the international 10-20 electroencephalography coordinate system, as in (Hodsoll et al., 2008), which corresponds to the right angular gyrus (Mevorach et al., 2006). In the mPFC group, the electrode was positioned over right BA10, one of the clusters most consistently activated during mind-wandering in a recent meta-analysis by Fox et al. (2015). The Montreal Neurological Institute (MNI) peak coordinates for that cluster ($x = 3$, $y = 61$, $z = 13$) were transformed into 10-20 electroencephalography system coordinates using the Münster T2T-converter software (www.neuro03.uni-muenster.de/ger/t2tconv/), and the cathode was applied 1.5 cm to the right of Fpz. In the sham group, the electrodes were placed in the same positions as in the PPC group (in half of the participants) or the mPFC group (in the other half), but the stimulator was turned off after 30 seconds of cathodal stimulation. Thus, participants felt the initial itching sensation associated with active tDCS, but they received no current for the rest of the “stimulation” period. This procedure ensures successful blinding of participants. Immediately after the stimulation, participants rated on a 10-point Likert scale the discomfort they experienced during the stimulation, if any (from 1 – ‘no discomfort’ to 10 – ‘extreme discomfort’).

2.2.2. Visual search task and assessment of external distraction

Participants then underwent two sessions of a visual search task (lasting about 15 minutes each), one before and one after the tDCS stimulation, with occasional thought probes aimed at assessing mind-wandering (see Figure 1). The ongoing task was a visual search task modified from Hodsoll et al. (2008) to include thought probes (see below). Participants sat at 70 cm from the

computer monitor. The visual search display consisted of 6 shapes positioned on a circle of radius 4.6° from the fixation cross. One of the 6 shapes was a circle of diameter 1.9° (target), and the remaining 5 shapes were diamonds of 1.7° square, meaning that the circle and the diamonds occupied approximately the same area. In the centre of each of the six shapes was a segment of length 1° that could be oriented vertically (in 3 cases) or horizontally (in the other 3 cases). The vertical and horizontal orientations were randomized across the 6 segments/shapes.

A trial consisted of a fixation cross for 500 ms, followed by the search displays that were present until a response was made. Participants had to signal whether the orientation of a line within the target circle was horizontal or vertical, by pressing the left-arrow key or the up-arrow key, respectively (Figure 1). A session of the visual search task consisted of 350 trials. In 210 of the 350 trials, all shapes and segments were gray (Standard condition), whereas the remainder contained a green color singleton shape, which could be the target circle (70 trials; Singleton target condition), or a diamond distractor (70 trials; Singleton distractor condition). The effect of color singletons on visual search was assessed by comparing visual search performance in the Singleton distractor or Singleton target conditions with that in the Standard condition with no color singleton shape. Performance costs associated with the Singleton distractor (vs. Standard) condition were used as an index of attention towards task-irrelevant *external* information.

2.2.2.1 Assessment of mind-wandering

Mind-wandering was assessed through 10-12 'thought probes' presented during each session (pre-tDCS, post-tDCS) of the visual search task, at a rate of approximately one thought probe every 25-35 visual search trials. Thought probes were presented visually, as a series of three screens. First, participants were required to rate, on a Visual Analog Scale (VAS), the degree to which immediately before the probe their attention was on-task (focused on performing the task) vs. off-task (focused on something unrelated to doing the task), from 0 – 'completely on-task' to 100 – 'completely off-task'. In a second screen, participants then classified the thoughts they were having just before they were

interrupted into 4 qualitative categories: (1) on-task thoughts (i.e., thoughts related to doing the visual search task; e.g., "the segment is horizontal so I press this key"), (2) internal thoughts (**mind-wandering**; i.e., thoughts unrelated to the task and originated endogenously; e.g., "I am so going for a walk after this!"), (3) task-related thoughts (i.e., thoughts triggered by the task, but not necessarily functional to doing the task; e.g., "this task is so boring"), and (4) external distractions (i.e., thoughts triggered by external stimuli; e.g., "Was that a thunder?"). If participants chose category 2, a third screen further probed them to specify whether the internal thought they were having focused on (1) the past (e.g., "The holiday in Turin was the worst ever"), (2) the present (e.g., "I wonder what my girlfriend is doing now"), (3) the future (e.g., "I am seeing the dentist later"), (4) atemporal, 'semantic' considerations (e.g., "I'm lucky to have a friend like her"), or (5) whether they were unaware about the temporal connotation of their thoughts. Internal thoughts, which are both stimulus-independent and task-unrelated (Stawarczyk, Majerus, Maj, et al., 2011), were used as an index of attention towards task-irrelevant *internal* information.

Participants were familiarized with the task with a short pilot session comprising 25 to 35 visual search trials and 1 mind-wandering assessment at the end. The software MATLAB R2015a (MathWorks, Inc., Natick, MA) with Psychtoolbox ([Brainard, 1997](#)) was used to run the visual search task and record accuracy and response times (RTs) as well as mind-wandering ratings.

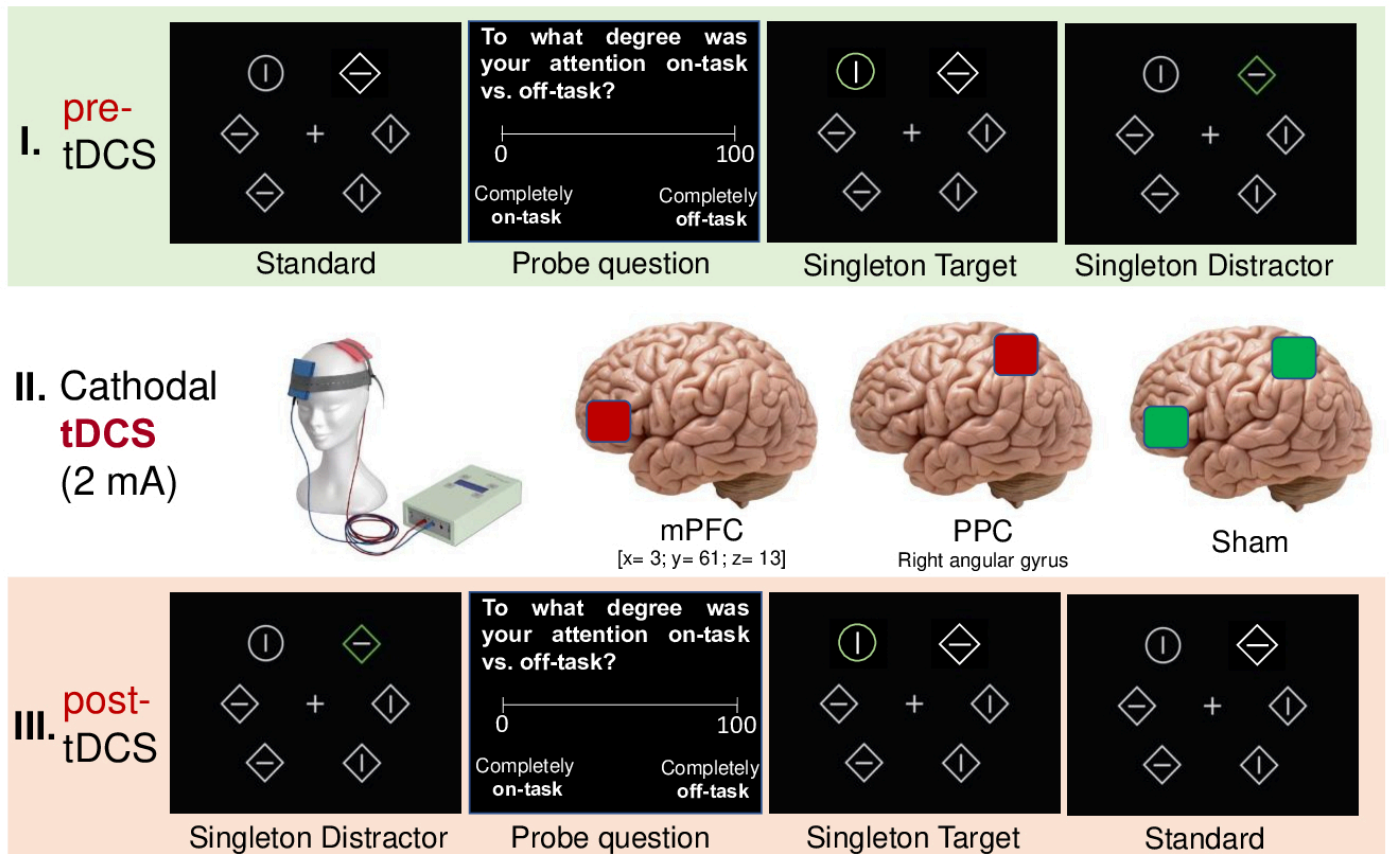


Figure 1. Experimental paradigm and design. Participants performed a visual search task while their thoughts were occasionally probed for mind-wandering both before and after receiving **cathodal tDCS** to the right posterior parietal cortex (PPC) or medial prefrontal cortex (mPFC).

3. Results

3.1 Effect of tDCS on visual search

Trials with response times (RTs) more/less than three standard deviations from each participant's mean (1.5% of RTs) were excluded from the analysis. RTs were longer in the Singleton distractor compared to the Singleton target and Standard (singleton absent) conditions (see Table 2). Accuracy was very high across conditions, with minimal changes again in the direction of lower performance in the Singleton distractor compared to the other conditions (See Table 3).

	No Singleton		Singleton Target		Singleton Distractor	
	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>
Sham group	613 (75)	577 (69)	582 (75)	548 (74)	725 (112)	679 (102)
PPC group	621 (50)	576 (40)	597 (46)	550 (37)	707 (79)	631 (54)
mPFC group	609 (60)	567 (49)	589 (63)	544 (47)	698 (96)	639 (76)

Table 2. Mean RTs (and SD) for correct responses by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	No Singleton		Singleton Target		Singleton Distractor	
	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>
Sham group	0.99 (0.01)	0.98 (0.01)	0.99 (0.02)	0.99 (0.02)	0.98 (0.02)	0.99 (0.02)
PPC group	0.98 (0.02)	0.98 (0.02)	0.98 (0.02)	0.98 (0.02)	0.97 (0.03)	0.98 (0.02)
mPFC group	0.98 (0.02)	0.98 (0.02)	0.99 (0.01)	0.98 (0.02)	0.98 (0.02)	0.97 (0.03)

Table 3. Mean accuracy (and SD) in the visual search task by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

For data analysis, RTs and accuracy relative to each singleton condition were combined in an ‘inverse efficacy score’, computed as $iRTs = RTs/accuracy$ (Townsend & Ashby, 1983, 1978; see also Kajimura et al., 2019) which accounts for changes in both RTs and accuracy data, therefore controlling for potential speed/accuracy trade-offs (see Table 4).

	No Singleton		Singleton Target		Singleton Distractor	
	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>
Sham group	620 (75)	588 (68)	589 (75)	555 (75)	739 (116)	688 (98)
PPC group	631 (50)	590 (42)	610 (44)	560 (39)	728 (81)	645 (57)
mPFC group	620 (56)	577 (46)	593 (61)	554 (47)	711 (99)	659 (77)

Table 4. Mean inverse efficacy scores (iRTs) (and SD), measured as the ratio between RTs and accuracy, by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

In a preliminary analysis, we made sure that participant groups were matched with respect to their baseline performance in the visual search task (pre-tDCS session), and that we could replicate the previously described effect of a singleton distractor on visual search (Fockert et al., 2004; Hodsoll et al., 2009; Theeuwes, 1991) despite we had thought probes for the assessment of mind-wandering embedded in the visual search task. An ANOVA on iRTs (i.e., =RTs/Accuracy) with Stimulation group (PPC, mPFC, sham) and Singleton condition (singleton distractor, singleton target, standard) as factors yielded a main effect of Singleton condition ($F_{2,124} = 231.03$; $p = 0.0001$; $\eta_p^2 = 0.78$). Post hoc comparisons, run with the Scheffè test, showed that iRTs in the Singleton distractor condition ($M = 726$ ms) were significantly longer than those in the Standard condition ($M = 624$ ms; $p = 0.0001$), which in turn were longer than those in the Singleton target condition ($M = 597$ ms; $p = 0.0001$). There was no effect of Stimulation group or Singleton condition x Stimulation group interaction ($F \leq 1.72$; $p \geq 0.19$; $\eta_p^2 \leq 0.05$ in all cases). This analysis confirms that the presence of a singleton distractor interfered with visual search performance, and that participant groups had comparable baseline visual search abilities (see Table 4).

To investigate the effect of tDCS on external attention, we computed a ‘distractor effect index’ subtracting the iRTs to the circle target in the absence of distractors (Standard condition) from those attained in the presence of the singleton distractor (Distractor effect = $iRT_{\text{Singleton distractor}} -$

$iRT_{Standard}$), separately for the pre- and post-tDCS sessions (see Figure 2). The distractor effect was then subject to an ANOVA with Stimulation group (PPC, mPFC, sham) and Session (pre-tDCS, post-tDCS) as factors. There was a significant Stimulation group x Session interaction ($F_{2,62} = 3.88$; $p = 0.03$; $\eta_p^2 = 0.11$). Scheffé post-hoc tests showed that in the pre-tDCS session the distractor effect was comparable across Stimulation groups ($p > 0.83$ in all cases). As predicted, cathodal tDCS over PPC attenuated the distractor effect significantly ($p = 0.001$), whereas no change in the distractor effect was observed from the pre- to the post-tDCS sessions in participants who received sham or mPFC tDCS (both p s > 0.51). The same ANOVA on the effect of a singleton target on visual search (Target effect = $iRT_{Standard} - iRT_{Singleton\ target}$) evinced instead no significant effects ($F \leq 2.30$; $p > 0.15$; $\eta_p^2 \leq 0.10$ in all cases; see Figure 3).

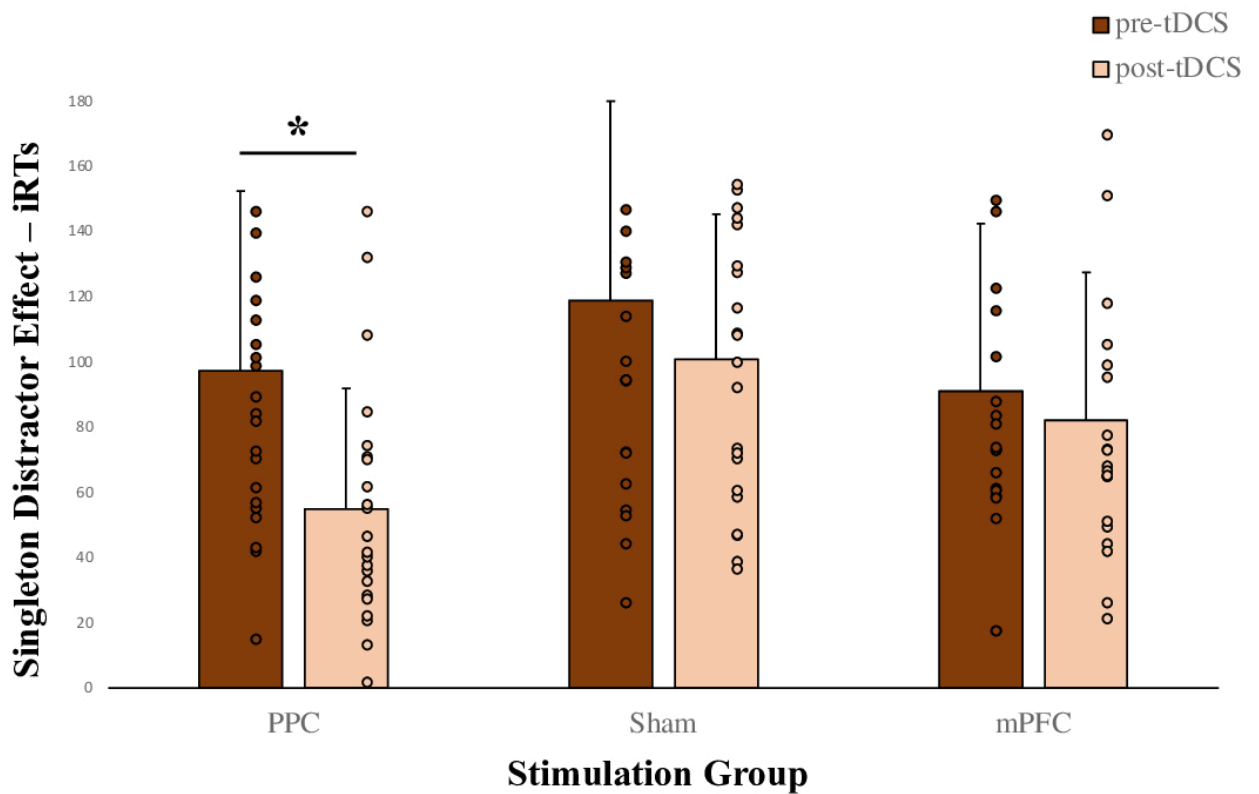


Figure 2. Distractor effect ($iRT_{Singleton\ distractor} - iRT_{Standard}$) by participant group and session. Error bars indicate standard errors of the mean. * $p < 0.05$. Dots indicate the performance of individual subjects.

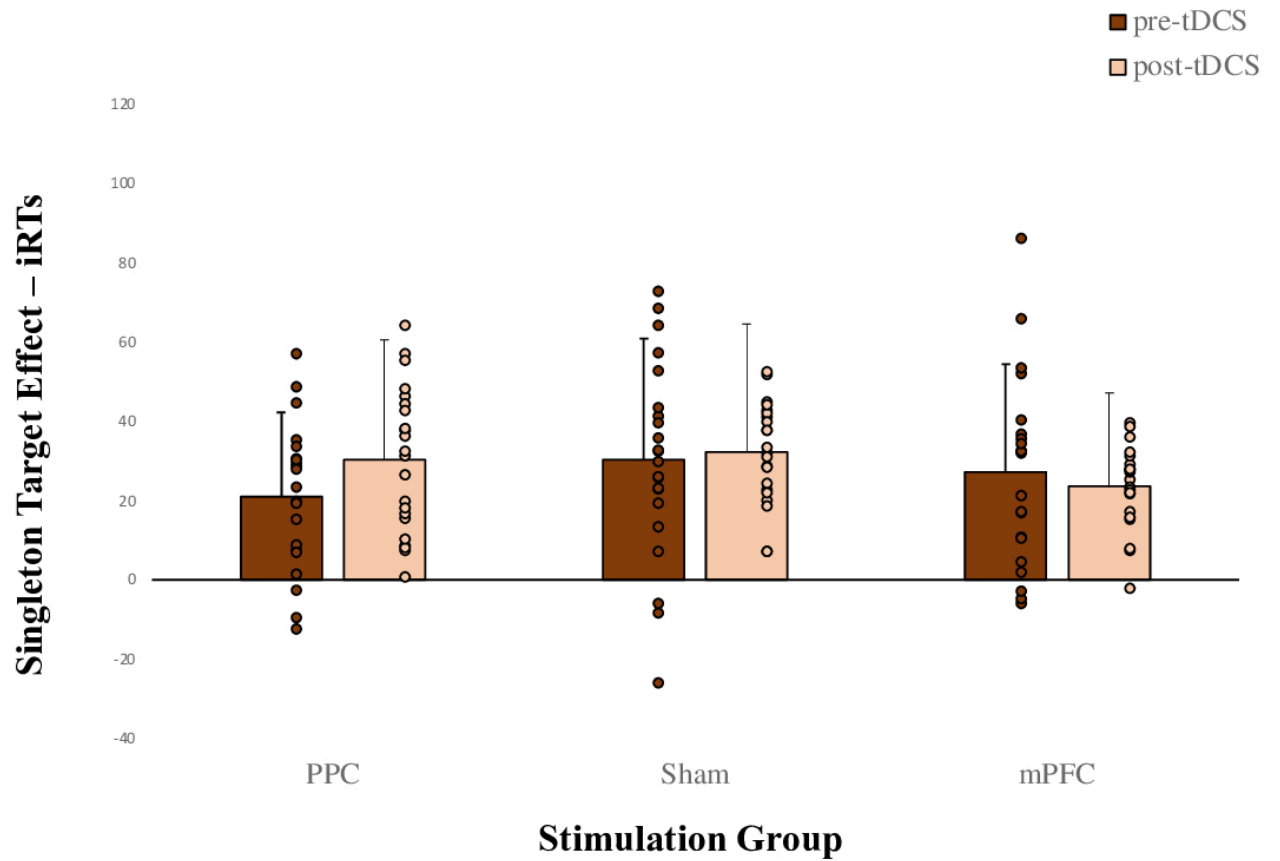


Figure 3. Target effect ($iRTs_{\text{Standard}} - iRTs_{\text{Singleton target}}$) by participant group and session. Error bars indicate standard errors of the mean. Dots indicate the performance of individual subjects.

3.2. Effect of tDCS on mind-wandering

Mind-wandering score. First, we calculated an off-task thought score considering both the frequency of off-task thoughts and their intensity (as assessed with the VAS) by multiplying these variables (we obtain the same findings in all the analyses also if we analyze only the frequency of off-task events, regardless of their intensity), separately for each type of off-task thought and temporal focus (see Table 5).

In a preliminary analysis, we made sure that participant groups exhibited a similar propensity towards different types of off-task thought at baseline (pre-tDCS session; Table 5). The variables were in most cases non-normally distributed (as indicated by visual inspection and the Shapiro-Wilk

test), and therefore the analyses were run with non-parametric tests. We conducted Kruskal-Wallis ANOVAs on the off-task thought score for internal thoughts (mind-wandering), external distractions, and task-related thoughts, separately, and for the different temporal (past, present, future) subcategories of internal thoughts, with Stimulation group as factor. No significant group differences emerged ($H < 3.27$; $p_s > 0.20$ in all cases; Table 5).

	Internal thoughts (mind-wandering)		External distractions		Task-related thoughts	
	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>
Sham group	229 (161)	388 (167)	73 (48)	36 (46)	101 (101)	83 (72)
PPC group	267 (185)	334 (259)	79 (90)	74 (78)	94 (77)	98 (86)
mPFC group	301 (222)	369 (216)	98 (65)	69 (59)	108 (89)	74 (60)

Table 5. Mean off-task thought scores (and SD) by type of off-task thought, participant group, visual search condition. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

We first described off-task score changes between sessions in each group, by comparing the score relative to different types of off-task-thought (Table 5) from the pre-tDCS to the post-tDCS session within each participant group, using the Wilcoxon signed rank tests. Internal thoughts generally increased from the first (pre-tDCS) to the second (post-tDCS) session. This increase in internal thoughts was significant in the sham group ($W = 9.00$; $p = 0.001$), significant but less pronounced in the mPFC group ($W = 55.00$; $p = 0.04$), and present only as a non-significant trend in the PPC group ($p = 0.09$). External distractions decreased significantly across sessions in the sham group ($W = 189.00$; $p = 0.01$) but did not change in the PPC ($p = 0.73$) and mPFC group ($p = 0.08$). Task-related thoughts decreased significantly from the pre- to the post-tDCS session in the mPFC group ($W = 149.00$; $p = 0.03$) but did not change significantly in the PPC ($p = 0.94$) and sham groups

($p = 0.48$). This initial set of analyses show that the passage of time generally resulted in changes in mind-wandering, with internal thoughts that tended to increase with time, and externally-driven forms of thought (external distractions and task-related thoughts) that tended to decrease with time, albeit to a variable degree across groups (Table 5).

We then investigated directly whether tDCS altered the magnitude of these changes. We computed change indices for internal thoughts, external distractions, and task-related thoughts as the difference in off-task scores between the post-tDCS and the pre-tDCS session for each category of off-task thought separately (see Figure 4). We conducted Kruskal-Wallis ANOVAs on each of these change indices with Stimulation group as factor. The ANOVA on the change index for internal thoughts yielded a significant effect of Stimulation group ($H = 7.84$; $p = 0.02$). Post hoc comparisons, performed with the Dunn test, showed that, compared to sham stimulation, cathodal tDCS to both the PPC ($p = 0.01$) and mPFC ($p = 0.04$) attenuated the increase in internal thoughts observed in the post- vs. pre-tDCS session significantly, with no difference between PPC and mPFC stimulation ($p = 0.27$). By contrast, the Kruskal-Wallis ANOVAs on change indices for external distractions and task-related thoughts gave no significant results ($H < 1.55$, $p > 0.54$ in both cases). This second set of analyses showed that inhibition of both mPFC and PPC reduced the normal tendency of internal thoughts to increase across sessions, indicating that both regions are crucially linked to mind-wandering.

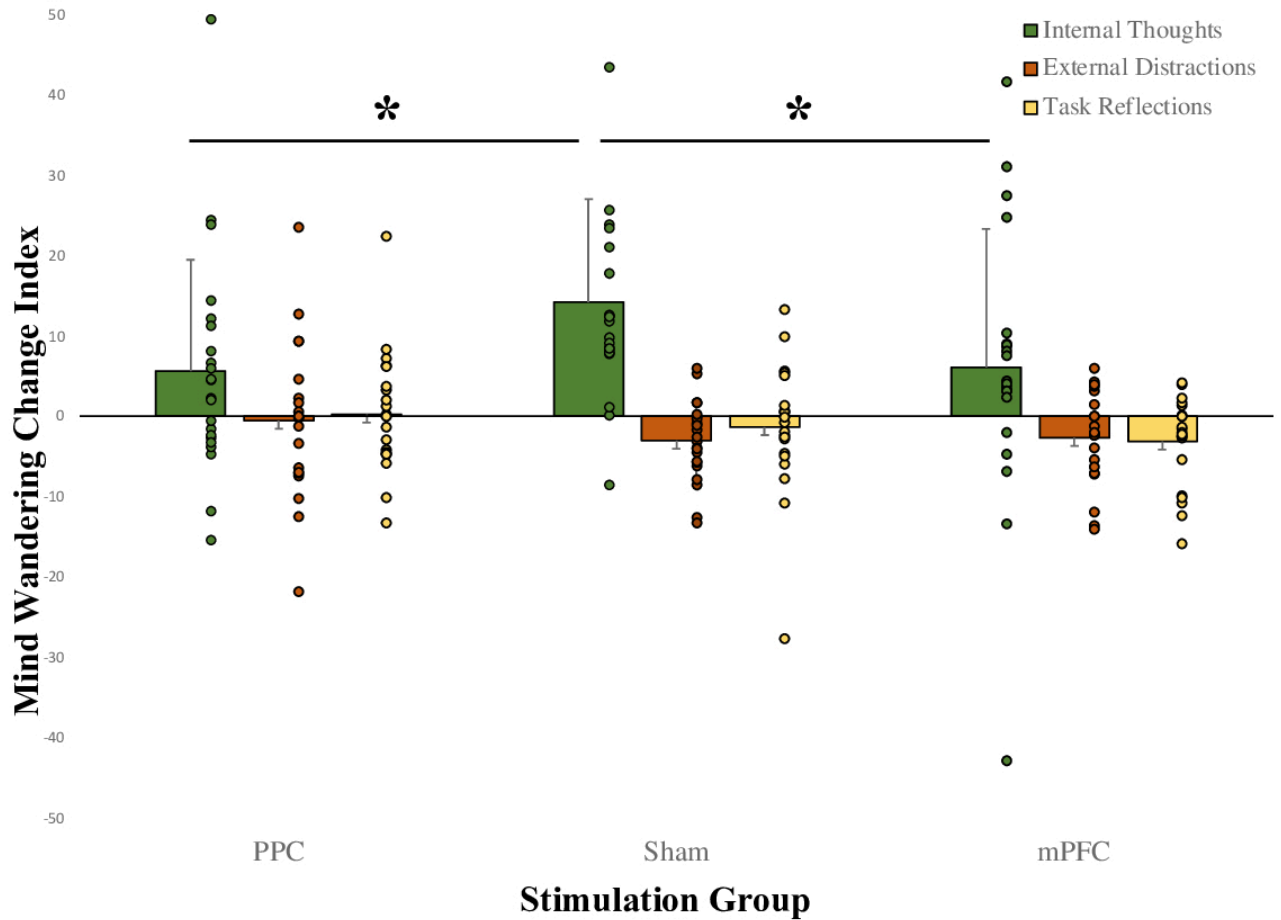


Figure 4. Change index (post-tDCS – pre-tDCS) for Internal Thoughts, External Distractions and Task Reflections by Stimulation Group. Error bars indicate the standard error of the mean. * $p < 0.05$. Dots indicate the performance of individual subjects.

3.2.1. Temporality of mind-wandering

A final observation concerns the temporality of internal thoughts (Supplementary Table 1; Appendix A). The increase in internal thoughts in the Sham group from the pre-tDCS to the post-tDCS session was driven by future-oriented thoughts, which increased significantly across sessions ($W = 9.00$; $p < 0.001$). The increase in future-oriented internal thoughts was also observed in the PPC group ($W = 47.00$; $p = 0.03$), but not significantly in the mPFC group ($p = 0.16$). Internal thoughts with a different temporal focus (past, present, atemporal) did not change significantly between sessions across groups ($W < 93.00$, $p > 0.07$ in all cases). Given that mPFC and the right PPC have been associated respectively with future-oriented (Ciaramelli, Anelli, et al., 2021) and past-oriented self-projection (Anelli et al., 2018), we also analyzed a ‘future thought index’, calculated as the

difference between future-oriented and past-oriented internal thoughts, separately for the pre- and post-tDCS session. We then subtracted the future thought index at the pre-tDCS session from that at the post-tDCS session and compared this difference score across participant groups (see Figure 5). Mann–Whitney tests showed that, compared to sham tDCS, cathodal tDCS of mPFC ($W = 315.00$; $p = 0.04$), but not PPC ($W = 190.00$; $p = 0.23$), reduced the increase in the future thought index observed between sessions, attenuating the tendency of internal thoughts to become more future-oriented from the first (pre-tDCS) to the second (post-tDCS) session, in line with previous reports of reduced future-oriented mind-wandering following mPFC lesions (Bertossi, Aleo, et al., 2016).

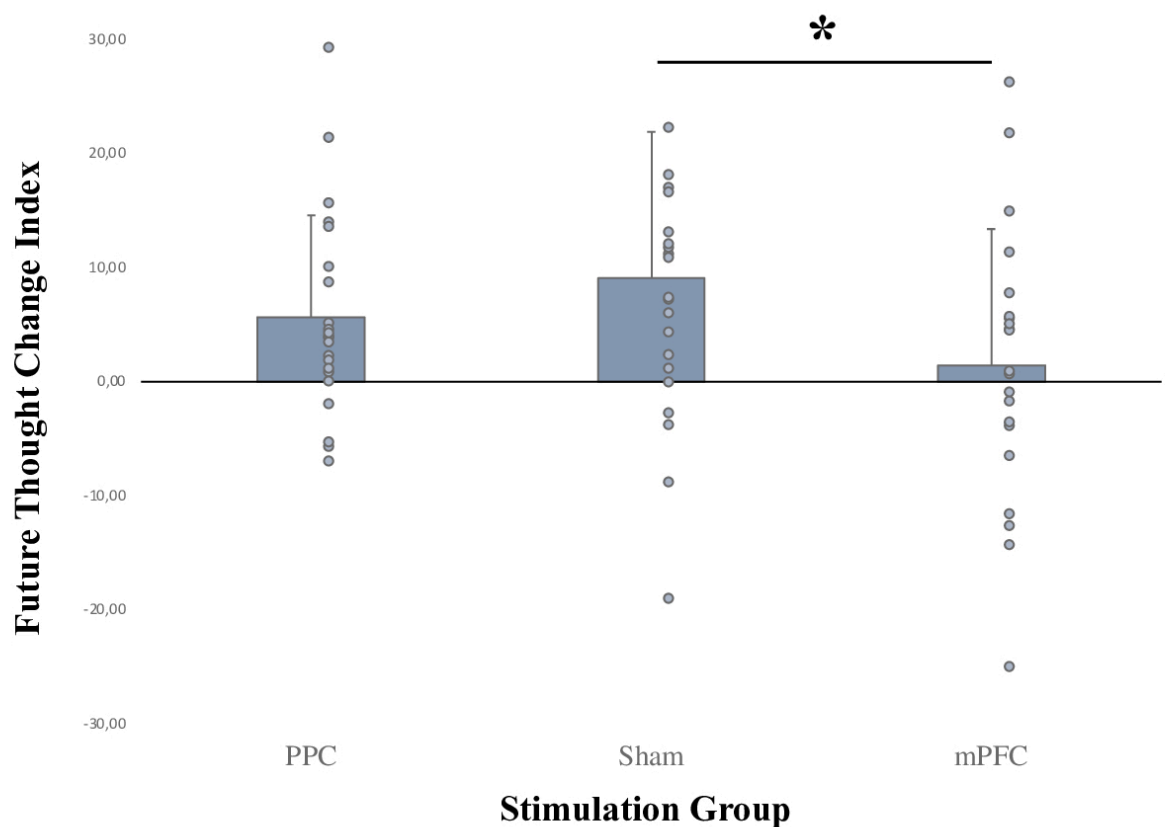


Figure 5. Mean difference in the future thought index between the pre-tDCS and the post-tDCS session by stimulation group. Error bars indicate the standard error of the mean. * $p < 0.05$. Dots indicate the performance of individual subjects.

4. Discussion

The present study assessed the neural bases of the attentional capture by external and internal information by interfering with the activity of the right PPC and mPFC during a visual search task that allowed the concomitant evaluation of the two types of distraction.

First, we replicated previous findings (Hodsoll et al., 2009; Mevorach et al., 2006) that the presence of a color singleton distractor caused significant visual search costs, despite the insertion of thought probes that modified the original structure of the task (Hodsoll et al., 2008). These findings are consistent with a capture of attention by the colored distractor, which interferes with target detection. Notably, the detrimental effect of the distractor on visual search was reduced following cathodal tDCS of the right PPC. In the PPC stimulation group, indeed, distractor-induced performance costs decreased significantly from the pre- to the post-tDCS session, as if the distractor were less capable to capture attention bottom-up. The same decrement of distractor-induced performance costs was not present in participants receiving mPFC or sham tDCS. These findings reinforce the view that right PPC is implicated in mediating automatic shifts of attention to task-irrelevant external information. By contrast, our findings argue against a role for mPFC in external distraction.

Next, we found that individuals mind-wandered intensely during visual search, which mainly involved generating endogenous thoughts unrelated to the task (internal thoughts; see [Bertossi et al., 2017](#); [Killingsworth & Gilbert, 2010](#); [Smallwood & Schooler, 2015](#)). Mind-wandering interfered with the ongoing task (see also [Franklin et al., 2011](#); [McVay & Kane, 2010](#); [Smallwood et al., 2007](#)): a supplementary analysis showed that individuals indeed were faster and less accurate in trials preceding intense vs. weak mind-wandering reports, which is indicative of more impulsive responding (see Supplementary Materials; Appendix A). Across participant groups, internal thoughts tended to increase from the pre- to the post-tDCS sessions (see also [Bertossi et al., 2017](#)). This is presumably because, with time, participants generally became more efficient in the task, or bored, and dedicated more resources to mind-wandering (Mittner et al., 2016; Smallwood et al., 2003).

Crucially, this increase of mind-wandering was attenuated by cathodal tDCS, whether it was delivered to mPFC, as predicted, or even to PPC, suggesting that both regions are associated with the generation of mind-wandering.

As a core region of the default network (Stawarczyk, Majerus, Maj, et al., 2011), the mPFC is an important neural substrate of mind-wandering (J. R. Andrews-Hanna, Reidler, Huang, et al., 2010; Christoff et al., 2009; K. C. R. Fox et al., 2015). This evidence is corroborated by lesion studies showing reduced (future-oriented) mind-wandering in vmPFC patients (Bertossi & Ciaramelli, 2016; see also Bernhardt et al., 2014; O’Callaghan et al., 2019; Philippi et al. 2021). vmPFC patients are also impaired in the voluntary construction of complex events, with a more prominent impairment of future event construction (Bertossi, Aleo, et al., 2016; Bertossi, Tesini, et al., 2016; McCormick, Ciaramelli, De Luca, et al., 2018). For example, Bertossi et al., (2016) found a reduced experiential index while constructing future compared to atemporal scenarios in vmPFC patients but not in control patients and healthy controls. Ciaramelli et al. (2021) showed a selective impairment in self-projection towards a future (compared to past or present) time perspective and in the recognition of future (compared to past) events in vmPFC patients compared to healthy and brain-damaged controls, highlighting the role of vmPFC in future-oriented cognition (Stawarczyk & D’Argembeau, 2015). It is possible, therefore, that vmPFC contributes to the construction of the (future-oriented) mental contents that typically populate mind-wandering, possibly by mediating schema-related knowledge driving event construction (Ciaramelli et al., 2019; Ciaramelli & Treves, 2019; D’Argembeau, 2020; Moscovitch et al., 2016). On this view, the tDCS-induced inhibition of mPFC downregulated mind-wandering by reducing the quality of constructed (future) events, rendering them less capable to draw attention inward. Consistent with this hypothesis is the present evidence that cathodal tDCS over mPFC reduced future-oriented mind-wandering relatively more than past-oriented mind-wandering (as in Bertossi et al., 2017), which aligns with the asymmetry in future vs. past event construction observed in vmPFC patients (Bertossi & Ciaramelli, 2016; see also Ciaramelli et al., 2021). An alternative view is that mPFC mediates the meta-awareness associated with mind-wandering, that is,

the explicit knowledge about the current contents of thought (J. Schooler et al., 2011). On this view, inhibition of mPFC would reduce the frequency with which people become aware of, hence report, mind-wandering (Smallwood & Schooler, 2015). Were this the case, however, cathodal tDCS of vmPFC should cause a general underreporting of off-task experiences, including task reflections and external distractions, while we observed a selective reduction of internal thoughts.

Our results show that also cathodal tDCS of the right PPC reduced mind-wandering compared to sham stimulation, suggesting that the right PPC is necessary to direct attention towards internal, in addition to external, information. This findings aligns with recent models of attention that maintain that the right PPC mediates the flexible allocation of attentional resources between external and internal information depending on the relative salience of percepts and mental contents (i.e., memories, personal goals, current concerns), modulating the activity and functional connectivity with the ventral attention network and the default network (Christoff et al., 2016; Ciaramelli & Moscovitch, 2020; Cabeza et al., 2012; Corbetta et al., 2008; Kajimura et al., 2019; Mittner et al., 2016). Of course, one could argue that because both types of active tDCS led to a reduction in mind-wandering, inhibiting any other brain region would do as well. We do not think this is likely. First, in a previous tDCS study, inhibiting the occipital cortex did not affect mind-wandering (Bertossi, Peccenini, et al., 2017). Moreover, the present study evinced some evidence of regional specificity, with the inhibition of mPFC, but not PPC, attenuating future-oriented more than past-oriented mind-wandering. This finding is compatible with the idea that during mind-wandering the right PPC mediates attention to salient internal information (regardless of its temporal focus; see also (M. E. Berryhill et al., 2007; Ciaramelli et al., 2010), whereas mPFC mediates the construction of future-oriented mental contents capable to capture attention. An interesting question for future research pertains to the differential roles of the right and left PPC in mind-wandering. Previous evidence suggests a more prominent role of the right PPC in directing attention to external stimuli (Corbetta & Shulman, 2002), and of the left PPC in directing attention to internal sources of information (e.g., memories; Ciaramelli et al., 2008; Ciaramelli & Moscovitch, 2020), but our data argue for a role of

the right PPC in mind-wandering as well. Interestingly, [Kajimura et al. \(2019\)](#) found that while during rest the right PPC (angular gyrus) was involved in the inhibition of mind-wandering and the left PPC in the generation of mind-wandering, during a task both right and left PPC were associated with the generation of mind-wandering. Future studies should investigate whether the left and right PPC play crucial and different roles in mind-wandering, for example testing mind-wandering in patients with lesions to the PPC.

We end by commenting on the limits and future developments of this study. First, we found that tDCS of PPC and mPFC reduced mind-wandering, especially towards the future, but not other forms of off-task thought such as external distractions and task-related thoughts. While this finding is generally consistent with our hypotheses, it is worth noting that future-oriented mind-wandering was the most prominent type of off-task thought in our study, hence the one more likely to be influenced by tDCS. Future studies should try to promote alternative types of off-task experience (e.g., external distractions or task-related thoughts) or past-oriented mind-wandering (e.g., through a memory induction technique), and verify whether inhibiting the activity of mPFC would still result in a most pronounced effect on future-based mind-wandering. Another future development of this study would be to move beyond a specific region approach (e.g., inhibiting PPC or mPFC) and consider a network-based approach, for example to assess inter-regional coupling (e.g., [Hampstead et al., 2014](#); [Kajimura et al., 2019](#)), or inhibit multiple nodes of distributed brain networks supporting the interaction between external distraction and mind-wandering (e.g., ventral attention network, default network; e.g., [Turrini et al., 2023](#); [Hebscher et al., 2021](#)).

To conclude, this study shows that the right PPC and mPFC play a crucial role in directing attention to task-irrelevant internal or external information, though the nature of the involvement in distraction is different in each case. The PPC supports both internal and external distraction, possibly by implementing the disengagement of attention from the current task and its reorienting to salient information, be this a percept or a mental content. The mPFC is uniquely involved in internal distraction, allowing the mind to wander away from the task at hand towards endogenously generated

thoughts, mainly about the future. The operation of these two regions, and of the more distributed networks they participate in, supports the adaptive orchestration of attentional resources between the outer and inner (memory) space, warranting perception, introspection, and their interaction.

Chapter 2.

Spontaneous thought:

content regulation and meta-awareness

In Chapter 1, we were able to identify some key neural substrates underlying internal and external attention. In Chapter 2, instead, we will primarily focus on the phenomenology of spontaneous thought.

From the introduction, we have understood that mind-wandering is not only problematic, but can sometimes be *adaptive*. One of the main functions of mind-wandering, in this sense, is autobiographical planning—thinking about one's future, which is closely tied to personal goals. We have also highlighted that mind-wandering can occur with or without meta-awareness, and that aware vs. unaware forms of thought are associated with distinct functional outcomes.

In the section on neural bases, we learned instead that high-level knowledge structures (e.g., schemata) have been associated with the emergence of spontaneous thought. We have also understood that some of these schemata, e.g., the *self-schema* - play a special – distinctive – role in determining the way we shape the reality that surrounds us.

Building on these assumptions, the aim of this project was to investigate whether it is possible to trigger the activation of relevant - schematic - representations in a lab setting to induce more adaptive -future-oriented - forms of spontaneous thought.

Study 2.

Face the future!

How the Self and Time shape mind-wandering

Giovanni Cantarella^{1,2}, Alberto Massimiliano Umiltà¹, Debora Stendardi^{1,2},
Eleonora Bonifazi², Agnese Tarantelli², Elisa Ciaramelli^{1,2}

¹ *Department of Psychology 'Renzo Canestrari', University of Bologna, Bologna, Italy*

² *Center for Studies and Research of Cognitive Neuroscience, University of Bologna, Cesena, Italy*

Abstract

Adaptive mind-wandering is mostly self-related and future-oriented. This study investigates whether the activation of the Self (vs. another person's) schema and of a representation of the future (vs. present) time is followed by changes in the frequency and content of aware and unaware mind-wandering. Four groups of healthy young adults viewed their current face (Present Self condition) or aged face (Future Self condition), or the current (Present Other condition) or aged face of a famous person (Future Other condition) and attributed personality traits to the individual they viewed. Participants then engaged in a Choice Reaction Time task with concomitant assessment of self-caught (aware) and probe-caught (unaware) mind-wandering. We found that viewing an older compared to a younger face was associated with higher rates of aware mind-wandering, while viewing one's own compared to someone else's face was associated with higher rates of unaware mind-wandering, involving self-related and future-oriented thoughts. These findings show that both Self and time concepts are associated with the frequency and content of off-task thought, with dissociable effects on aware and unaware forms of mind-wandering.

1. Introduction

"Our minds contain multitudes, with thoughts and feelings that ebb and flow like the tide, sometimes pulling us in one direction, sometimes in another" (Jonathan Haidt, 2006).

As we navigate through the conscious human experience, the ever-changing nature of our spontaneous thoughts renders them a constant flux. Mind-wandering - i.e., the tendency to drift away from the current task towards task-unrelated/irrelevant thoughts - occurs frequently, accounting for 20 to 50 percent of our daily contemplative time, and consists mainly of memories, personal concerns, and plans for the future (Kane et al., 2007; Killingsworth & Gilbert, 2010; Song & Wang, 2012). Mind-wandering is mediated by a network of brain regions (*the default mode network, DMN*; (J. R. Andrews-Hanna, Reidler, Huang, et al., 2010; Christoff et al., 2009; Mason et al., 2007), including the hippocampus and the ventromedial prefrontal cortex, which are also connected to memory and future thinking (Schacter et al., 2008; Schacter & Addis, 2007; Stawarczyk et al., 2011; Buckner, 2010).

Although mind-wandering is frequently perceived as detrimental, its widespread occurrence suggests that it might confer advantages for our species (Schooler et al., 2011; Smallwood & Schooler, 2006). In line with this view, several studies have shown that in young adults the content of mind-wandering is mostly goal-oriented, self-relevant and future-directed (Baird et al., 2011; D'Argembeau et al., 2011; Smallwood et al., 2009; Song & Wang, 2012; Stawarczyk, Majerus, Maj, et al., 2011). For example, Baird et al. (2011), investigated participants' thought patterns in terms of temporal focus and cognitive orientation (self-related or goal-directed), to characterize the prevalence of mind-wandering episodes during an undemanding task (Choice Reaction Time; CRT). First, participants' thoughts were mainly future-oriented when they reported being off-task compared to when they were on-task, indicating a propensity for prospective thinking during mind-wandering. Then, a detailed analysis of the content of off-task thoughts revealed that future-oriented mind-wandering involves a combination of self-relevant and goal-oriented content, and that individuals

with higher working memory scores have an increased tendency to engage in future- rather than present- or past-oriented mind-wandering, suggesting that during undemanding activities cognitive resources are deployed in the service of prospective thinking. The prospective nature of mind-wandering may have functional implications (Smallwood, Schooler, et al., 2011), allowing for future planning and contemplation, and the potential adaptive modulation of behavior (Bar, 2007; Boyer, 2008; D. T. Gilbert & Wilson, 2007; Wheeler et al., 1997). For example, individuals with a high propensity to mind-wander show reduced delay discounting (Smallwood et al., 2013) and increased volume in ventromedial prefrontal cortex (Bernhardt et al., 2014). On the other hand, clinical populations exhibit anomalies in mind-wandering, such as rumination (Christoff et al., 2016; Watkins, 2008) and a diminished tendency for thoughts to be future-oriented (Smallwood & O'Connor, 2011). Moreover, in general it may be difficult to steer the contents of mind-wandering towards desired as opposed to unpleasant contents, to the point that people may refrain from periods of rest allowed to think (Killingsworth & Gilbert, 2010).

One important question, then, is whether it would be possible to foster self-relevant, future thinking during mind-wandering by probing the activation of the self-schema and of a representation of the future time. In this regard, Smallwood et al., (2011) had participants view a sequence of 32 trait adjectives (N. H. Anderson, 1968) on a computer screen. Participants were then asked whether these adjectives applied to a specific referent (i.e., themselves, their best friend, or the UK prime minister). The presentation of experience-sampling probes allowed to assess participants' mind-wandering while they were engaged in an ongoing, low-demanding task (CRT). Reflecting on one's own personality resulted in an increase of future-oriented thoughts during subsequent periods of off-task mental activity. Hence, a brief period of self-reflection increased the prospective bias in mind-wandering, confirming the link between self-referential thought and future thinking.

Another key feature of mind-wandering is its relation with meta-awareness, i.e., the moment at which we realize that our mental experience has departed from the task at hand (Schooler, 2002;

Schooler et al., 2004). Research in this field has highlighted that individuals frequently overlook their own wandering minds (Schooler, 2002; Schooler et al., 2004) and that several factors can influence the occurrence of mind-wandering and its recognition (Baird et al., 2013; Sayette et al., 2009; 2010; Reichle et al., 2010). First, aware versus unaware forms of mind-wandering differ in their impact on performance and their content (Smallwood & Schooler, 2015). For example, unaware mind-wandering has been linked to higher depression levels (Nayda & Takarangi, 2021) and more substantial interruptions in daily activities than aware mind-wandering (McVay et al., 2009). Second, a stronger neural recruitment of the DMN and the executive network has been shown in unaware compared to aware mind-wandering, complementing the behavioral evidence that mind-wandering is most disruptive to concurrent task performance when it lacks meta-awareness (Christoff et al., 2009).

To test whether probing the representations of the Self and of the future would steer the contents of mind-wandering, we had four groups of healthy young adults view their current face (present self condition), aged face (future self condition), the current face of famous person of a similar age (present other condition), or the aged face of the same famous person (future other), and attributed personality traits to the individual viewed. Participants then performed a CRT task with concomitant assessment of the frequency of both aware (self-caught) and unaware (probe-caught) mind-wandering and of its content, including self-relatedness and temporal focus. We hypothesized that viewing one's own face, and especially its older version, would increase future-oriented, self-focused mind-wandering. Investigating this effect on both aware and unaware mind-wandering can help further elucidate the role of meta-awareness in spontaneous thought (Smallwood & Schooler, 2015).

2. Methods

2.1. Participants

One-hundred-eleven young adults (73 females) aged 18 to 35 years (mean age = 22.28, SD = 5.86), and with a mean level of education of 15.74 years (SD = 1.81), were recruited from among the students of an introductory course of Psychology at the University of Bologna. Participants were randomly assigned to one of 4 groups: the *present-self* group (N = 27, mean age = 21.93, mean education = 15.85), the *present-other* group (N = 29, mean age = 22.32, mean education = 15.68), the *future-self* group (N = 28, mean age = 22.76, mean education = 15.69), and the *future-other* group (N = 27, mean age = 22.11, mean education = 15.74). Participants groups did not differ in age [$F(3,107) = 0.522$; $p = 0.668$], education [$F(3,107) = 0.051$; $p = 0.985$], and females/males' ratio ($\chi^2 = 1.226$; $p = 0.747$). This sample size was estimated through a power analysis run with the G*Power software (v. 3.1.9; [Faul et al., 2007](#)). Based on the results of a previous study (Smallwood, Schooler, et al., 2011) we estimated an effect size of 0.16 for the effect of temporal focus, with a significance level $\alpha = 0.05$, and a desired power $(1-\beta) = 0.80$. Participants gave informed consent to participate in the study, which was approved by the Bioethical Committee of the University of Bologna and carried out in agreement with international norms (Declaration of Helsinki 1964).

2.2. *Materials and Procedure*

The experimental procedure was comprised of two (seemingly unrelated) computerized tasks: a face and adjective task and a choice reaction time (CRT) task (*see Fig. 1*).

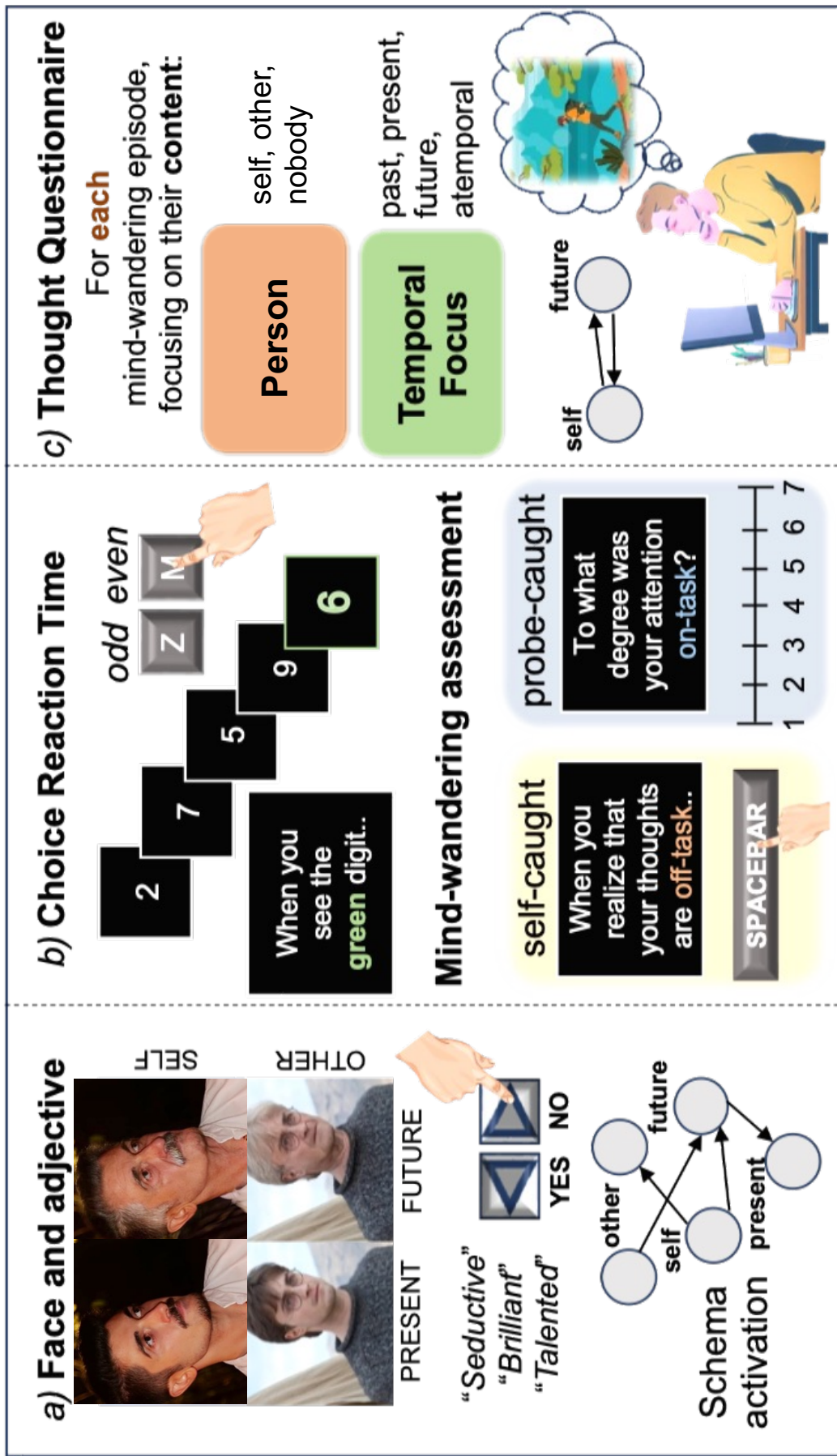


Figure 1. Illustration of the experimental procedure. a) Face and adjective task and the concomitant activation of schematic knowledge b) Choice Reaction Time and experiential assessment of mind-wandering. c) Thought Questionnaire.

2.2.1. *Face and adjective task*

The face and adjective task was a modified version of the trait and adjective task by Sanders et al., (2017). In this task, depending on the experimental group, participants saw their face (present-self group), their aged face (future-self group), the face of a famous individual their age (*Daniel Radcliffe* for males, *Emma Watson* for females; present-other group), or the aged face of the same famous individual (Daniel Radcliffe/Emma Watson; future other group). We created the aged faces (i.e., to look approximately 50) of all our participants and of Daniel Radcliffe and Emma Watson through the app *FaceApp*.

After seeing their own or the other's current or aged face, participants saw a list of 32 adjectives (16 positive and 16 negative; e.g., “seductive”, “talented”, “irritable”, “inconclusive”; see also Anderson, 1968), which were presented on the screen in randomized order at a rate of one every 6 seconds. Participants were instructed to indicate, for each adjective, whether they thought it was descriptive of the person they just saw, by pressing directional keys for “yes” or “no.” Participants were told that we were interested in exploring how people attribute personality traits to themselves as opposed to others. In fact, by using this task we aimed at activating self vs. other schemata, and a representation of the present vs. future time (see the Materials section below).

2.2.2. *Choice Reaction Time task and experimental assessment of mind-wandering*

Participants then underwent a CRT task adapted from previous studies (Bertossi, Peccenini, et al., 2017; Bertossi & Ciaramelli, 2016; Smallwood, Schooler, et al., 2011). In the CRT task, participants see a stream of digits (1-8), each appearing in the center of the screen, written in black (non-targets) or, more rarely, in green ink (targets), and they are required to indicate whether each target green number was even or odd. Stimuli were arranged in ten randomized blocks, containing 5

targets and 35 non-targets each, and presented at a rate of 1 item every 1000 ms, preceded by a 1500 ms fixation cross.

Mind-wandering was assessed through both a “self-caught” and a “probe-caught” measure (J. Schooler et al., 2011; Smallwood & Schooler, 2006). First, participants were required to press the spacebar whenever they noticed their attention was drifting away from the task at hand (*self-caught measure*). When they did, a question mark appeared on the screen that probed them to report on the content of their thoughts by typing a short sentence on the screen (e.g., “*it rains, and I don’t have an umbrella*”). In addition, 10 thought probes sampled participants’ thoughts during the CRT task (*probe-caught measure*), one for each block. A first screen probed participants to rate the degree to which, immediately before the probe, their attention was *on-task*, i.e., focused on performing the CRT task, or *off-task*, i.e., focused on something unrelated to task execution (levels of off-task thought), by using a Likert scale from 1 – “completely on-task” to 7 – “completely off-task”. If the answer was ≥ 2 , they then described the content of their thoughts in a short sentence (as for the self-caught measure). In a second screen, participants classified their off-task thoughts into 3 qualitative categories: (1) internal thoughts (i.e., mind-wandering; thoughts unrelated to the task and originated endogenously; e.g., “I am so going for a walk after this!”), (3) task-related thoughts (i.e., thoughts triggered by the task though not related to doing the task; e.g., “this task is so boring”), and (4) external distractions (i.e., thoughts triggered by external stimuli; e.g., “Was that a thunder?”).

The thought probe appeared in every block at trial 11 (in a fixed manner) if participants had not reported any self-caught thoughts earlier in the block. To avoid sampling the same off-task thought repeatedly, the insertion of the thought probe within each block was constrained to follow any self-caught report of off-task thought by 9 trials. Moreover, if participants signaled more than 4 self-caught off-task thought events in a block, then no thought probe was presented in that block.

2.2.3. Thought Questionnaire

At the end of the CRT task, participants received a link to a Qualtrics page (Qualtrics, Provo, UT) to answer additional questions about the thoughts they had during the CRT task. Participants were presented with the short labels they had provided for each off-task thought they had experienced, and required to state whether each thought was (5) self-related (e.g. “I still have to decide what I will do after my PhD”), (6) other-related (e.g. “My uncle is going through a hard time”); (7) unrelated to people (e.g. “The weather is getting better”), and whether it pertained to the (8) past (e.g., “Last summer I skipped vacation”), (9) present, including the current period of one’s life (e.g. “I wonder what is happening upstairs”; “my friend is going through a hard time), (10) future (e.g., “Next week I will celebrate my graduation”), or (11) it was atemporal (e.g., “Lab experiences are always very inspiring”).

In addition, at the end of the CRT task, participants were asked to self-report the overall level of boredom (on a Likert scale, ranging from 1 to 7) they had experienced during the task.

3. Results¹⁹

3.1. *Frequency of mind-wandering*

3.1.1. *Self-caught mind-wandering*

We conducted a repeated measures Analysis of Variance (ANOVA) on the number of self-caught off-task thoughts, with Time (present, future) and Self (self, other) as between-subject factors, and Type of thought (internal, external, task-related) as within-subjects factor. Since the distributions of self-caught thoughts violated the assumption of sphericity, we applied the Greenhouse-Geisser correction to prevent an increase in false positive rate. The analysis yielded a main effect of **Type of thought** [$F(1.586) = 8.081$; $p = .001$; $\eta_p^2 = .070$]: participants reported more internal thoughts (mean =

¹⁹ For Supplementary Results, see Appendix B.

3.35) than external distractions (mean=2.30; $p < .001$) and task-related thoughts (mean= 2.49; $p < .001$). This effect was qualified by a significant interaction **Type of Thought*Time** [$F(1.586) = 5.395$; $p = .009$; $\eta_p^2 = .048$]: post-hoc tests (Holm corrected), showed that more internal thoughts were experienced after viewing an older face (i.e., future-self and future-other conditions; mean = 3.98) compared to a young face (i.e., present-self and present-other conditions; mean = 2.72, $p = .033$), whereas task-related thoughts and external distractions were not modulated by seeing an older vs. young face ($p > .99$ in all comparisons). Moreover, whereas after seeing a young face participants had similar rates of internal thoughts, external distractions and task-related thoughts (all $ps. > .65$), after viewing an older face participants had more endogenously triggered (internal) thoughts (mean=3.98) than external distractions (mean= 2.3; $p < .001$) or task-related thoughts (mean= 2.35; $p < .001$) (see *Fig. 2*). The between-subject factors Time [$F(1.107) = 2.693$; $p = .104$], Self [$F(1.107) = 0.904$; $p = .872$] and the interaction Type of thought*Self [$F(1.586) = .079$; $p = .884$] were not significant.

This first set of analyses shows that seeing an older face, be this one's own or another person's aged face, increases the tendency to have aware self-generated and task-unrelated thoughts (aware mind-wandering), without altering the propensity towards off-task thoughts triggered by external stimuli or the ongoing activity.

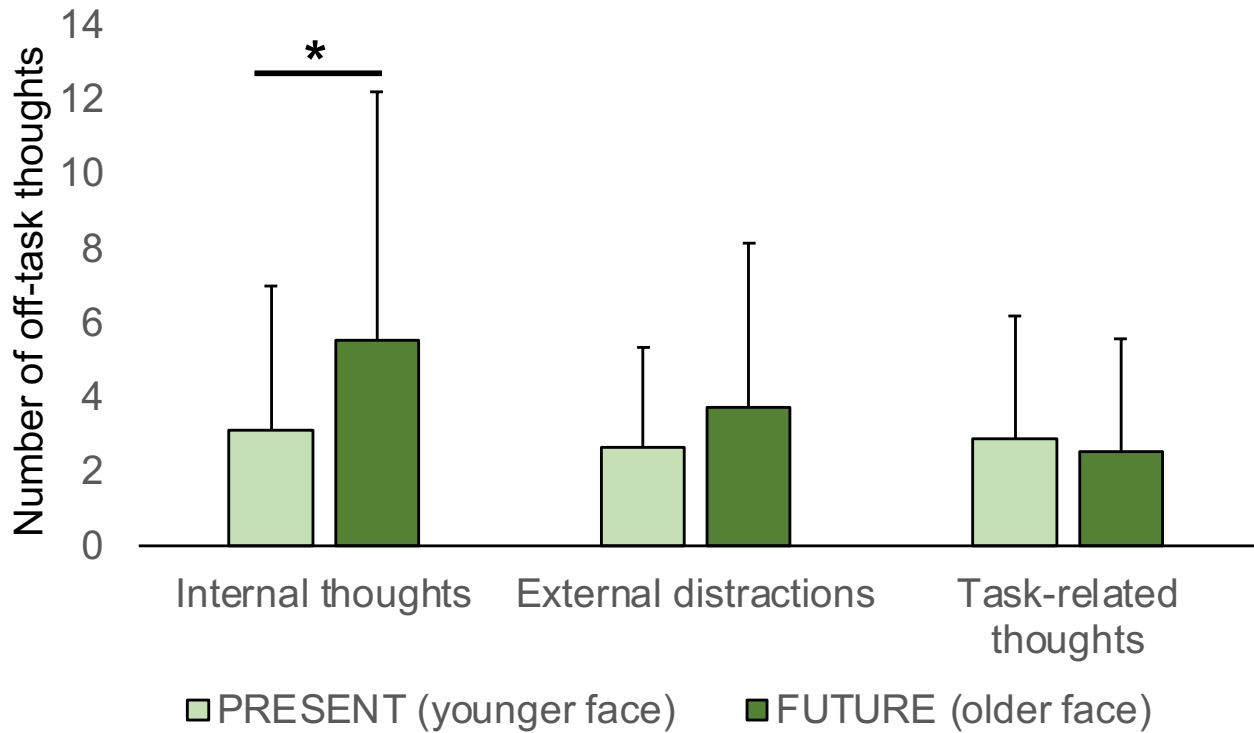


Figure 2. Mean number of self-caught mind-wandering episodes by Time (younger vs. older face) and Type of thought (internal thoughts, external distractions, and task-related thoughts). Error bars indicate standard deviations from the mean. * $p < 0.05$.

3.1.2. Probe-caught mind-wandering

Since not all participants received the same number of probes – that depended on the number of self-caught thoughts reported – we performed the analysis on probe-caught thoughts based on their mean frequency (i.e., number of mind-wandering episodes divided by the number of probes; see Methods) rather than their raw number. Thus, we conducted the same ANOVA on the mean frequency of probe-caught mind-wandering, with Time and Self as between-subject factors. The Greenhouse-Geisser correction was applied to prevent an increase in false positive rate. We found again a main effect of **Type of Thought** [$F(1.872) = 10.750$; $p < .001$; $\eta_p^2 = .091$], indicating significantly higher frequencies of internal (mean = 0.27) and task-related thoughts (mean = 0.24) compared to external distractions (mean = 0.16). This effect was qualified by a significant interaction **Type of**

Thought*Self [$F(1.872) = 3.388$; $p = .039$; $\eta_p^2 = .031$]: post-hoc analyses (Holm-corrected) revealed that participants who had seen their own face (present-self and future-self groups) had more internal thoughts caught (mean = 0.30) than external distractions (mean = 0.17; $p = .002$), while those who had seen the face of another person (present-other and future-other groups) did not show the same increase in the frequency of internal thoughts (mean = 0.24) compared to external distractions (mean = 0.16; $p = .69$). Rather, they had more task-related thoughts caught (mean = 0.28) than external distractions ($p = .008$; see *Fig 3*). The between-subject factors Time [$F(1.107) = 0.0005636$; $p = .981$] and Self [$F(1.107) = 0.006$; $p = .940$] and the interaction Type of thought*Time [$F(1.872) = 2.706$; $p = .073$] were not significant.

This second set of analyses shows that seeing one's own face increases the tendency towards unaware mind-wandering, whereas seeing someone's face increases off-task thoughts related to the ongoing activity.

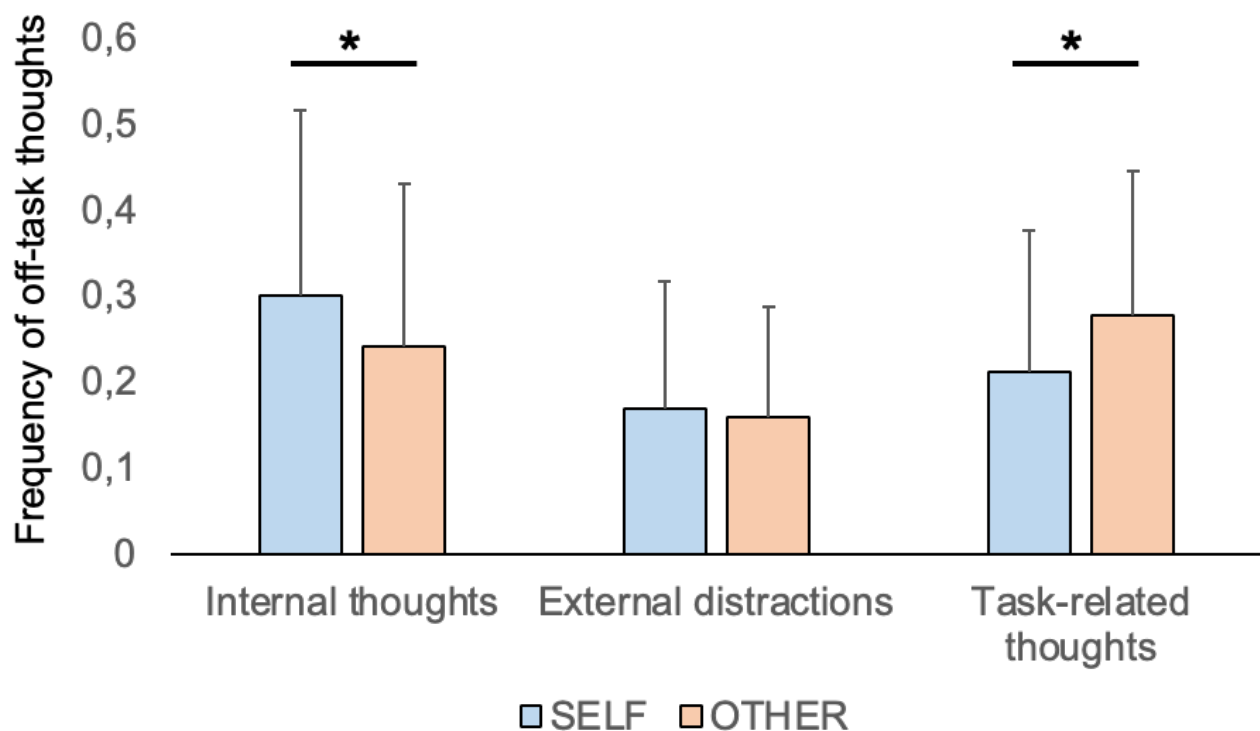


Figure 3. Mean frequency of probe-caught mind-wandering for Self groups (own vs. other's face) by Type of thought (internal thoughts, external distractions, and task-related thoughts). Error bars indicate standard deviations from the mean. * $p < 0.05$.

3.2. Content of mind-wandering: self-relatedness and temporal focus

We conducted additional, confirmatory analyses restricted to internal thoughts (mind-wandering), aimed at testing the effect of activating the Self schema or a representation of the future time (showing older vs. younger faces) on the content of full-fledged mind-wandering events, including self-relatedness and temporal focus.

3.2.1. Self-caught internal thoughts

We conducted a repeated measures ANOVA on the number of self-caught internal thoughts, with Time (younger, older) and Self (self, other) as between-subject factors, and Person (Self, Other, Nobody) and Temporal focus (Past, Present, Future, Atemporal) as within-subjects factors. We applied the Greenhouse-Geisser correction for the values that violated the assumption of sphericity. The effect of **Time** [$F(1.86) = 11.41$; $p = .001$; $\eta_p^2 = .12$] and the effect of **Person** were significant [$F(1.424) = 29.028$; $p < .001$; $\eta_p^2 = .24$] and were qualified by a significant interaction **Person * Time** [$F(4.15) = 3.69$; $p = .04$; $\eta_p^2 = .04$]. Post hoc tests showed that individuals who had seen an older face mind-wandered more about the self (mean = 0.77) than individuals who had seen a younger face (mean = 0.40; $p < .001$) (*see Fig. 4*), whereas there was no effect of Time on thoughts about someone else or none (all $ps > .19$). The effect of **Temporal Focus** was also significant [$F(1.58) = 47.39$; $p < .001$; $\eta_p^2 = .36$], and qualified by a significant interaction **Person * Temporal focus** [$F(2.75) = 27.15$; $p < .001$; $\eta_p^2 = .24$], showing that self-related mind-wandering was more future oriented or present-oriented compared to other-related mind-wandering (*future*: 0.70 vs 0.27, $p < .001$; *present*: 1.23 vs. 0.49, $p < .001$) or mind-wandering focusing on nobody (*future*: 0.70 vs. 0.12, $p < .001$; *present*: 1.23 vs. 0.42, $p < .001$), whereas the frequency of past-oriented and atemporal mind-wandering did not

depend on whether mind-wandering was self-related or not (all p s > .21). No other effects or interactions were significant (p > .11 in all cases).

This set of analyses shows that the content of aware mind-wandering is affected by whether individuals viewed an older vs. younger face: activating a representation of the future- by viewing an older face - led participants to mind-wander more about the self, and to have thoughts mostly oriented towards the present and the future.

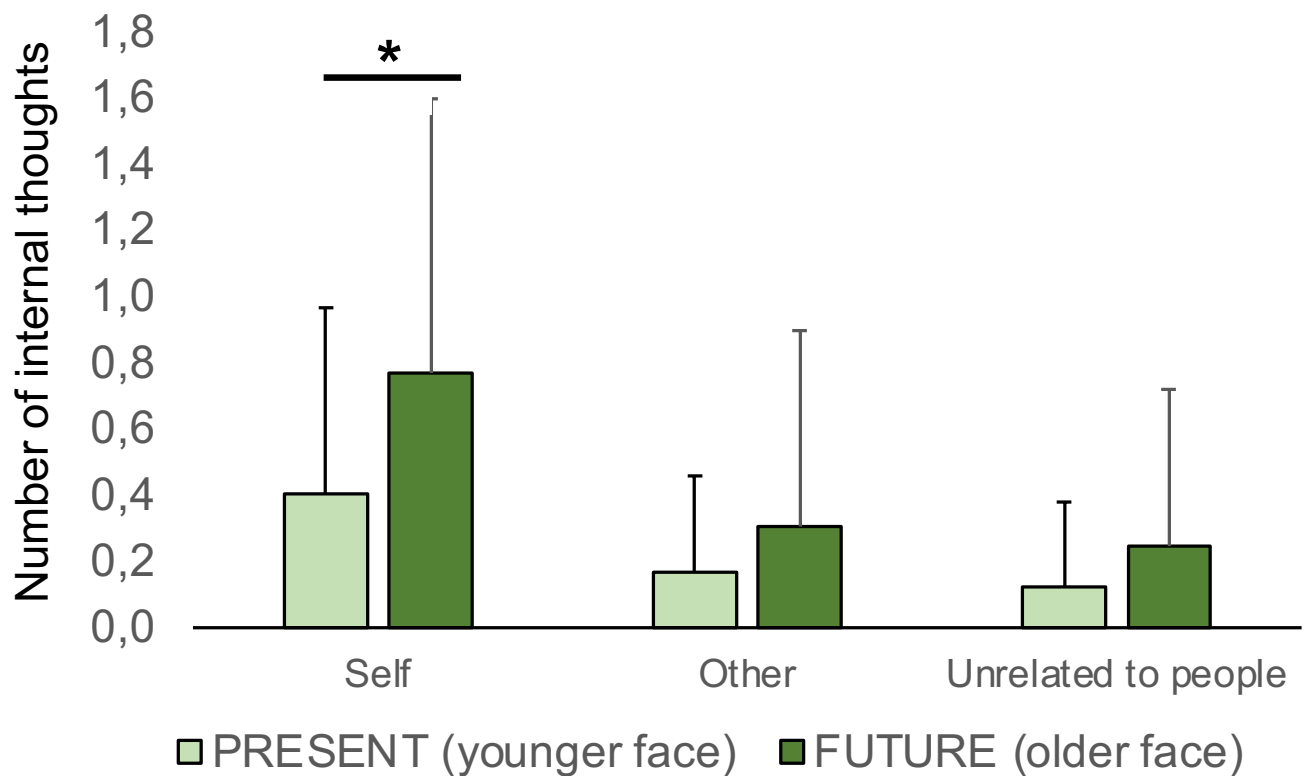


Figure 4. Mean number of self-caught mind-wandering episodes for Time groups (younger vs. older face) by Person (self, other, nobody). Error bars indicate standard deviations from the mean. * p <0.05.

3.2.2. Probe-caught internal thoughts

The same ANOVA on the frequency of probe-caught internal thoughts evinced a significant effect of **Person** [$F(1.537) = 52.1$; $p < .001$; $\eta_p^2 = .33$], and a significant interaction **Person * Self** [$F(1.537) = 3.441$; $p = .046$; $\eta_p^2 = .03$], indicating that participants who saw their own face showed a

higher frequency of self-focused thoughts (mean= 0.06) compared to those who had seen the face of another person (mean= 0.04; $p = .04$), whereas seeing one's own vs. another face had no effect on the frequency of thoughts about someone else or nobody (all $ps > .99$) (see Fig.5). **Temporal focus** was also significant [$F(1.58) = 47.39$; $p < .001$; $\eta_p^2 = .36$], and there was a significant interaction **Person * Temporal focus** [$F(2.544) = 19.620$; $p < .001$], revealing again that self-focused mind-wandering was more future-oriented or present-oriented compared to other-related mind-wandering (*future*: 0.05 vs. 0.02; *present*: 0.11 vs. 0.02, $p < .001$) or mind-wandering focusing on nobody (*future*: 0.05 vs. 0.003; *present*: 0.11 vs. 0.02, $p < .001$), whereas the frequency of past-oriented and atemporal mind-wandering did not depend on whether mind-wandering was self-related or not (all $ps > .17$). No other effects or interactions were significant ($p > 0.17$ in all cases).

This set of analyses shows that the content of unaware mind-wandering is affected by whether individuals viewed their own or someone else's face: viewing one's own face increases unaware mind-wandering about the self, mostly oriented towards the present and the future.

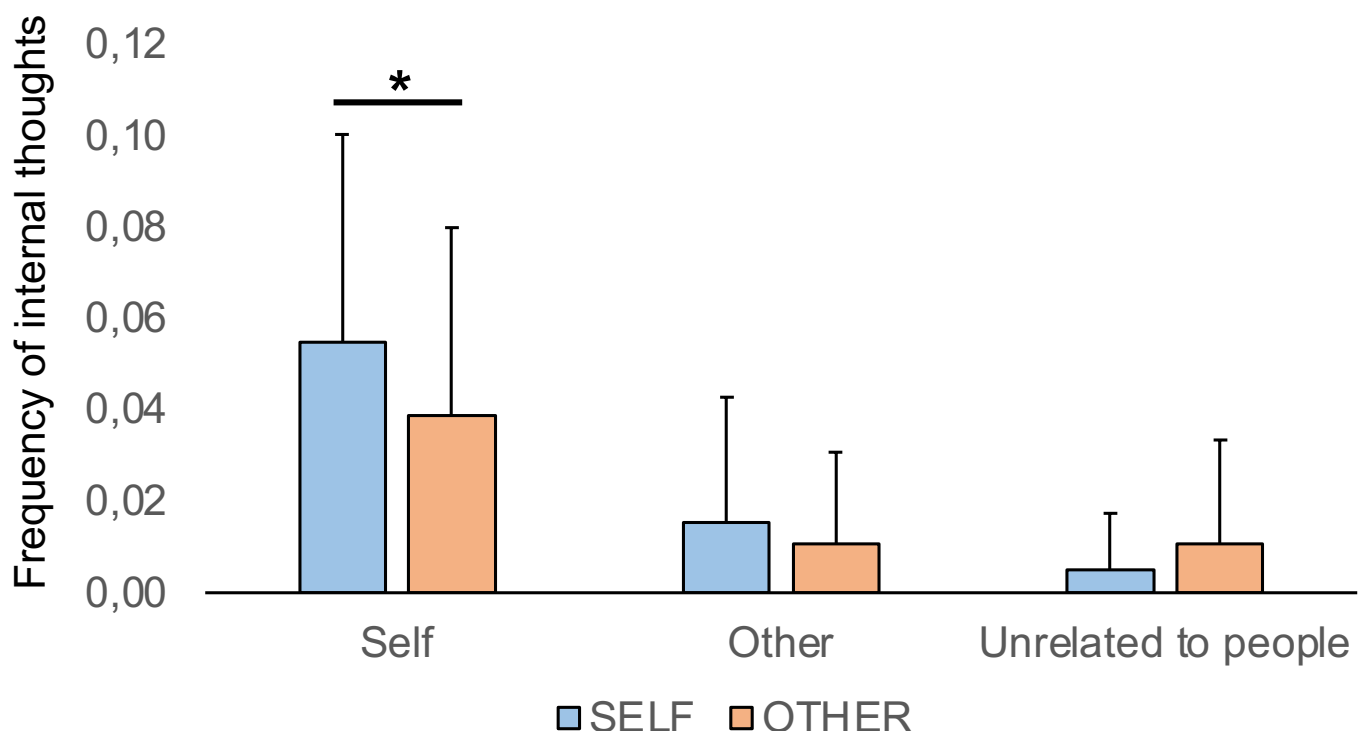


Figure 5. Mean frequency of probe-caught mind-wandering for Person groups (own vs. other's face) by Thought Reference (self, other and nobody in particular). Error bars indicate standard deviations from the mean. * $p < 0.05$.

4. Discussion

The present study tested the hypothesis that probing the representations of the Self and of the future affects the frequency and the content of aware and unaware mind-wandering. Contrary to our hypothesis, viewing an older compared to a younger face increased mind-wandering frequency, regardless of whether the face was one's own or someone's. On the other hand, viewing one's own vs. someone's face increased unaware mind-wandering, regardless of whether it was in its current or aged state. These findings suggest that activating a representation of the future increases propensity for aware mind-wandering, whereas the activation of the Self-schema increases the frequency of unaware mind-wandering. Moreover, viewing one's own (as opposed to someone's) face and viewing an older (as opposed to a younger) face shaped the content of mind-wandering towards being more self-related and future- or present-oriented, confirming a capacity of both the Self-schema and future representations to shape the content of thought. We discuss each of these findings in turn.

First, we demonstrated that activating a representation of the future, by presenting an older vs. a younger face, increases the frequency of self-reported aware mind-wandering, without altering other forms of off-task thought (external distractions and task-related thoughts). Past research employing both forced choice (Smallwood et al., 2009) and content analysis of experience sampling protocols (Baird et al., 2011) had already shown how a considerable proportion of human mind-wandering states consist of future-oriented thoughts. Our results can be interpreted as further evidence of the existing relationship between prospective thinking and spontaneous cognition: the activation of future-oriented schemata might represent the privileged condition under which mind-wandering episodes are triggered.

Second, the increase in internal thoughts after the activation of future-oriented schemata occurred for aware, but not unaware, mind-wandering. This dissociation reinforces the hypothesized relationship between future-oriented thoughts and metacognition. Aware mind-wandering, i.e., the recognition that the experience has occurred (Schooler, 2002; Schooler & Schreiber, 2004; Smallwood & Schooler, 2006), has indeed been suggested to play a self-regulatory function (J. Schooler et al., 2011), whereby the intermittent explicit assessment of the current experience can enable the detection of attentional lapses. Accordingly, the *decoupling hypothesis* (J. Schooler et al., 2011), explains how executive functions are required to coordinate an internal train of thought (particularly, those involving planning or anticipating the future) and to insulate the experience from the disruptive influence of external distractions (Baird et al., 2011; Barron et al., 2011; Schooler et al., 2011; Smallwood, 2010; Smallwood, Schooler, et al., 2011; Smallwood & Schooler, 2006). Participants in our study, thus, after exposure to their aged faces and while engaged in a long and boring task, might have deployed their executive resources to engage in mind-wandering. Different from our predictions, the increase in internal thoughts observed after the exposure to aged faces was found even if the face was not one's own. It is important to note, however, that participants were exposed to faces of famous people their age, and could recognize their aged appearance. It is plausible that reflecting on well-known, aged individuals may have led participants to engage in mind-wandering as well, activating future-oriented schemata.

By contrast, activating the self-schema, whether by presenting an older or younger face, increased unaware mind-wandering and shaped its contents to be more self-related. Previous literature has often interpreted unaware mind-wandering reports as a failure to effectively regulate behavior (Baird et al., 2013; J. Schooler et al., 2011). According to this view, unaware mind-wandering may occur because of a failure to suppress thought: in particular, an effective metacognitive monitoring of thought may be hindered when access to top-down control (and, hence, cognitive resources) is prevented. The emotional salience of thoughts has also been shown to play a role in failures to suppress thought (Baird et al., 2013). Unaware mind-wandering, hence, might reflect some elements

of the ongoing experience that people have difficulties in recognizing or admitting to themselves. Why should activating the Self-schema selectively impact the unaware contents of self-related thought? The response may rely on the intrinsic nature and the emotional saliency of the self-schema (Markus, 1977), since it is a robust cognitive schema (Craig et al., 1999) that can increase mental elaboration. In line with this view, past research (e.g., Daamen et al., 2016; Huijser et al., 2018) reported how self-discrepancy (i.e., reflecting on materials that conflict with the sense of self – in our case, self-related traits and adjectives) triggers elaborative thought in the attempt to solve these discrepancies with the current goals and values, thus interfering with performance on a concurrent - working memory - task. This attempt would be due to people's need for *self-coherence*, a concept that – considering the relationship between self-reference and autobiographical memory (Conway et al., 2004) - has been shown to play a role in informing the individual of personal aims and principles (Barnhofer et al., 2007; Conway et al., 2004; Conway & Pleydell-Pearce, 2000; Wessel et al., 2014). Crucially, both thought suppression – driven by the emotional salience of certain thoughts - and stronger attentional decoupling from the ongoing activity have been associated with unaware mind-wandering (Baird et al., 2013). Building from these assumptions, we suggest that the activation of the Self-schema, along with potential self-discrepancies, might have triggered more intense self-related thoughts. After having reflected on their faces, participants' might have attempted to suppress thoughts and/or resolve self-discrepancies, which might have increased mental elaboration, yet preventing mind-wandering to reach meta-awareness. This speculation, while supporting previous theorization on thought-suppression (Wegner, 1997; Wegner & Zanakos, 1994) and probe-caught thoughts (Schooler et al., 2005; Smallwood et al., 2008), awaits further empirical evidence.

Lastly, activating both the Self-schema and the future, whether by viewing the own face or an aged face, shaped the content of mind-wandering to be more self-related and future- or present-oriented. Smallwood et al. (2011) had already shown how a small period of self-reflection could increase the frequency of prospective probe-caught thoughts. In the present study, we replicated their findings but observed the inverse relation as well: reflecting on the future can actually maximize the

probability of reporting self-related thoughts. This further corroborates the relationship between self-reference and future-oriented mind-wandering (Baird et al., 2011; D'Argembeau et al., 2011; Smallwood, Schooler, et al., 2011).

We conclude by outlining some relevant future directions that arise from the current findings. Considering the importance of spontaneous thinking in determining both long-term benefits (Baird et al., 2011, 2012; Mooneyham & Schooler, 2013) and psychological distress (Burg & Michalak, 2011; Killingsworth & Gilbert, 2010; Smallwood et al., 2007; Smallwood, O'Connor, et al., 2004), it becomes crucial to identify which conditions trigger and maximize the most adaptive forms of mind wandering. In this regard, consistent with the *content regulation hypothesis* (Andrews-Hanna et al., 2014; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015), future research in this field could identify the - internal and external (e.g., current concerns) - circumstances that promote the emergence of aware future-oriented mind-wandering, possibly adopting physiological (e.g., pupil sizes) and/or imaging measures (e.g., resting state functional connectivity). For example, future controlled experimental studies could randomly assign participants to either a self-schema activation condition—using priming with future-oriented, self-relevant cues—or a neutral control condition, while measuring resting state functional connectivity. We expect that those in the future-self group would report a higher frequency of adaptive - future-oriented - thoughts, along with observable physiological changes (e.g., enhanced pupil dilation) and neuroimaging markers (e.g., increased functional connectivity between the DMN and the FPCN in support of goal-directed cognition). Another promising avenue would be to explore whether similar effects occur in more naturalistic settings, such as virtual reality simulations. An immersive virtual reality study could, in fact, recreate real-world scenarios that require goal setting and future planning, and we predict that the enhanced immersion provided by virtual reality would amplify adaptive, future-oriented mind wandering, leading to measurable improvements in cognitive performance. For the time being, we have shown that activating a representation of the future and the Self-schema is associated with changes in the

frequency, the temporal focus, and the self-relatedness of off-task thought, and that the future and the Self have different relations with aware and unaware mind-wandering.

Chapter 3.

The role of the vmPFC

in deliberate thought:

Remembering the past, imagining the future

After distinguishing the neural bases of external and internal attention (Chapter 1) and unraveling some distinctive features associated with the phenomenology of spontaneous thought (Chapter 2), we will now focus on the neural bases of deliberate thought.

As mentioned in the Introduction, MTT allows us to recall past events or imagine future scenarios, and this process relies on two crucial and interconnected elements: *autobiographical knowledge* and *episodic simulation*. Specifically, autobiographical knowledge encompasses a range of representations related to the knowledge we have accumulated throughout our lives, from the most abstract (personal semantic knowledge) to the most concrete (specific events). We have also learned that the *integration* of these higher-order representations with episodic details generated by simulation processes has been associated with the vmPFC, though the underlying mechanisms still remain unclear.

In Chapter 3, we will delve into the role of the vmPFC in deliberate thought, examining the impact of selective brain damage to the vmPFC on the temporal unfolding of MTT.

Study 3.

**The temporal unfolding of memory structures
following vmPFC damage**

Giovanni Cantarella^{1,2}, Angelo Pisani ^{1,2}, Debora Stendardi^{1,2}, Matteo Cetraro¹,
Emma Pasquini¹, Elisa Ciaramelli^{1,2}

¹. Department of Psychology, University of Bologna, Bologna, Italy.

². Centre for studies and research in Cognitive Neuroscience, Cesena, Italy.

Abstract

Mental time travel (MTT) – i.e., the human ability to mentally project backward and/or forward in time - relies on a hierarchical organization of mental representations, ranging from abstract (e.g., personal semantics, repeated events) to relatively more concrete memory structures (e.g., specific events). Past research has attributed a crucial role to the ventromedial prefrontal cortex (vmPFC) in activating and maintaining higher-level semantic information to support event construction. However, its precise role in the temporal dynamics of memory structures during MTT remains unclear. In the present study, patients with focal vmPFC lesions, brain-damaged controls, and healthy participants completed a Personal Semantic Interview, followed by an event construction task under the "think aloud" method. vmPFC patients showed degraded personal semantic information in the Personal Semantic Interview but accessed abstract memory structures (e.g., personal semantics and repeated events) more frequently than controls during event construction. While vmPFC patients did not differ from controls in initiating event construction, in the later stages of the retrieval dynamics they activated more repeated and fewer specific events. Moreover, vmPFC patients exhibited atypical backward transitions from more concrete (e.g., repeated and extended events) to relatively more abstract (e.g., personal semantics) memory structures. These findings confirm that vmPFC damage disrupts the retrieval dynamics of MTT, hindering access to specific events and determining a regression toward more abstract mental representations.

1. Introduction

A core feature of human cognition lies in the intrinsic tendency, despite the abundance of external stimuli in our surroundings, to decouple from the present environment and engage in what is named as “*mental time travel*” (MTT; Suddendorf & Corballis, 2007; Tulving, 2005). MTT is a remarkable cognitive ability, allowing us to re-locate ourselves backward in time for recalling past events and forward for envisioning future scenarios. MTT serves as a fundamental driver for decision-making processes (Baumeister, Vohs & Oettingen, 2016), and fosters the awareness of who we are (Prebble et al., 2013), with impact on personal wellbeing (Quoidbach et al., 2010).

MTT has been studied extensively in cognitive psychology and neuroscience (e.g., D’Argembeau, 2016; Schacter, 2012a; Suddendorf & Corballis, 1997; Szpunar, 2010). A recent theoretical framework (Conway & Pleydell-Pearce, 2000; D’Argembeau, 2020; D’Argembeau & Mathy, 2011) argues that MTT depends on the ability to flexibly navigate through a set of hierarchically structured mental representations. The apex of this hierarchy involves **personal semantics**, abstract knowledge about personally-significant people and places, and one’s preferences and goals, spanning broad ranges of time (*lifetime periods*, e.g., *childhood*). Moving down the hierarchy, general events encompass summary mental representations of **repeated events** (e.g., “*my holidays in Viareggio in my childhood*”), of single events yet spanning an extended time period (e.g., “*the trip to Geneva last weekend*”) and sequences of events that follow a typical order (e.g., “*the steps to complete a university degree*”, Barsalou, 1988; Brown & Schopflocher, 1998). At the deepest, most concrete level of the hierarchy, **specific events** contain episodic memories from past experiences, serving as detailed records of sensory, perceptual, and emotional content originally derived from working memory (e.g., “*that family gathering, with the smell of a favorite dish and the sound of laughter*”; Conway, 2009). Activating a specific event can occur both directly (bottom-up), when access to the contextual details of the event is immediate, or indirectly, through a generative, iterative process, that requires first the activation of abstract knowledge structures (personal semantics, general events) that are used as cues to frame the search for the specific event. D’Argembeau & Mathy (2011)

showed that the same hierarchical structures are activated while constructing future as opposed to past events, even though direct access to specific events is less frequent for future events compared to past events, and that future imagining relies more often on the indirect, generative pathway, using semantic knowledge structures (mainly about personal goals) to drive construction of mental events.

Neuroimaging evidence has shed light on the neural bases of MTT, defining a common core network of brain regions - also taking part in the *default network* (Raichle et al., 2001). This network includes the MTL, ventromedial prefrontal cortex (vmPFC), retrosplenial cortex, posterior cingulate, and lateral parietal areas (e.g., [Addis et al., 2007](#); [Benoit & Schacter, 2015](#); [Botzung et al., 2008](#); [Okuda et al., 2003](#); [Szpunar et al., 2007](#)), and exhibits significant activation during rest periods, wherein individuals typically focus their attention inward, on mental contents such as memories, desires, and future plans (J. R. Andrews-Hanna, Reidler, Huang, et al., 2010; Schacter et al., 2012).

In particular, several neuropsychological studies have highlighted the crucial role of the vmPFC and hippocampus in event construction. Preliminary lesion studies showed that patients with frontal lesions, including the vmPFC, retrieved fewer autobiographical memories than healthy controls, and this deficit was closely linked to impairments in executive functions like planning (Kopelman et al., 1999; Sala et al., 1993). This led to hypothesize that vmPFC damage disrupts retrieval strategies (Moscovitch, 1995; Moscovitch & Melo, 1997). [Bertossi et al. \(2016\)](#) observed that vmPFC patients exhibited significant impairments in recalling extended autobiographical events from the past, and at constructing plausible future experiences (see also Bertossi et al., 2017). The same deficit in episodic remembering and future thinking is also present in patients with hippocampal damage (Hassabis, Kumaran, Vann, et al., 2007; Race et al., 2011). Crucially, whereas in scene construction tasks hippocampal patients mainly fail in providing the spatial details of constructed experience, vmPFC patients show a more basic deficit in providing multiple types of details, including event, sensory, and emotion details ([De Luca et al., 2018](#)). Based on this evidence, McCormick et al. (2018) proposed that the vmPFC would play a *superordinate* role in event construction, initiating MTT through the activation of semantic knowledge and then engaging in

feedback loops with the hippocampus and the neocortex to supervise the collection of individual details to fill extended mental events while the hippocampus would help bind the relevant details into coherent scenes. Research on *schematic knowledge* (Burgess & Shallice, 1996; Ghosh et al., 2014) further supports the view that vmPFC guides event construction by activating and maintaining stable schematic representations of relevant events (e.g., “*a typical day out for a picnic*”), then acting as sources of episodic details (Preston & Eichenbaum, 2013). Indeed, a damage to the vmPFC has been associated with an impairment in classifying the belongingness of a series of words (e.g., “*bride*”) to their correspondent event schema (e.g., “*attending a wedding*”; Ghosh et al., 2014). On this view, a failure in activating superordinate, schema-related knowledge may explain why vmPFC patients generate personal events lacking in episodic detail (Bertossi, Tesini, et al., 2016).

An important research question, then, is to determine the exact role of the vmPFC in activating and maintaining the superordinate memory structures supporting MTT. Examining external details at the Autobiographical Interview (e.g., Bertossi, Aleo, et al., 2016; Bertossi, Tesini, et al., 2016; Levine, 2004; Verfaellie et al., 2019) is not suited for our aim, because participants generally provide very few external details as the task typically requires explicitly to recall unique episodes and not general (semantic) information. Moreover, only a subset of external details at the Autobiographical Interview are semantic in nature (AI; Levine et al., 2002).

For this reason, in the present study we adopted two approaches to investigate personal semantic knowledge structures in vmPFC patients. First, we recruited patients with focal damage to the vmPFC, healthy control individuals, and brain-damaged control patients and had them complete a ‘Personal Semantic Interview’ concerning personal semantic information from their past and future. Then, participants underwent an event construction task, in which they were asked to construct past or future events using a lifetime period as the cue (remote past, recent past and future). Crucially, in so doing we used the “think aloud” method (see also Barsalou, 1988; Burgess & Shallice, 1996; D’Argembeau & Mathy, 2011; Haque & Conway, 2001; Reiser et al., 1986; Wank et al., 2021) in which participants are instructed to simply report everything that comes to mind, allowing us to

examine the activation of all types of memory structures involved in MTT—from superordinate semantic structures to unique episodes—along with the order with which these structures get activated. Using the think aloud method, D’Argembeau and Mathy (2011) has shown that, in healthy adults, personal semantic knowledge is typically activated before accessing the specific event in the future, and this also applies to past events (e.g., Haque & Conway, 2001). If the vmPFC effectively enables the activation of semantic structures that then guides the access to specific events, then we would expect vmPFC patients to exhibit a deficit in activating higher order personal semantic structures, and/or a disarticulation of the temporal unfolding of knowledge structures during MTT, with a consequent deficit in generating specific events. In particular, we expect vmPFC patients to show degraded personal semantic information—as measured by the Personal Semantic Interview—and a reduced access to personal semantics, along with other higher-order memory structures, during the initial stage of event construction (i.e., when they begin to “*think aloud*”). Examining the full retrieval dynamics in vmPFC patients as they attempt to construct specific events, will allow us to thoroughly characterize the temporal unfolding of knowledge structures during MTT.

2. Methods

2.1. Participants

Thirty-six participants were included in the study: 15 patients with brain damage and 21 healthy controls. Patients were recruited at the Centre for Studies and Research in Cognitive Neuroscience (Cesena, Italy), based on their lesion site, as documented by MRI or computerized tomography (CT) scans. Nine patients had lesions involving the vmPFC (*vmPFC patients* - 6 males; mean age = 59.8 years; range = 50-73; mean education = 10.2 years, range: 5-13). vmPFC patients’ lesions resulted, in all cases, from the rupture of an aneurysm of the anterior communicating artery. They were bilateral in six cases, left lateralized in two cases and right lateralized in one case. Six ‘control’ patients had lesions not involving the vmPFC (*CP* - 3 males; mean age = 59.9 years; range = 31-76; mean education = 13.5 years, range: 5-18). These were caused by ischemic or hemorrhagic

stroke and were in the left hemisphere in two cases and in the right hemisphere in four cases. Lesion sites mainly included the temporo-parietal cortex, extending into the occipital area (one case) and subcortical regions (four cases). Included patients were in the stable phase of recovery (at least 7 months post-morbid). The healthy control group comprised 21 participants without neurological or psychiatric history (HC - 10 males; mean age = 55.9 years, range = 50-65 mean education = 12.5 years, range = 8-13), which were matched to patients on age, education ($F_{2,33} < 2.84$; $P \geq .07$ in both cases) and gender balance ($\chi^2 < .94$, $p \geq .63$ in all cases).

The sample size of the vmPFC patients' group was derived from previous lesion studies on event construction in vmPFC patients (e.g., Bertossi, Aleo, et al., 2016; Bertossi, Tesini, et al., 2016). Based on the results of a previous study using the "think aloud" method (D'Argembeau & Mathy, 2011), we estimated a minimum sample size of $N = 6$ control participants to replicate an effect size of $\eta_p^2 = .45$ for the main effect of the *level of abstraction* (critical $F = 3.49$), with a significance level of $\alpha = 0.05$ and a desired power ($1 - \beta$) of 0.95. Participants gave written informed consent to participate in the experiment, which was performed in agreement with the 2013 World Medical Association Declaration of Helsinki and approved by the Bioethical Committee of the University of Bologna and the Ethical Committee of Area Vasta (CEIIAV) of Emilia Romagna.

2.2. Neuropsychological assessment

Patients received an extended neuropsychological assessment, aimed at specifying their cognitive profile. Table 1 represents the standardized mean scores of the two groups of patients on individual tests.

Their general cognitive functioning, as indicated by the scores attained in tests assessing attentional skills (i.e., the *Raven Standard Matrices* and *Attentional Matrices*; Spinnler & Tognoni, 1987) was on average within the normal range. Patients also attained normal scores in tests assessing verbal and spatial short-term memory (*Digit Span*, Orsini et al., 1987; *Corsi test*, Spinnler & Tognoni, 1987), long-term memory (*Prose passage recall test*, Spinnler & Tognoni, 1987); *Rey*

Complex Figure – Recall; Caffarra et al., 2002), language and executive abilities (*Phonemic and Semantic Fluency*, Novelli et al., 1986; *Tower of London*, Keith Berg & Byrd, 2002; *Stroop's Test*, Caffarra et al., 2002). The only exception was performance on the Wisconsin Card Sorting Test (Grant & Berg, 1948), indicating a deficit in cognitive flexibility in both groups of patients, and an impaired copy performance in control patients. There were no significant differences in test scores between patient groups ($t < -2.097$; $p \geq .09$ in all cases).

	CP	vmPFC patients
<i>N</i>	6	9
<i>Sex</i>	3 M, 3 F	6 M, 3 F
<i>Age (years)</i>	59.3 (7.43)	59.8 (16.46)
<i>Education (years)</i>	13.5 (3.33)	10.2 (5.89)
<i>Progressive Raven Matrices</i> (cut-off ≤ 15)	22.9 (6.15)	28.78 (7.17)
<i>Digit Span</i> (cut-off ≤ 3.75)	5.75 (1.17)	5.39 (1.51)
<i>Corsi Block Tapping</i> (cut-off ≤ 3.75)	4.08 (0.89)	4.57 (1.11)
<i>Attentional Matrices</i> (cut-off ≤ 31)	40.83 (3.78)	49.03 (10.95)
<i>Prose Passage Recall (ES)</i>	10.34 (5.32)	8.51 (5.11)
<i>Rey Complex Figure – Copy</i> (cut-off ≤ 28.9)	27.85 (3.96) *	33.39 (13.79)
<i>Rey Complex Figure – Recall</i> (cut-off ≤ 9.5)	14.80 (9.86)	15.40 (7.10)
<i>Phonemic Fluency</i> (cut-off ≤ 17)	30.40 (9.46)	28.44 (15.69)

<i>Semantic Fluency</i> (cut-off ≤ 25)	39.80 (10.87)	40.22 (12.97)
<i>Stroop Test – Errors</i> (cut-off $\geq 4,24$)	0.96 (5.23)	2.50 (1.16)
<i>Stroop Test – Interference time</i> (cut-off $\geq 36,92$)	28.54 (20.88)	29.67 (19.93)
<i>Tower of London - Total Move Score</i> (cut-off ≤ 70)	72.00 (25.63)	87.33 (9.93)
<i>Tower of London - Rule Violation Score</i> (cut-off ≤ 70)	71.00 (23.58)	91.11 (22.00)
<i>WCST - Tot Number of Errors</i> (cut-off = corrected for age and education)	79.75 (20.42) *	77.63 (33.73) *
<i>WCST - Number of Perseverative Errors</i> (cut-off = corrected for age and education)	74.00 (25.39) *	83.75 (46.95) *

Table 1. Patients' demographic and clinical data. Unless otherwise specified, we report corrected scores. Impaired performance is indicated by an *.

2.3. Lesion mapping

We derived patients' individual lesions from the most recent MRI or CT scans. They were manually drawn by two trained neuroscientists directly on each slide of the normalized T1-weighted template MRI-scan from the Montreal Neurological Institute distributed with MRICro (Rorden & Brett, 2000). The MRICro software was used to estimate lesion volumes (in cc) and generate lesion overlap images. Figure 1 shows the extent and overlap of brain lesions in vmPFC patients. The region of maximal lesion overlap occurred in BA 11 (mean= 17.59 cc; st.dev.= 10.686), BA 10 (mean= 9.08 cc; st.dev.= 7.23) and BA 32 (mean= 5.88 cc; st.dev.= 5.66). There was no significant difference in lesion volume between vmPFC patients and control patients ($t_{13} = 0.56$, $p = 0.59$, Cohen's $d = 0.29$).

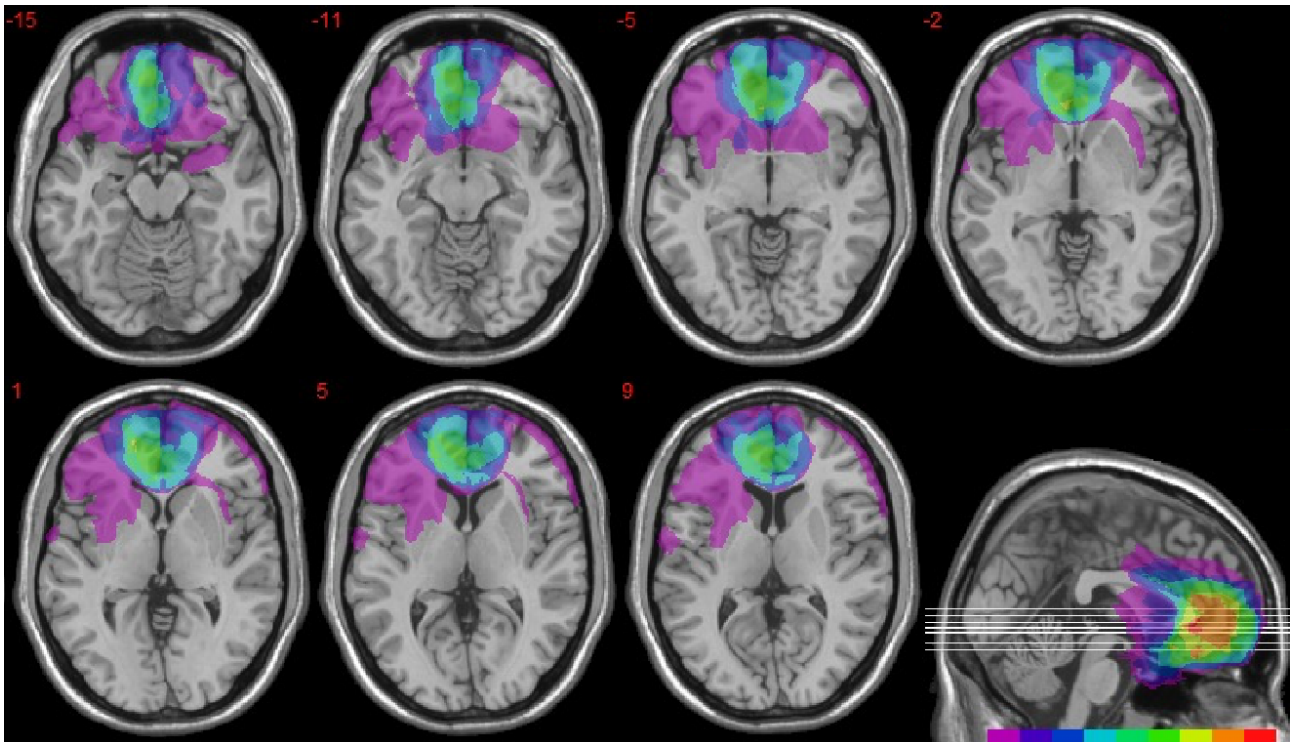


Figure 1. *Location and overlap of vmPFC patients' brain lesions.* This panel displays the brain lesions of the 9 patients with vmPFC damage, all projected onto the same seven axial slices and the mesial view of the standard Montreal Neurological Institute brain. The level of each axial slice is marked by white horizontal lines on the mesial view, with corresponding z-coordinates. The color bar represents the number of overlapping lesions, with the greatest overlap occurring in BA 11, BA 10, and BA 32 of the vmPFC. In the axial slices, the left hemisphere is shown on the left.

3. Materials and Procedure

The experimental procedure comprised three computerized tasks, distributed into three separate sessions: a *personal semantic interview* (session 1) and an *event construction task* (sessions 2 and 3). Session 1 assessed participants' ability to access personal semantic information (i.e., lifetime periods), while the other sessions evaluated their ability to construct past and future events starting, respectively, from personal semantic information (i.e., lifetime periods) and from generic cues (i.e., four words). The order of sessions 2 and 3 was counterbalanced between participants. The cue-words session, however, is not subject of the present work.

During Session 1, participants were told that we were interested in investigating semantic facts about their lives, and in particular 4 life-time periods: “*childhood*” (0-18 years), “*adulthood*” (18-30 years), “*recent past*” (last 10 years) and “*near future*” (next 10 years). During the event construction session, for three of the four lifetime periods (*childhood, recent past and near future*), we asked participants to retrieve or to imagine a specific event happened/to happen in that period. Patients’ relatives attended all sessions to verify the truthfulness of patients’ statements.

3.1. Personal Semantic Interview

The personal semantic semi-structured interview was adapted by the semantic section of the “*Autobiographical Memory Interview*” (Kopelman et al., 1989). It was divided into 4 main sections, corresponding to separate life-time periods: “*childhood*” (*age-range*: 0-18 years), “*adulthood*” (18-30 years), “*recent past*” (last 10 years) and “*near future*” (next 10 years). For each time-period, subjects were required to provide semantic information regarding their knowledge of 4 types of facts, i.e., (1) the names and surnames of people they frequently met/will meet, (2) the names of places they frequently visited/will visit, (3) the names of schools they attended or the job they had/will have, and (4) their home addresses.

Each of the 4 categories explored during the Personal Semantic Interview was scored separately. For each category, we assigned a score of 1 to each new piece of information provided by the participants. In the *people* and *places* categories, scores for each piece of information were summed, while in the *address* and *work* categories, scores were averaged across the items mentioned. Participants could identify a maximum of 3 items per category. The total scores for each category were then summed to generate a comprehensive index, with a maximum score of 20 (for further details, see Table 2 and Supplementary Table 1 – Appendix C).

At the end of each section, we also asked participants to provide at least five *cultural life-scripts*, i.e. culturally shared personal events that are expected to be experienced by individuals within

a given society (Berntsen & Rubin, 2004) in that life-time period. The duration of this session was about 1 hour.

<i>Life-time periods</i>	Semantic facts to be recalled (or imagined)	Maximum score
Childhood	1. Names and surnames of frequently met people (friends, parents, colleagues).	6
Adulthood	2. Names of frequently visited places.	6
Recent Past	3. Personal address	4
Future	4. Names of institutions (schools and/or jobs)	4

Table 2. *Personal semantic interview schedule.*

3.2. *Event construction task*

The event construction task was a modified version of the Crovitz method (Crovitz & Schiffman, 1974) and was programmed on Open Sesame (Mathôt et al., 2012). Participants were required to recall specific events that happened in their personal past and to imagine specific events that might reasonably happen to them in the future, in response to three life-time periods (“*remote past - childhood*”, “*recent past*”, “*near future*”; e.g., imagine an event that might happen to you in the near future). Participants performed two trials per time condition, with the order of time conditions counterbalanced across participants.

Participants were instructed to recall/imagine specific events, i.e. a unique event taking place in a precise place at a specific time and lasting no more than a day (see D’Argembeau & Mathy, 2011). They were provided with some examples to illustrate what would or would not be considered

as a specific event. The instructions further specified that the event should refer to personal experiences and that future events should be plausible (something that could reasonably happen) and novel (something that was not experienced in the past).

We asked participants to say aloud everything that came into their minds while trying to retrieve (*condition*: past) or to imagine (*condition*: future) the specific event (i.e., the “*think aloud*” method; *see also* D’Argembeau & Mathy, 2011). The description had to begin from the time the subjects read the stimulus (life-time period) on the screen and continue until they considered their description of the event to be complete for a maximum of 3 minutes. This procedure allowed us to delineate the entire temporal progression of memory structures in participants’ discourse (from abstract semantic structures to specific events).

Following the instructions of the Autobiographical Interview (Levine et al., 2002) manual, if the participant was unable to generate an event after the instructions, general probes were provided to clarify the instructions or for eliciting more details. An example of these probes was: “*Is there anything else you could tell me?*” If general probes did not work, we prompted participants with one of the typical life-events (*cultural life-scripts*) they reported in Session 1. If, again, participants failed to start the event construction process, we provided them with a cue regarding one of the frequently visited places they provided during Session 1.

After the generation of each - past or future - event, participants were asked to rate (using a 5-point Likert scale; *see also* Rasmussen & Berntsen, 2023) the event for *emotional valence* (1 = very pleasant, 2 = quite pleasant, 3 = neither pleasant nor unpleasant, 4 = quite unpleasant, 5 = very unpleasant), *personal importance* (1 = an event that changes your life, 2 = a fairly important event, 3 = an average important event, 4 = an event of little importance, 5 = an irrelevant event) and relation to *personal goals* (1 = very much, 2 = much, 3 = quite, 4 = little, 5 = at all).

3.3. Scoring procedure

3.3.1. Levels of abstraction

The scoring procedure was adapted from D'Argembeau & Mathy (2011). Participants' reports were recorded and transcribed. The information provided was then segmented and classified into 5 levels of abstraction: *general semantics*, *personal semantics*, *repeated events*, *extended events*, *specific events*, plus one extra *nothing in mind* category.

We defined *general semantics* (GS) the general, semantic, information that applies to everyone (e.g., "*A friend is seen in times of need*" or "*The best restaurants are sometimes not the most expensive ones*"). With *personal semantics* (PS) we meant instead the semantic information specific to the speaker, including his/her characteristics, tastes (e.g., "*I actually prefer to eat at home than at the restaurant*"), people, places, (e.g., "*My best friend at that time was my classmate Roberta*") and main life-time periods (e.g., "*It reminds me of when I was in the high school*"). We considered as *repeated events* (RE) any information referring to personal episodes that happened more than once (e.g., "*I spent every afternoon studying before that exam*"); they also included personal habits (e.g., "*every Saturday my wife and I went to the restaurant*"). Personal episodes that are unique but extended in time (over days or weeks, e.g., "*I imagine myself going on holiday with my cousin in the near future*") and/or unique but sparsely detailed episodes (an event title, e.g., "*I remember when I bought my house*") were scored as *extended events* (EE). Finally, we defined as *specific events* (SE) all the unique, personal, and detailed episodes, contextualized in space and time and accompanied by numerous contextual details and associations (e.g., "*Last week I went to the beach all day with my sister. It was very hot and we got stuck in traffic in the morning. I felt very nervous*").

Finally, the extra-category *nothing in mind* included hesitations, non-specific or abstract expressions and repetitions of the cues, but also any expression indicating that the elaboration of the instructions was still in progress or could not be processed at that time (e.g., "*I find myself in a bit of difficulty with respect to this lifetime period...*" or "*Friend, friend, friend, mmh... let me think...*").

All responses were independently scored by two trained raters who were blind to the study's hypotheses. Any discrepancies were then resolved through discussion with a third rater.

3.3.2 Temporally ordered units

Since the main purpose of this study was to examine the temporal progression of knowledge structures across the previously defined levels of abstraction, we segmented participants' discourses into temporally ordered units (see D'Argembeau & Mathy, 2011). According to this procedure, the level of abstraction of the first element (or elements) of the speech was considered as the first description unit. Thus, the first unit (as well as the following units) could comprise multiple elements all referring to the same level of abstraction. We noted a distinct description unit when participants shifted forward to another level of abstraction (e.g., from RE to SE; see also D'Argembeau & Mathy, 2011). In contrast, if a memory structure was activated (e.g., EE) and immediately followed by a backward shift to a more abstract level (e.g., RE), the latter was not scored as a new unit. Thus, in total, there could be a maximum of 5 description units for each trial, with each unit corresponding to one of the 5 levels of abstraction described earlier.

3.3.3. Transitions between levels of abstraction

After segmenting the participants' speeches into units, we also identified all possible transitions between levels of abstraction. To this aim, we conducted a second scoring in which every shift between levels of abstraction was considered — even backward shifts, i.e., from a more specific memory structure to a more abstract one. This allowed us to detect all cases where, for example, a participant activated the SE level and then went back to the PS level.

4. Data analysis & Results

4.1. Personal Semantic Interview

Since their distribution violated the assumption of normality, the scores attained at the Autobiographical Interview underwent a logarithmic transformation. To compare the availability of personal semantic information between groups, we conducted a repeated-measure ANOVA on these

normalized scores, with *group* (HC: healthy controls; CP: control patients and vmPFC patients) as between-subject factor, *life-time period* (childhood, adulthood, recent past and near future) and *semantic information* (people, places, address and work) as within-subject factors. Since the assumption of sphericity (Mauchly's test) was also violated, we applied the Greenhouse-Geisser correction on this model.

The analysis yielded a main effect of *semantic information* [$F_{2,75} = 147.39$; $p < .001$; $\eta_p^2 = .82$], showing that scores related to the category *people* were higher (mean = 0.77, st.dev. = 0.07) than those for *places* (mean = 0.73, st.dev. = 0.13; $p = .007$); these were higher than scores for *addresses* (mean = 0.55, st.dev. = 0.09, $p < .001$) that, in turn, were higher than scores for the category *work* (mean = 0.47, st.dev. = 0.14; $p < .001$). There was also a main effect of *group* [$F_{2,33} = 7.75$; $p = .002$; $\eta_p^2 = .32$], with vmPFC patients exhibiting overall lower scores (mean = 0.59, st.dev. = 0.19) than HC (mean = 0.64, st.dev. = 0.16, $p = .005$) and CP (mean = 0.65, st.dev. = 0.14, $p = .005$). These effects were qualified by a significant interaction *group * semantic information* [$F_{5,51} = 3.13$; $p = .010$; $\eta_p^2 = .16$]: vmPFC patients attained lower scores to the category *places* (mean = 0.66, st.dev. = 0.17) compared to HC (mean = 0.75, st.dev. = 0.12, $p = .013$) and CP (mean = 0.77, st.dev. = 0.05, $p = .040$); the same pattern emerged for scores related to the category *work*, with vmPFC patients showing lower scores (mean = 0.40, st.dev. = 0.16) than the other groups (HC: mean = 0.49, st.dev. = 0.13, $p = .005$; CP: mean = 0.50, st.dev. = 0.10; $p = .037$). No differences emerged for scores related to the categories *people* and *address* (all $ps. > .99$; see Figure 2).

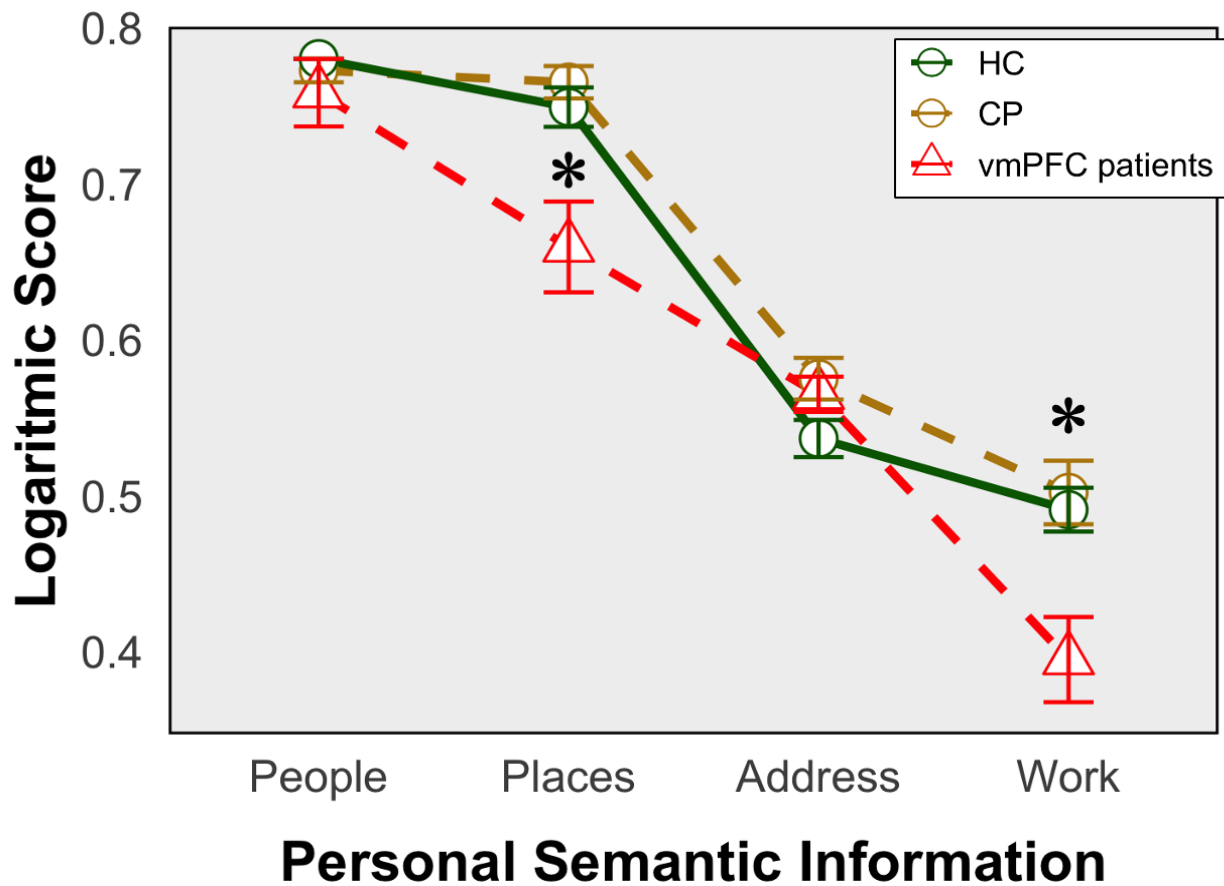


Figure 2. Logarithmic transformed mean scores at the personal semantic interview by *group* (healthy controls, control patients and vmPFC patients) and *semantic information* (people, places, address, work). Error bars indicate standard error of the mean. * $p < 0.05$.

This set of analyses demonstrated that vmPFC patients exhibited impairments in accessing personal semantic information, particularly when related to attended places and jobs, regardless of the life-time period considered.

4.2. Event construction task

4.2.1. Distributions of levels of abstraction

As a preliminary analysis, to compare the frequencies of levels of abstraction across groups, we run a repeated-measure ANOVA on the overall number of levels of abstraction for each subject,

with *group* as between-subject factor, *level of abstraction* (GS, PS, RE, EE and SE) and *time* (remote past, recent past and near future) as within-subject factors. We found a main effect of *group* [$F_{2,33} = 7.59$; $p = .002$; $\eta_p^2 = .32$], indicating that vmPFC patients expressed overall a higher number of levels of abstraction (mean = 10.64, st.dev = 2.52) than healthy participants (mean = 5.98, st.dev. = 1.07, $p = .002$). A main effect of *level of abstraction* [$F_{2,31} = 28.6$; $p < .001$; $\eta_p^2 = .23$] also emerged, with all groups reporting a higher number of PS overall (mean = 13.09, st.dev. = 5.72), compared to RE (mean = 8.40, st.dev. = 5, $p < .001$), EE (mean = 10.01, st.dev. = 4.38, $p = .007$) and SE (mean = 7.98, st.dev. = 4.22, $p < .001$) that, in turn, were also higher than GS (mean = 3.06, st.dev. = 3.59, all $ps < .001$). These effects were qualified by the significant interaction *group * level of abstraction* [$F_{5,32} = 13.78$; $p < .001$; $\eta_p^2 = .46$], whereby vmPFC patients exhibited a higher number of PS (mean = 19.22; st.dev. = 8.96), RE (mean = 14; st.dev. = 8.32) and EE (mean = 13.78; st.dev. = 6.30) compared to HC (PS: mean = 7.71; st.dev = 4.28, $p < .001$; RE: mean = 3.71; st.dev = 2.49, $p < .001$; EE: mean = 6.57, st.dev = 3.40, $p = .008$), but a lower number of SE (mean = 3.33, st.dev. = 3) than the HC group (HC: mean = 9.62, st.dev = 3.76, $p = .044$; see Figure 3). By contrast, there was no difference in these levels of abstraction between HC and CP (all $ps \geq .99$) or between the CP and the vmPFC (all $ps \geq .10$). The results also showed a significant interaction *time*level of abstraction* [$F_{5,91} = 6.75$; $p < .001$; $\eta_p^2 = .17$]: all groups expressed more EE in the future (mean = 4.59, st.dev = 1.98) compared to the remote past (mean = 2.32, st.dev = 1.76, $p < .001$); no differences between times emerged instead in the other levels of abstraction (all $ps > .07$).

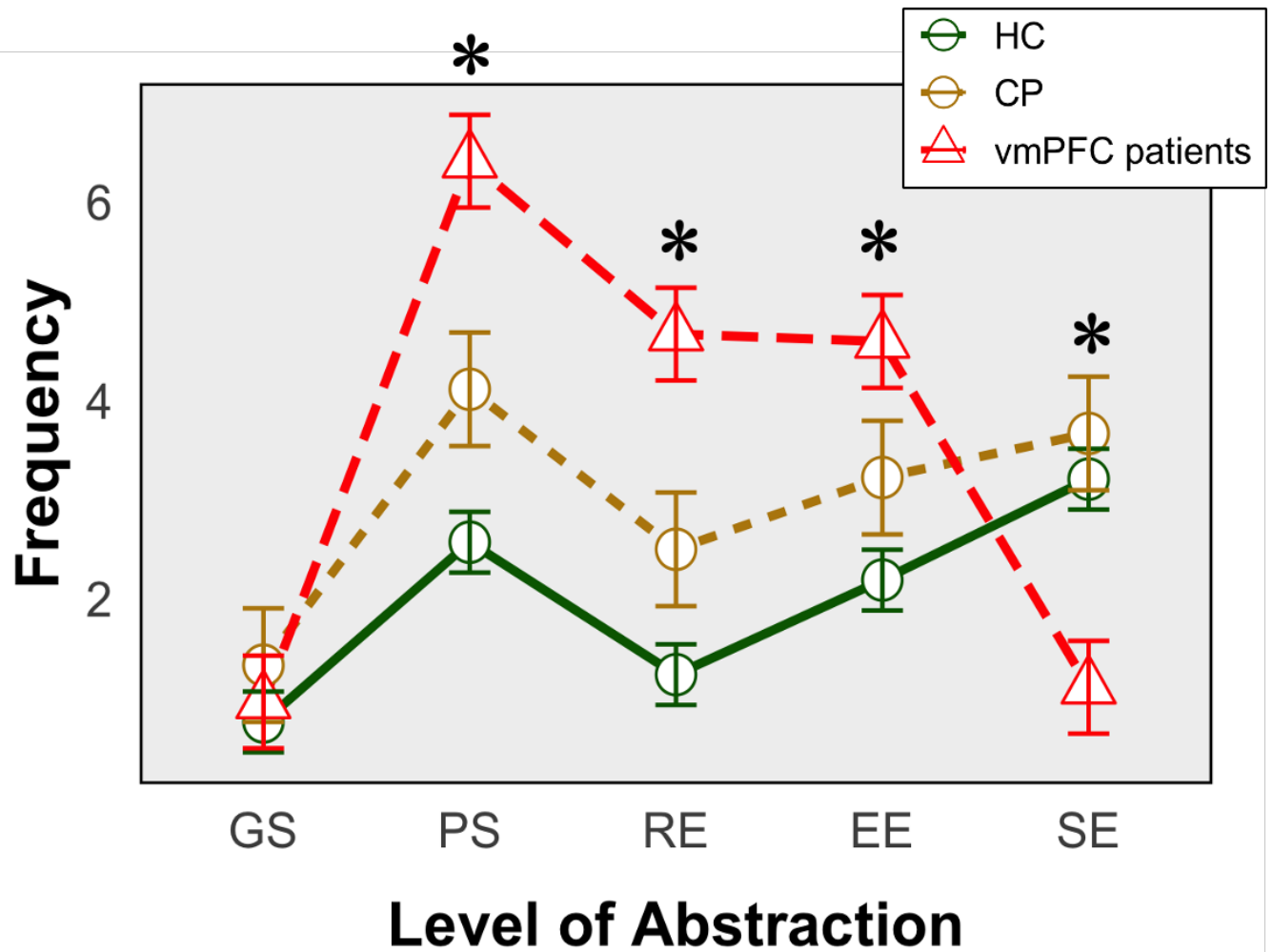


Figure 3. Mean frequency of levels of abstraction by group by *group* (healthy controls, control patients and vmPFC patients) and *level of abstraction* (general semantics, personal semantics, repeated events, extended events and specific events). Error bars indicate standard error of the mean. * $p < 0.05$.

The preliminary analyses revealed that vmPFC patients accessed higher-order knowledge structures (PS, RE, and EE) more frequently and SE less frequently compared to the control groups. Due to the low usage rate of GS (7%) reported by participants, this level of abstraction was excluded from all the subsequent analyses.

4.2.2. The temporal unfolding of event construction

To capture the temporal dynamics of the event construction process, participants' reports were then segmented into discrete units based on shifts in abstraction levels (as described above; see also D'Argembeau & Mathy, 2011). Each trial was divided into a maximum of four units. To examine the levels of abstraction that were accessed first (i.e., Unit 1) by participants while constructing the event, for each time (remote past, recent past and near future), we calculated the proportions of PS, RE, EE and SE described in Unit 1. Next, we calculated the proportion of levels of abstraction reported in Unit 2 for trials in which a specific event had not already been produced in Unit 1. We then adopted the same procedure to compute the proportions of levels of abstraction reported in Units 3 and 4 for trials in which a SE had not been generated in the previous unit (see also D'Argembeau & Mathy, 2011).

For Units 1, 2 and 3, these proportions were subject to repeated-measure ANOVAs with *group* as between-subject factor, *time* (remote past, recent past and near future) and *level of abstraction* (PS, RE, EE and SE) as within-subject factors. Since most participants did not cover Unit 4 in their speech, and because the variance in the repeated measures was zero for all groups, it was not possible to conduct the same analysis for Unit 4.

Regarding Unit 1, we found a main effect of *level of abstraction* [$F_{1,95} = 8.27$; $p < .001$; $\eta_p^2 = .20$], indicating more personal PS (mean = 0.27, st.dev. = 0.35) and EE (mean = 0.24, st.dev. = 0.33) expressed in the first part of the reports rather than the other levels of abstraction (RE: mean = 0.06, st.dev. = 0.14, $p < .001$; SE: mean = 0.14, st.dev. = 0.25, $p < .029$) (see Figure 4), with no difference between these levels (all $ps \geq .75$). The factors *group* [$F_{2,33} = 0.24$; $p = .79$] and *time* [$F_{1,36} = 0.91$; $p = .37$], and the interaction *level of abstraction* * *group* [$F_{3,89} = 1.30$; $p = .28$] failed to reach statistical significance.

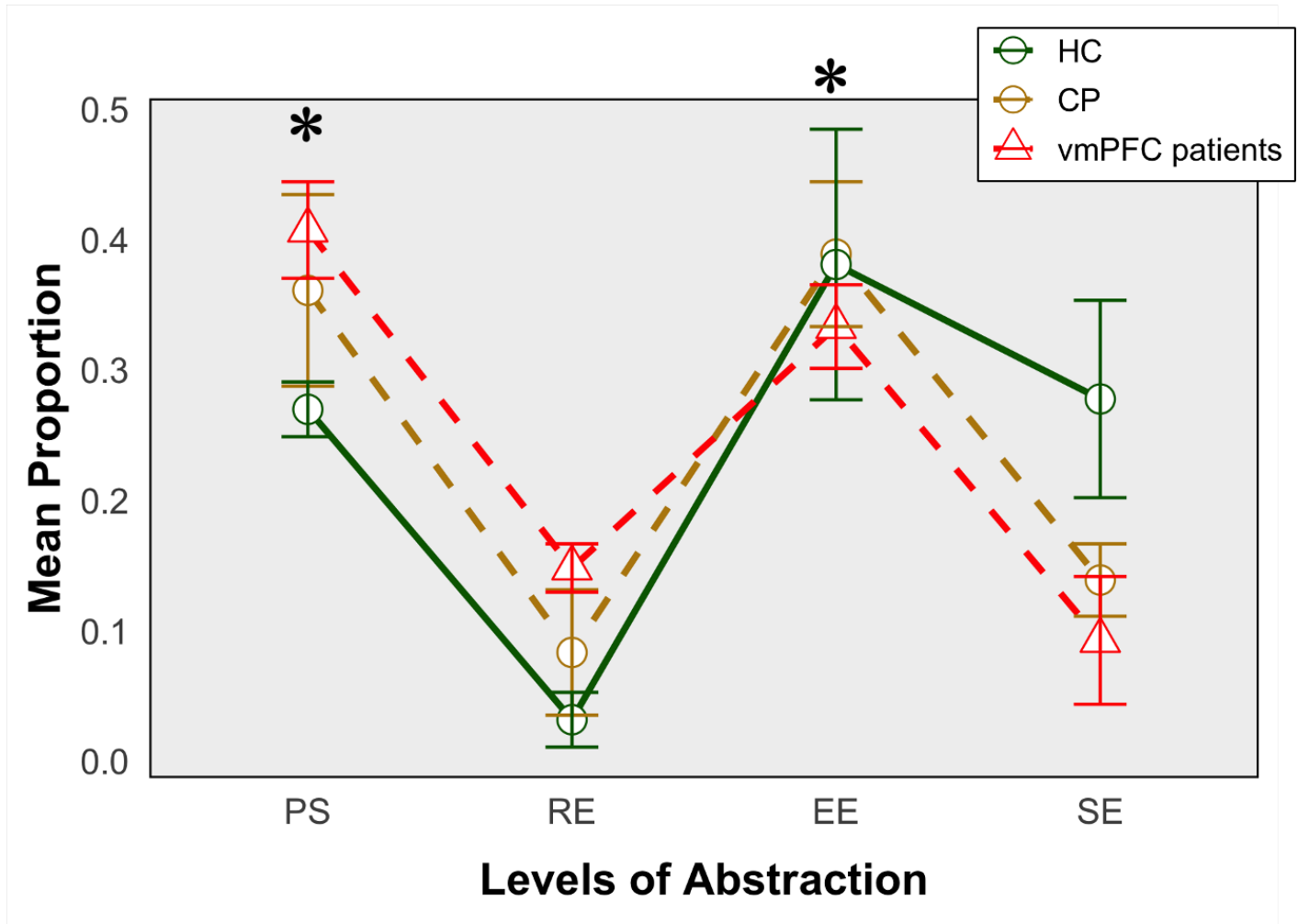


Figure 4. Unit 1. Mean proportions of levels of abstraction by *group* (healthy controls, control patients and vmPFC patients) and *level of abstraction* (personal semantics, repeated events, extended events and specific events). Error bars indicate standard error of the mean. * $p < 0.05$.

Regarding Unit 2, we found a main effect of *level of abstraction* [$F_{1,95} = 28.464$; $p < .001$; $\eta_p^2 = .46$], with higher proportions of SE (mean = 0.33, st.dev = 0.38) and EE (mean = 0.26, st.dev = 0.40) compared to RE (mean = 0.08, st.dev = 0.15) and higher proportions of RE than PS (mean = 0.009, st.dev = 0.03, $p = .017$). We also found a significant interaction *group*level of abstraction* [$F_{3,89} = 9.22$; $p < .001$; $\eta_p^2 = .36$]: post-hoc analyses, performed with the Holm's correction, revealed significantly higher proportions of RE expressed by vmPFC patients (mean = 0.26; dev.st. = 0.38) compared to HC (mean = 0.03; dev.st. = 0.12; $p < .001$), while vmPFC patients expressed a lower proportion of SE (mean = 0.15; dev.st. = 0.30) compared both to CP (mean = 0.44; dev.st. = 0.42, $p = .034$) and HC (mean = 0.56; dev.st. = 0.45, $p < .001$). No differences emerged between groups in the remaining levels

(all p s $\geq .21$; see Figure 5). The factor *time* [$F_{1,85} = 0.44$; $p = .63$] and *group* [$F_{2,33} = 0.70$; $p = .51$] instead were not significant.

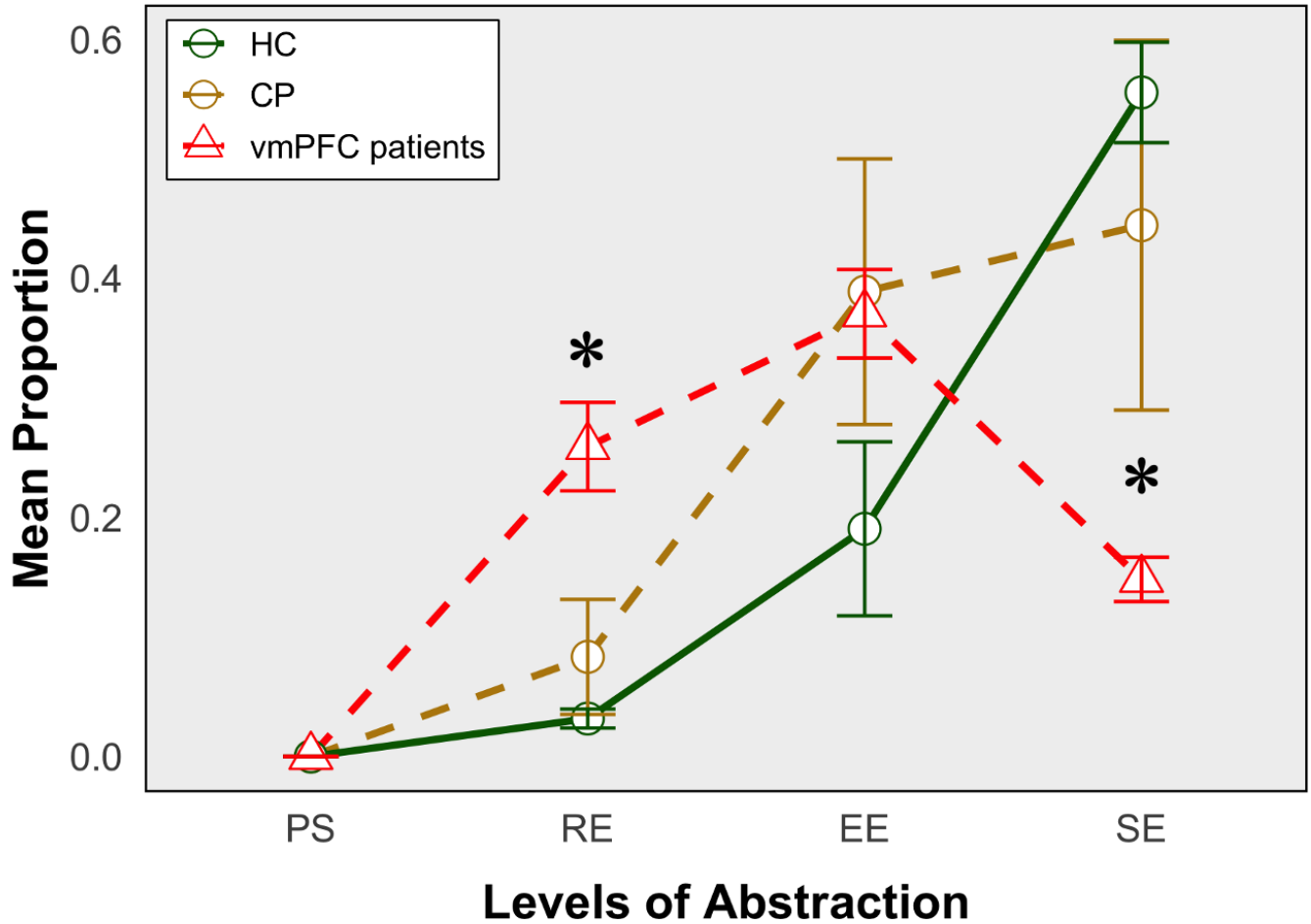


Figure 5. *Unit 2.* Mean proportions of levels of abstraction by *group* (healthy controls, control patients and vmPFC patients) and *level of abstraction* (personal semantics, repeated events, extended events and specific events). Error bars indicate standard error of the mean. * $p < 0.05$.

Regarding Unit 3, the results showed a main effect of *level of abstraction* [$F_{3,99} = 15.89$; $p < .001$; $\eta_p^2 = .33$], with significantly higher proportions of SE (mean = 0.23; dev.st = 0.41) compared to EE (mean = 0.09; dev.st = 0.29, $p = .015$), and significantly higher proportions of EE than RE (mean = 0.00; $p = .015$) and PS (mean = 0.00; $p = .015$). The triple interaction *group*time*level of abstraction* [$F_{12,198} = 2.83$; $p = .001$; $\eta_p^2 = .146$] was also significant. vmPFC patients expressed more SE

(mean=0.56; st.dev.= 0.46) in the remote past, compared to the recent past (mean= 0.11, st.dev.= 0.33, $p= 0.05$) and the future (mean= 0.00, $p <.001$), while no significant differences between time periods in the distribution of levels of abstraction emerged in the HC and the CP groups (all $ps > .22$) (see Figure 6).

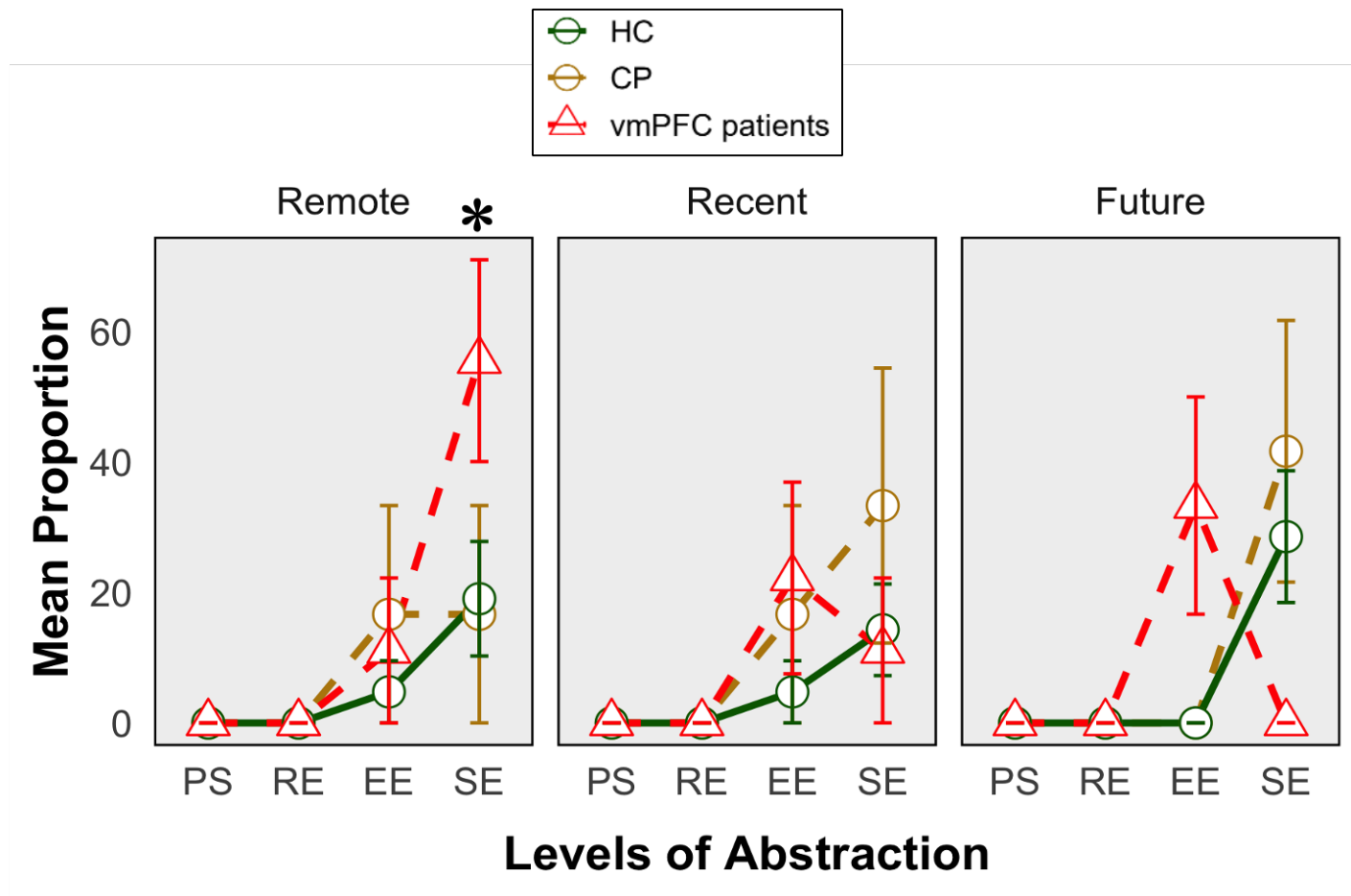


Figure 6. *Unit 3.* Mean proportions of levels of abstraction by *time* (remote past, recent past and near future), *group* (healthy controls, control patients and vmPFC patients) and *level of abstraction* (personal semantics, repeated events, extended events and specific events). Error bars indicate standard error of the mean. * $p < 0.05$.

This set of analyses showed that all groups began (Unit 1) the event construction process by activating PS or EE more frequently, while rarely activating RE or SE. In Unit 2, vmPFC patients

were less able to reach SE than the other groups did, and tended to access RE instead. In Unit 3, vmPFC patients were able to access SE, but selectively in the remote past.

4.2.3. *Atypical activation patterns in memory structures: compensation or impairment?*

In the previous analysis, vmPFC patients compared to the controls demonstrated a preserved ability to access SE - though less frequently - and a higher tendency to activate RE. Therefore, we investigated whether accessing RE served as a *compensatory strategy*—allowing vmPFC patients to reach the SE - or, alternatively, represented the failure of their event construction process. To do so, we performed Beta Generalized Linear Mixed Models (*GLMM*) on the proportions of levels of abstraction, with level of abstraction (PS, RE and EE) and group as factors, but the vmPFC patients' sample was divided into two subgroups: *vmPFC - correct* (all trials in which they successfully accessed a SE) and *vmPFC - incorrect* (all trials missing the SE). As opposed to the vmPFC patients' group (61,1% of incorrect trials), the HC and CP groups had negligible percentages of trials not ending on a SE (respectively 13,5% and 19,4%). Hence, this set of analysis was performed on their correct trials only. Since the vmPFC - incorrect group did not activate SE by definition, we did not include this level of abstraction in the analysis.

Regarding Unit 1, we found a main effect of *level of abstraction* (Wald $\chi^2_{(2)} = 16.451$; $p < .001$], confirming the higher proportion of PS (mean = 0.30, st.dev.= 0.36) and EE (mean= 0.29 , st.dev = 0.36) rather than RE (mean = 0.06, st.dev = 0.18, all ps = .012), with no difference between PS and EE ($p = .98$). No other factors were significant [all ps > 0.603].

Regarding Unit 2, we found a main effect of *level of abstraction* [Wald $\chi^2_{(2)} = 7.064$ $p = .029$], with higher proportions of EE (mean = 0.19, st.dev = 0.40) compared to PS (mean= 0.00 , st.dev=

0.00, $p = .002$) and RE (mean = 0.07, st.dev = 0.23; $p = .03$), with no difference between PS and RE ($p = .27$). The other factors were not significant [all $ps > 0.231$].

Regarding Unit 3, the interaction *group*level of abstraction* [Wald $\chi^2_{(6)} = 16.56$; $p = .011$] was significant, with more EE expressed by vmPFC – incorrect (mean= 0.50, st.dev = 0.52) compared to HC (mean= 0.05; st.dev = 0.21; $p < .001$) and vmPFC – correct group (mean= 0.00; dev.st.= 0.00; $p < .001$). We did not observe other significant differences between groups (all $ps \geq .063$). The remaining factors did not reach statistical significance [all $ps > 0.06$].

This set of analyses revealed that, similar to HC and CP, vmPFC patients - regardless of trial correctness - activated more abstract memory structures (e.g., PS and RE) during the early stages of the event construction process. However, in incorrect trials, i.e., where vmPFC patients were unable to successfully generate SE, their progression to the late stage was limited to the activation of an EE.

4.2.4. Backward transitions

To track the temporal unfolding of event construction, previous analyses have focused between transitions from relatively more to relatively less abstract memory structures. We noted, however, that also backward transitions occurred (i.e., from relatively less to relatively more abstract memory structures; e.g., SE to PS). Thus, to further specify the temporal progression between abstraction levels during event construction, we here tracked not only forward but also backward transitions between memory structures. To do so, we counted the overall number of – forward and backward - passages between each level of abstraction and all the others (e.g., from PS to RE, EE, and SE). Since this number could be affected by the specific distribution of each level of abstraction in the reports, their values for each participant were corrected by the sum of the levels of abstraction covered by that subject [e.g., n° transitions between RE and PS/ (n° RE + n° PS)].

The corrected numbers of transitions starting from each level (PS, RE, EE and SE) were then subject to Beta GLMM, with *group* (HC, vmPFC patients and CP), *arrival level* (defined as the level

of abstraction to which the transitions ended, i.e., PS, RE or EE) and *time period* as fixed effects and *participant* as random effect. To maintain conciseness, here we report only backward transitions, whereas forward transitions are reported in the Supplementary materials (see Appendix C; the findings confirm those reported in the previous sections).

Regarding the corrected number of backward transitions from RE to PS, the results showed a significant main effect of *group* [Wald $\chi^2_{(2)} = 46.23$; $p < .001$], with vmPFC patients reporting a significantly higher number of backward transitions from RE to PS (mean = 0.07; st.dev. = 0.02) compared to both groups of HC (mean = 0.02; st.dev. = 0.03, $p < .001$) and CP (mean = 0.03; st.dev. = 0.02, $p < .001$), with no difference between HC and CP ($p = .19$). The factor *time period* [Wald $\chi^2_{(2)} = 0.57$; $p = .75$] and the interaction *time period* * *group* [Wald $\chi^2_{(4)} = 0.24$; $p = .99$] failed instead to reach statistical significance.

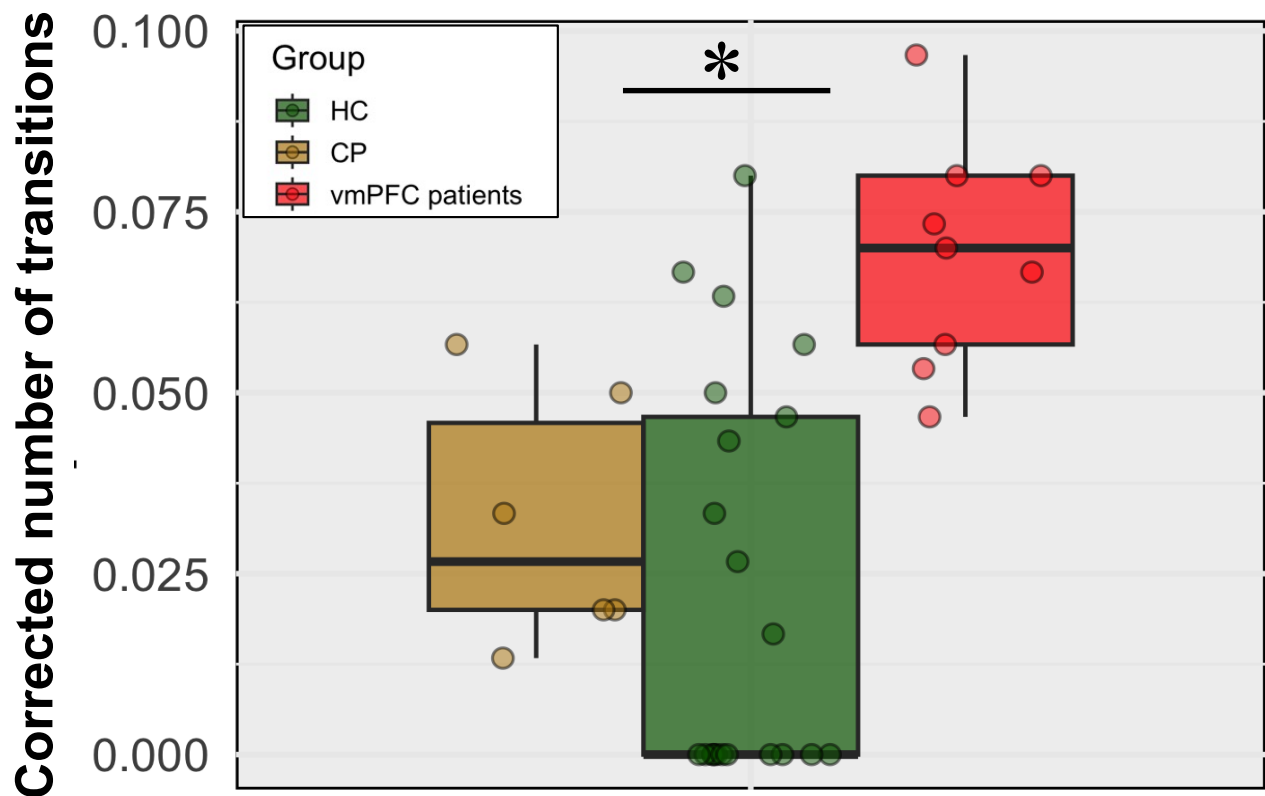


Figure 7. Corrected number of transitions starting from repeated events (RE) to personal semantics (PS) by *group* (healthy controls, control patients and vmPFC patients). Error bars indicate standard error of the mean. * $p < 0.05$.

The analysis on the corrected number of backward transitions starting from EE yielded a main effect of *group* [Wald $\chi^2_{(2)} = 42.60$; $p < .001$], with vmPFC patients expressing a higher number of backward transitions from EE (mean = 0.06; st.dev. = 0.05) compared to HC (mean = 0.03; st.dev. = 0.06, $p < .001$) and CP (mean = 0.04; st.dev. = 0.05, $p = .012$). The factor arrival level was also significant [Wald $\chi^2_{(2)} = 12.04$; $p < .001$], indicating that participants expressed more backward transitions from EE to PS (mean = 0.05; st.dev. = 0.07) than to RE (mean = 0.03; st.dev. = 0.04). Moreover, there was a main effect of *time period* [Wald $\chi^2_{(2)} = 19.46$, $p < .001$], with participants reporting overall more backward transitions of this type in the future (mean = 0.06; st. dev. = 0.07) than in the recent (mean = 0.06; st. dev. = 0.07, $p = .002$) or the remote past (mean = 0.06; st. dev. = 0.07, $p < .001$), with no difference between the remote and the recent past ($p = .19$).

While both the interactions *time period * arrival level* [Wald $\chi^2_{(2)} = 10.49$, $p = .005$] and *group * arrival level* [Wald $\chi^2_{(2)} = 6.25$, $p = .044$] were significant, their effects were further clarified by the triple interaction *group * time period * arrival level* [Wald $\chi^2_{(4)} = 12.01$, $p = .02$]. For backward transitions from EE to PS, in both the future (mean = 0.10; st.dev. = 0.06) and remote past (mean = 0.07; st.dev. = 0.05), vmPFC patients demonstrated more transitions compared to HC (*future*: mean = 0.09; st.dev. = 0.09, $p = .003$; *remote past*: mean = 0.004; st.dev. = 0.01, $p = .003$) but not to CP ($ps \geq .99$), that in turn showed more transition than the HC (all $ps \leq .048$). Regarding backward transitions from EE to RE, again, in both the future (mean = 0.07; st.dev. = 0.04) and the remote past (mean = 0.03; st.dev. = 0.04), vmPFC expressed more transitions compared to the HC (*future*: mean = 0.02, $p = .01$; st.dev. = 0.04; *remote past*: mean = 0.026; st.dev. = 0.04, $p = .047$) but not to the CP (all $ps \geq .18$), with no difference between the HC and the CP (all $ps \geq .99$). By contrast, no significant differences between groups and transitions emerged in the recent past [all $ps \geq .72$]

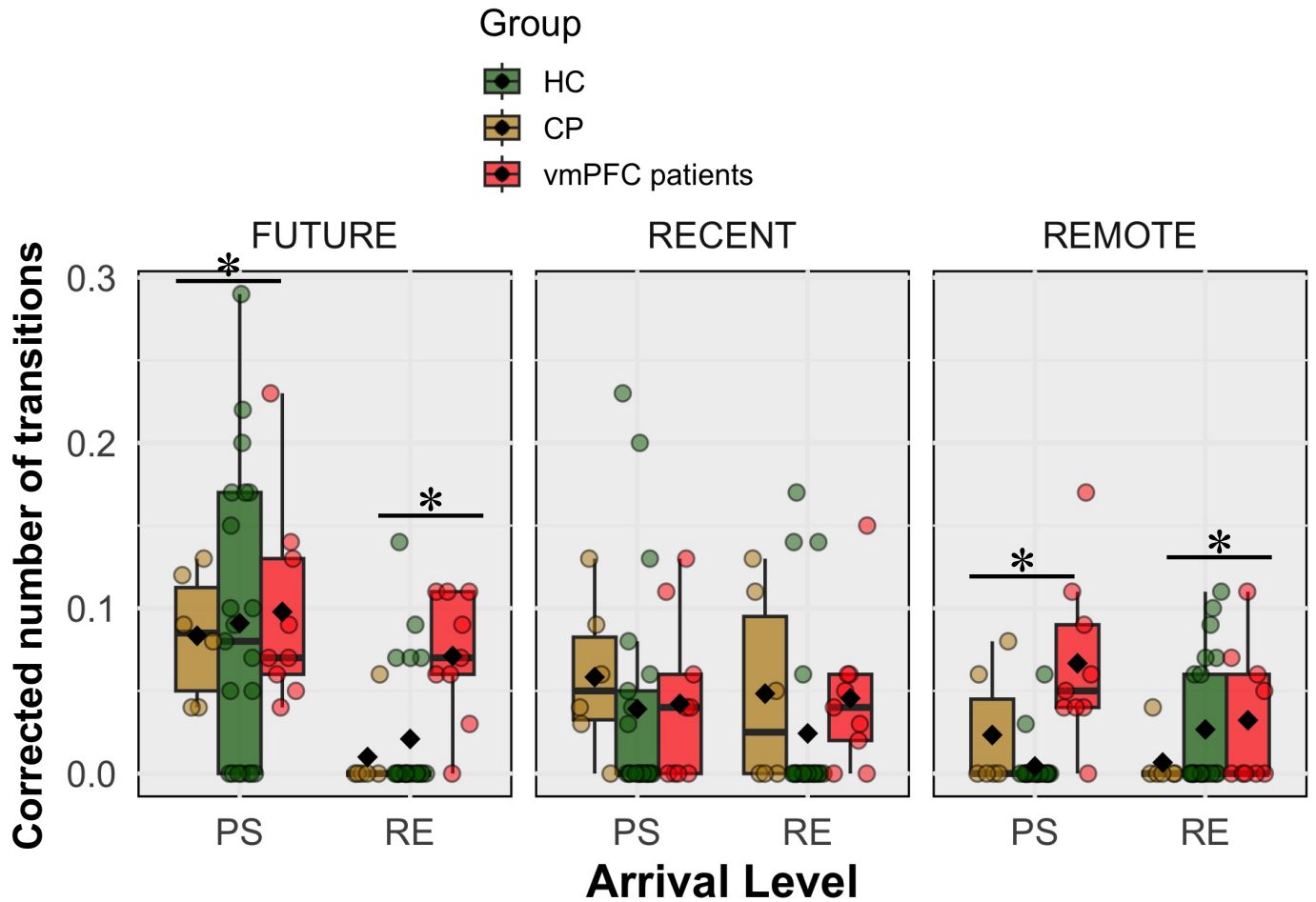


Figure 8. Corrected number of backward transitions starting from extended events (EE) by *group* (healthy controls, control patients and vmPFC patients) and time period (*remote past, recent past and future*). Black diamonds indicate the mean values, with error bars reporting the standard error of the mean. * $p < 0.05$.

Regarding the corrected number of backward transitions starting from SE, we found a main effect of arrival level [Wald $\chi^2_{(2)} = 6.95$; $p = .03$]. Participants showed more backward transitions from SE to PS (mean= 0.03; st.dev.= 0.02) compared to transitions from SE to EE (mean= 0.01; st.dev.= 0.01, $p = .022$), but not from SE to RE ($p = .13$). The remaining factors instead were not significant [all $ps \geq .06$].

In this section, the results showed that vmPFC patients exhibited more backward transitions from relatively lower to higher-level memory structures (e.g., from RE to PS or from EE to PS or RE)

compared to the control groups. These differences, in backward transitions starting from EE, were time-dependent, emerging selectively in the remote past and the future, but not in the recent past.

5. Discussion

The present study aimed to investigate the temporal progression of memory structures following damage to the vmPFC, to better specify the role vmPFC plays in event construction. As expected, we found that vmPFC patients had reduced access to personal semantic information, particularly regarding places attended in the past and previous job positions. This finding suggests that personal semantic memory is impaired following vmPFC damage.

We also replicated previous findings that vmPFC patients are impaired in event construction, and access fewer specific events compared to healthy and brain-damaged controls (Bertossi, Tesini, et al., 2016). In most cases, patients were not capable to activate a specific event, and could activate EE at best.

Different from our predictions, we did not find that vmPFC patients were impaired at activating higher order personal semantic structures. On the contrary, vmPFC patients relied more on higher-order memory structures (e.g., PS, RE, and EE) during event construction, but showed impairments accessing specific events (SE) both in the past and the future. Crucially, we were able to characterize the entire temporal progression of knowledge structures in vmPFC patients, revealing an increase in backward transitions from more concrete (e.g., RE) to more abstract (e.g., PS) memory structures, particularly when recalling events from the remote past and the future. Taken together, these findings highlight that a damage to the vmPFC disarticulates the event construction process, hindering access to SE, but also causing time-dependent abnormalities in the temporal progression across more abstract memory structures. We will now examine each of these findings in detail.

5.1. Availability and distribution of memory structures

First, vmPFC patients exhibited reduced availability of personal semantic information compared to the control groups. Reduction in PS following vmPFC damage confirms previous evidence for a privileged role of the vmPFC in representing higher-order memory structures (e.g., (D'Argembeau, 2013; Verfaellie et al., 2019; Wheeler & Stuss, 2003)). This impairment, however, was selective for places and jobs. Both these types of semantic information can be considered fundamental *cues* for event construction: mental simulation of events, in fact, requires integrating episodic details and semantic knowledge (*episodic simulation*; (Schacter, 2012b; Schacter et al., 2008) within spatial contexts (*scene construction*; Hassabis & Maguire, 2007). Burgess et al. (2001), for example, proved the pivotal role of spatial context in memory, showing how events associated with places (spatial contexts) were recalled more vividly and described in greater detail than those without (see also Robin & Moscovitch, 2014). The category jobs instead can be linked to an individual's *personal goals* and several lines of evidence (D'Argembeau, 2016; D'Argembeau, Stawarczyk, et al., 2010; D'Argembeau & Mathy, 2011; D'Argembeau & Van der Linden, 2004b; Schacter et al., 2012) suggest how personal goals play a crucial role in shaping the way humans construct mental – especially future-oriented - events. The lower availability of semantic information serving as a cue for event construction - e.g., places and events – thus, might partially explain the vmPFC patients' impairment in this process.

During event construction, vmPFC patients relied more on higher order memory structures (i.e., PS, RE and EE), but constructed fewer specific events both in the past and in the future. Hence, it seems that damage to the vmPFC does not compromise the activation of superordinate memory structures (or, alternatively, schematic knowledge; Ghosh et al., 2014), but instead it impoverishes those representations (see above), making them less likely to act as sources to construct - past or future – events (Preston & Eichenbaum, 2013). This view also aligns with the suggested role of the vmPFC as an *integrative hub* (D'Argembeau, 2020) between distinct mental representations with varying levels of abstraction to support both past and future MTT.

5.2. The temporal unfolding of memory structures: forward transitions

Our results confirmed that healthy participants could construct mental events both directly (i.e., activating SE in Unit 1) and indirectly (i.e., activating PS or EE in Unit 1, followed immediately by SE in Unit 2). During the indirect pathway, they relied on PS or EE first, reinforcing the view of autobiographical knowledge as a framework for retrieving, integrating and interpreting episodic details while constructing SE (D'Argembeau, 2020; D'Argembeau & Mathy, 2011). vmPFC patients instead, while exhibiting a preserved ability to activate PS or EE in Unit 1, displayed an impairment in the event construction process that manifested in a higher proportion of RE (instead of SE) in Unit 2. Activating RE typically does not require recall of a specific instance (like SE) but rather extraction of common features from a series of similar episodes (Neisser, 1981). RE also tend to be recalled less vividly and are rated lower in personal significance and emotional intensity compared to SE (Addis et al., 2004b; Holland et al., 2011; Levine et al., 2004). These differences have been confirmed by neuroimaging studies (Addis et al., 2004; Holland et al., 2011; Levine et al., 2004; see also Martinelli et al., 2013), reporting higher activation in the mPFC for SE, while increased activity in distinct brain regions (i.e., the left parahippocampal gyrus, and the right inferior temporal cortex) for RE. Moreover, Serra et al. (2014) demonstrated that confabulators (i.e., individuals who generate spontaneous narrative reports of events that never happened, an impairment often attributed to vmPFC damage; see Schneider, 2008) often misreport habits and repeated occurrences as unique events occurred in a specific temporo-spatial context. In our study, a damage to the vmPFC might have thus hindered access to detailed, context-rich memory structures (SE), activating instead more semanticized forms of knowledge (RE). Activation of RE, at times, allowed vmPFC patients to reach the SE, albeit more slowly - in Unit 3 - and selectively in the remote past. Accordingly, past research (Barsalou, 1988; Conway & Pleydell-Pearce, 2000; Cowan et al., 2005) highlighted the pivotal role of RE as an alternative pathway to retrieve autobiographical memories. The relative stability or slow updating of RE, in fact, would facilitate their privileged integration into self-related life narratives (Conway, 2005; Conway & Pleydell-Pearce, 2000; see also McAdams, 2001; Neisser, 1988). However, this

activation pattern (more RE and less SE) in vmPFC patients occurred regardless of trial correctness, suggesting that vmPFC damage presumably results in a *systematic* alteration in the temporal progression of memory structures – rather than a compensatory strategy or paradigmatic failure - that slows down or hinders access to the specific event.

When not able to access the SE, vmPFC patients reached EE at best in the event construction process. Previous studies (Levine et al., 2004; Moscovitch & Melo, 1997) had already observed impoverished narratives of specific events during autobiographical retrieval in patients with vmPFC damage, interpreting this deficit as indicative of a state of consciousness anchored to the present moment, that limits their capacity for MTT (Bertossi, Aleo, et al., 2016; Ingvar, 1985) and impedes the generation of event-specific sensory and emotional details (De Luca et al., 2018). An alternative perspective (e.g., Cabeza & St Jacques, 2007; Svoboda et al., 2006) suggested instead that the early activation of the vmPFC during event construction allows monitoring the output of memory search, which is essential for refining cues and guiding subsequent memory search processes. Following vmPFC damage, this lack of monitoring during event construction might result in the iterative autobiographical memory search process terminating to a more generalized level (e.g., EE), compromising access to SE (Conway, 2005). Accordingly, some studies (e.g., Conway, 2001, 2005; McDonough et al., 2015) have shown that effective monitoring of memory retrieval is crucial for enhancing event specificity, as it allows individuals to navigate through their memory representations more effectively. In our study, the lack of this vmPFC-mediated monitoring might have hindered retrieval of detailed autobiographical memories in vmPFC patients, often limiting their event construction process to the activation of EE.

It is worth noting, however, that all participants reported more EE than SE in the future compared to the remote and the recent past. Previous research (e.g., (Addis et al., 2008a, 2009; R. J. Anderson & Dewhurst, 2009; Benoit & Schacter, 2015; Schacter et al., 2008) has shown that simulating the future is more complex than retrieving the past, as it requires *simulation/generative* processes. This complexity may lead individuals to frequently forgo the construction of fully-fledged

specific representations of the mental event. Our finding of an increased reliance on EE activation selectively in the future supports the notion that achieving a certain level of event specificity is more complex when constructing future rather than. past events (Anderson & Dewhurst, 2009; D'Argembeau & Mathy, 2011; Schacter et al., 2008).

5.3. *Backward transitions*

Crucially, vmPFC patients expressed more backward transitions from relatively more concrete (e.g., EE) to more abstract (e.g., PS and RE) memory structures, especially when constructing events in the remote past and the future. This finding reveals that vmPFC damage not only prevents access to specific events, but also disrupts the typical temporal progression of knowledge structures in event construction, defining more precisely how this dysfunction manifests. In fact, the higher tendency for backward transitions across levels in vmPFC patients might be explained as an impairment in maintaining active memory structures with relatively higher levels of concreteness (e.g., EE and RE), causing instead a regression toward more semanticized representations. The time-dependent nature of backward transitions (i.e., in the remote past and the future) in vmPFC patients aligns with previous evidence on the role of the vmPFC in memory consolidation and episodic future thinking. Constructing events especially from the remote past and the future, in fact, requires semantic knowledge to a greater extent compared to the recent past (D'Argembeau & Van der Linden, 2004). For example, neuroimaging studies (Bonnici et al., 2012; Bonnici & Maguire, 2018) found an increased vmPFC activation when recalling remote vs. recent events. This was interpreted as evidence for a *memory consolidation* process that happens in the neocortex, which requires the vmPFC to initialize, coordinate, and iterate the retrieval process that allows the construction of detailed mental events (McCormick et al., 2018). Similarly, neuroimaging studies frequently reported vmPFC activation in future thinking (Addis, Wong, et al., 2007; Benoit et al., 2014; Campbell et al., 2018; D'Argembeau, Stawarczyk, et al., 2010). Lesion studies (Bertossi, Candela, et al., 2017; Ciaramelli, Anelli, et al., 2021) further supported these findings, revealing that vmPFC patients had a selective

impairment in future MTT, which was interpreted as an impairment in utilizing superordinate memory structures essential for future thinking.

6. Conclusions

The present study reveals that vmPFC damage disrupts the temporal progression of memory structures in event construction, increasing backward transitions from relatively more concrete to more abstract memory structures, and hindering access to SE. Taken together, our findings confirm the role of vmPFC as a *supervisor* (McCormick et al., 2018) and an *integration hub* (D'Argembeau, 2020) that warrants the integration of autobiographical knowledge and episodic simulations derived from the activity of the MTL and other brain regions involved in MTT.

Future research, however, exploring the entire temporal progression of memory structures (while thinking aloud) in vmPFC patients - possibly employing less constrained conditions and without directly prompting personal semantic knowledge (e.g. Crovitz task, starting from a cue word; Crovitz & Schiffman, 1974) - could further validate this vmPFC-mediated alteration/impairment in event construction. Similarly, examining the precise temporal progression of memory structures following hippocampal damage— eventually comparing hippocampal patients' reports with those from vmPFC patients—could provide deeper insights into the distinct contributions of these two critical brain regions to MTT.

Chapter 4.

Creating outward to think inward:

Simultaneous modulation of spontaneous and deliberate thought

The aim of the previous Chapters has been to identify the neural and phenomenological bases of spontaneous (*mind-wandering*; Chapters 1 and 2) and deliberate thought (*MTT*; Chapter 3). As highlighted in the Introduction, however, these two forms of thought rarely function entirely independently. Rather, the interaction of various large-scale neural networks (including the DMN and FPCN) shapes the ongoing unfolding of thought along a continuum between deliberate and automatic constraints. We have also examined how physiological parameters - such as pupil diameter - can serve as reliable indicators for tracking both spontaneous and deliberate thought. Lastly, we have introduced the concept of intention offloading, which involves externalizing aspects of our thought content, thereby reducing, for example, the cognitive load required to fulfill future intentions (deliberate thought).

In light of this evidence, Chapter 4 takes a further step by simultaneously investigating the effect of intention offloading on both spontaneous (mind-wandering) and deliberate thought (PM). The concomitant recording of pupil diameters allows us to track attentional fluctuations over time, enhancing the reliability of self-reported episodes of mind-wandering.

Study 4.

***Freeing the Mind with External Reminders:
Intention Offloading decreases Pupil Diameter
and Off-task thinking levels***

Giovanni Cantarella^{1,2}, Sarah White³, Elisa Ciaramelli^{1,2} & Sam J. Gilbert³

¹ *Department of Psychology 'Renzo Canestrari', University of Bologna, Bologna, Italy*

² *Center for Studies and Research of Cognitive Neuroscience, University of Bologna, Cesena, Italy*

³ *Institute of Cognitive Neuroscience, University College London, London, UK*

Abstract

Cognitive resources are continually allocated between external task demands and internal thought processes, making optimal cognitive control essential to prevent interference between these attentional shifts. Intention offloading—the use of external reminders to store future intentions—has been shown to reduce cognitive load and improve prospective memory performance. However, its simultaneous impact on external (prospective memory) and internal (off-task thinking) processes remains unclear. In two studies, we investigated how intention offloading influences both externally directed cognition (prospective memory) and internally directed cognition (off-task thinking). In Study 4a, participants performed an online prospective memory task under low and high memory load conditions. In some trials, they relied solely on internal memory, whereas in others they could offload their intentions using external reminders. In Study 4b, participants completed a similar prospective memory task in the laboratory while their pupil diameter was recorded using an eye tracker. They monitored for target-colored digits while simultaneously completing an odd/even judgment task under high (three targets) or low (one target) memory load conditions. In half of the trials, participants could offload their intentions via on-screen reminders; in the remaining trials, they relied solely on internal memory. In both studies, random thought probes—designed to measure levels of off-task thinking and thought intentionality—interrupted the task. In Study 4a, offloading improved task performance, particularly under high memory load, without significantly affecting off-task thinking or its intentionality. In Study 4b, offloading reduced pupil diameter (especially under high memory load) and decreased off-task thinking over time, but did not alter thought intentionality. Overall, these findings indicate that intention offloading preserves cognitive resources, facilitating a more efficient allocation between external and internal cognitive processes, as evidenced by both behavioral and physiological measures.

General introduction

Our existence is shaped by the ebb and flow of attention between internal and external sources. This occurs, for example, when we intensely focus on external tasks—like navigating through traffic—only to find ourselves soon after immersed in internal thoughts, reflecting on a future decision or recalling a past event. An important research question, then, would be to identify the conditions that minimize interference between these internal and external attentional shifts.

Externally directed cognition involves attention directed outward to stimuli in the external environment (Chun et al., 2011; Dixon et al., 2014; Lieberman, 2007). It can be spontaneous, such as when an external stimulus captures attention and its processing occurs without deliberate effort (*stimulus-driven attentional reorienting*, Corbetta & Shulman, 2002; Yantis & Hillstrom, 1994), and this type of cognition has been studied through priming studies (e.g., Dehaene et al., 1998; Greenwald et al., 1996). Otherwise, this process can be intentional, such when individuals consciously shift their attention toward a specific location/object based on an informative cue. In these cognitive states, external stimuli are processed through voluntary attentional control, that is often studied in laboratory using selective attention (Buschman & Miller, 2007; Corbetta & Shulman, 2002) and cognitive control (Egner & Hirsch, 2005; see also Miller & Cohen, 2001) tasks, i.e., where participants follow rules to intentionally respond to external stimuli.

High levels of intentionality for externally directed cognition are required, for example, in Prospective Memory (PM). PM refers to a complex interplay of higher-order cognitive processes that enable us to remember and execute intended actions in the future (Graf & Utzl, 2001). A standard PM paradigm typically requires participants to engage in a primary ongoing task while simultaneously performing an additional task, that might involve remembering to perform a specific action either at the appearance of a determined cue (event-based PM) or at designated time-points (time-based PM). The complexity of the PM task - often measured by memory load (e.g., the number of intentions to remember) - can significantly impact behavioral performance. This impact is evidenced by slower

reaction times and/or lower accuracy compared to conditions where participants perform the same task without monitoring for the PM target (M. A. Brandimonte et al., 2001). The behavioral findings of a *PM cost* (F. Anderson et al., 2019) suggest that both the ONG task and PM target monitoring rely, to some degree, on shared cognitive resources.

A portion of the memory load generated by a PM instruction can be delegated to the external environment. This strategy - employing external prompts or reminders to trigger the intended action at the appropriate time - is named *intention offloading* (Boldt & Gilbert, 2019; Gilbert, 2015). Externalizing information - through the use of a physical action into the external world - offers several potential benefits. For instance, offloaded intentions may be less susceptible to memory distortions compared to internally-stored intentions, thereby increasing the likelihood of successful task completion. Offloading is affected by *memory load*: people, in fact, tend rely more on external reminders when required to remember three items compared to just one, and exhibit reduced accuracy in their behavioral performance when relying solely on internal memory (Gilbert, 2015). Moreover, offloading intentions has been shown to affect brain activity, specifically by reducing deactivation in medial rostral PFC - a brain region typically involved in maintaining internal representations of task-relevant information, such as future intentions (Landsiedel & Gilbert, 2015).

The strategic deployment of cognitive resources is also essential for internally directed cognition (Dixon et al., 2014). Similar to external attention, in fact, we might spontaneously drift our attention away from the external current activity to think about task-unrelated contents, such as past events, future plans, or social relationships - i.e., *task-unrelated thought/mind-wandering* (Dixon et al., 2014; Giambra, 1995; McVay & Kane, 2009; Smallwood et al., 2003; Smallwood & Schooler, 2015). At other times, individuals may intentionally engage in task-unrelated thought: one example is during monotonous tasks, where they may consciously decide to *tune-out* (J. Schooler et al., 2011) and let their minds wander, thus recruiting attentional control over the direction of thought (Seli, Ralph, Konishi, et al., 2017; Seli, Risko, Smilek, et al., 2016).

The distinction between intentional and unintentional mind-wandering corresponds to dissociable behavioral and neural patterns (Golchert et al., 2017; Seli, Ralph, Konishi, et al., 2017). Unintentional mind-wandering reflects a failure of the executive system to sustain focus, particularly under high cognitive load (Seli, Konishi, et al., 2018). This is supported by its association with attention-deficit/hyperactivity disorder and obsessive-compulsive disorder (Seli et al., 2015; Seli, Risko, Purdon, et al., 2017). Moreover, task difficulty influences mind-wandering intentionality levels, with easier tasks increasing intentional mind-wandering (Seli et al., 2018). Golchert et al. (2017) suggested that the key distinction lies in the degree of executive control exerted, shaping whether internal thoughts are deliberate or spontaneous (Christoff et al., 2016; Seli, Risko, Smilek, et al., 2016).

Externally and internally directed cognition can either compete or coexist with minimal interference (Dixon et al., 2014). Generally, competition in the recruitment of cognitive resources occurs when both require a high level of intentionality, such when one is intentionally searching for a friend in the crowd while mentally planning a future event. In this regard, the *resource-control theory* suggests that cognitive control is crucial for sustaining intentional task focus and minimizing task-unrelated thoughts, which would increase as cognitive control declines (Thomson et al., 2015). An alternative view (i.e., *the opportunity cost model*; Kurzban et al., 2013) posits instead that as tasks become less rewarding, the mind seeks alternative stimulation, leading to mind-wandering and aversive states like boredom and fatigue (Westgate & Wilson, 2018; Wolff & Martarelli, 2020). Nonetheless, externally and internally directed cognition can coexist with minimal interference when one or both involve spontaneous processes that do not tax attentional resources. For example, automatized tasks involving externally directed cognition can be performed alongside frequent mind-wandering without significant disruption (Smallwood & Schooler, 2006). As well, mind-wandering does not interfere with unexpected stimuli that capture attention externally (Kam & Handy, 2013). Bengtsson et al. (2010) provided further evidence for this co-existence: participants primed to think

of themselves as *clever* during a working memory task showed improved performance and simultaneously increased neural activation in regions associated with self-reflection.

In summary, although externally and internally directed cognition rely on the same pool of cognitive resources, they can co-exist as long as neither demands high levels of cognitive control. One way to reduce the level of cognitive control - thus optimizing the availability of cognitive resources - is intention offloading. We hypothesize that the use of intention offloading decreases the level of intentionality required in tasks involving externally directed cognition (event-based PM), thereby allowing for more intentional forms of off-task thought (internally directed cognition). To verify this, we had participants perform an intention offloading task (external attention) with concomitant off-task thinking (internal attention) and intentionality levels assessment. We manipulated memory load (high vs. low) and allowed participants to offload their intentions in half of the blocks, while preventing them from doing so in the other half. If it is true that offloading frees up cognitive resources to think more intentionally, offloading blocks should determine higher levels of intentionality in participants' thought. This should apply selectively for the high memory load condition, i.e., where offloading is more effective in increasing the availability of cognitive resources (Gilbert, 2015).

Study 4a

1. Methods

1.1. Participants

Sixty-six participants were recruited through the Prolific website (<https://www.prolific.com>), an online platform where individuals receive payments for completing tasks. A standard sample was requested, without restrictions based on nationality or other criteria. The study was approved by the

UCL Research Ethics Committee (ICN-VW-28-22-2023), and all participants provided informed consent before beginning the experimental procedure.

A power analysis was conducted using G*Power 3.1 software (Faul et al., 2007). The primary aim was to power the study to detect a main effect of intention offloading on the frequency of off-task thoughts. Since this effect had not been previously explored, we considered the possibility of detecting a main effect of memory load (e.g., task difficulty) on off-task thought frequency, assuming that the effect of intention offloading could be comparable in magnitude. The computation was based on the findings of a previous study that examined the effect of performing different tasks with varying cognitive demands on intentional vs. unintentional mind-wandering (Robinson & Unsworth, 2018), which yielded an effect size (η_p^2) of .03. To achieve 80% power to detect an effect of this size (with $\alpha = .05$) in a within-subject comparison (correlation between repeated measures = 0.5), the analysis required a sample of $N=66$ participants.

The experiment lasted approximately 45 minutes in total, for which participants were remunerated £7.

1.2. Design

1.2.1. Intention Offloading task and concomitant off-task thinking assessment

The intention-offloading task (Gilbert, 2015; Gilbert et al., 2023; see Figure 1a) began with a short practice session to ensure that participants fully understood the task instructions. It included a total of 60 trials; in each trial, 15 randomly positioned yellow circles, numbered from 1 to 15, appeared within a square. Participants were instructed to sequentially drag the circles in ascending order (1, 2, 3, etc.) to the bottom of the square. Once a circle was dragged to the bottom, it disappeared, leaving the remaining circles on the screen. After the 15th circle was moved, the screen reset, initiating

the next trial. A 45-second timer was displayed on the screen for each trial, after which participants were prompted to complete the task more quickly to fit within the time limit.

During each trial, participants received delayed intentions. Specifically, they were instructed to drag one or three circles (representing low or high memory load conditions, randomly assigned to trials) to a predefined location (e.g., left, right, or top of the square) when the corresponding numbers appeared in the sequence. This required participants to form delayed intentions to perform specific actions upon encountering predetermined cues, with the possibility of reverting to the standard response (dragging the circle to the bottom) if they forgot. Correct placements were indicated by the circle turning green before disappearing, while incorrect placements turned red. The assignment of target numbers was constrained to occur between numbers 10 and 15.

In half of the trials (randomly assigned), participants were forced to offload their intentions. At the beginning of these trials, participants had to move the target circles to their intended location, thus eliminating the need to mentally rehearse the delayed intentions. Instead, the target circle's position itself served as a perceptual reminder when it was reached in the sequence. In these trials, participants were explicitly instructed, "*You MUST set reminders on this trial*". Offloading was ensured by forcing participants to position all target circles before removing any other circles from the bottom of the box. In trials where offloading was not allowed, participants were informed "*You CANNOT set reminders on this trial*". In these instances, offloading was blocked by locking the circles in place, apart from the next in the sequence, thus preventing participants from adjusting the position of upcoming target circles until it was their turn to be removed.

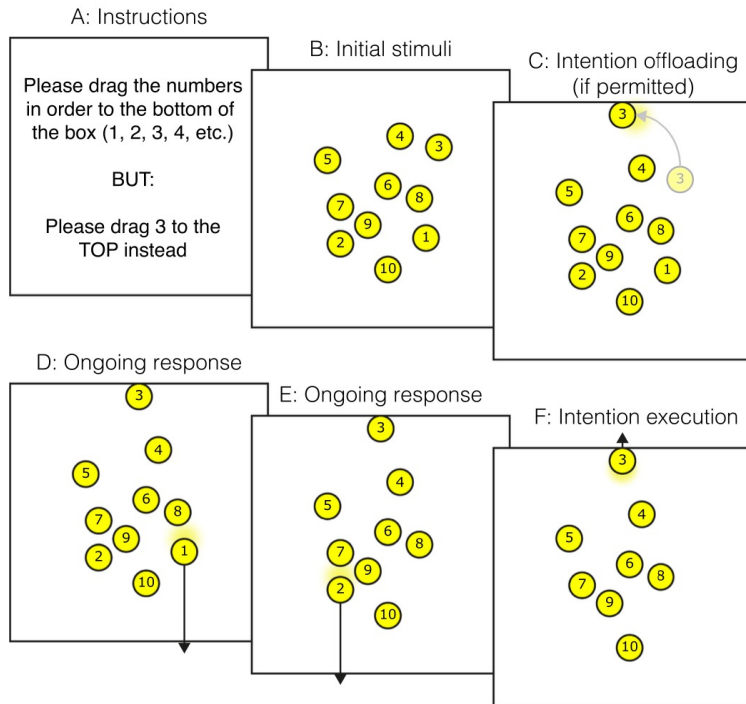
Off-task thinking was assessed using a probe-caught method (Schooler et al., 2011; Smallwood & Schooler, 2006; see Figure 1b), with 16 thought probes interrupting the intention-offloading task. The first screen of each probe prompted participants to rate, using a continuous slider ranging from 0 to 100, the extent to which their thoughts were on-task (i.e., focused on performing

the task) or off-task (i.e., focused on something unrelated to the task, such as personal thoughts, feelings about the experiment, or external distractions) immediately before the probe. On the second screen, participants rated the degree to which their off-task thoughts were intentional (i.e., they deliberately engaged in thinking about something unrelated to the task) or unintentional (i.e., the thought spontaneously occurred without their deliberate engagement), also using a continuous slider. To avoid response biases, for both probes, the order of the response options was counterbalanced across participants.

Participants received only one thought probe per trial. The thought probes were designed to maximize the likelihood of capturing moments when participants were maintaining the delayed intention, thereby making the effect of intention offloading more discernible. To achieve this, in all trials, the probes were presented between the encoding phase (when task instructions were presented) and the retrieval phase (when the delayed intentions were executed). Specifically, the probes appeared during the time window between dragging circles numbered 5 and 8.

Following each thought probe, the trial terminated, so no accuracy data were recorded for these trials. Thought probes were presented in trials 3, 7, 10, 15, 18, 22, 25, 28, 31, 35, 38, 43, 46, 50, 54, and 59, in a fixed sequence to ensure a probe interval of 3-5 trials (see also Seli et al., 2013). Moreover, experimental conditions were randomly assigned, with two of the sixteen probes corresponding to each of the cells in the 2x2 experimental design, presented in random order.

a) Intention offloading task

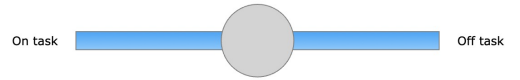


b) Thought probes

Off-task thinking

Please tell us to what your thoughts just now were

On Task (totally focused on the circle-dragging memory task), **Off Task** (totally focused on something else), or somewhere in between.



Intentionality

Now please tell us to what extent any Off task thoughts were **Intentional**, **Unintentional** or somewhere in between.

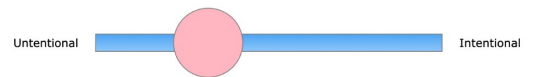


Figure 1. Schematic illustration of the experimental design. Panel a) illustrates the intention offloading task (Gilbert, 2015; Gilbert et al., 2023), where participants were instructed to drag numbers in sequential order (1, 2, 3, etc.) to the bottom of the screen, with the exception to drag one or three target digit to different locations of the screen. In the Offloading condition (top right), participants were forced to offload their intention by immediately dragging the target number (e.g., number 3) to the predefined position (e.g., top of the screen). In the no Offloading condition (bottom right), participants had to rely on their memory to execute the intention at the correct time. Panel b) shows some examples of thought probes with continuous measure that interrupted the task to assess participants' off-task thinking (top scale) and intentionality (bottom scale) levels.

1.2.2 Analyses

We defined *memory hits* as the proportion of targets successfully dragged to their instructed location, as opposed to being placed at the bottom of the screen. Only trials in which the target was moved to the correct location on the first attempt were considered accurate. For instance, if a participant initially attempted to drag the target to an incorrect location, realized the error, and then moved it to the correct location, the trial was not classified as correct. We identified *false alarms* as cases in which non-target circles were mistakenly moved to the top, left, or right border of the screen,

and *confusions* as instances where target circles were incorrectly dragged to one of the incorrect target locations (e.g. a circle that was instructed to the left being dragged to the right instead).

Participants were excluded from the analyses if their accuracy in the non-offloading condition deviated by more than three Median Absolute Deviation (MAD) units compared to other participants, or their accuracy in the offloading condition exceeded this threshold. Additionally, participants were excluded if they showed zero variance in their levels of off-task experience (e.g., consistently selecting one extreme end of the scale across all trials). Nine participants did not meet these criteria and were therefore excluded from the analyses, resulting in a final sample size of $N = 57$.

To assess whether participants' performance in the intention offloading task varied under different levels of cognitive load, we conducted a repeated-measures ANOVA on the percentage of memory hits in the intention offloading task, with Memory Load (high vs. low) and Offloading (yes vs. no) as factors. We also conducted paired sample t-tests on memory hits to compare offloading vs. no-offloading trials, separately for the 1-target and 3-target conditions. The same analysis was run for the percentages of confusions and false alarms. In all cases, post-hoc analyses were performed with Bonferroni's correction.

To examine whether off-task thinking measures were influenced by memory load and/or intention offloading, we run a Linear Mixed Model (LMM) on the off-task thought probe data, with *Memory Load*, *Offloading* and *Task Duration* (first half; 1-30 trials and second half; 31-60 trials of the entire task duration) as factors. The same analysis was then performed on the intentionality thought probe measure.

2. Results

2.1. Intention Offloading task

The ANOVA on the percentages of memory hits yielded a main effect of *Offloading* [$F_{1,56} = 7.499$, $p = .008$, $\eta_p^2 = .118$], and a significant *Memory Load*Offloading* interaction [$F_{1,56} = 18.075$, $p < .001$, $\eta_p^2 = .244$]. In the high memory load condition (3 targets), participants made a significantly higher percentages of memory hits in offloading blocks (93.75%) compared to no offloading blocks (87.03%, $p < .001$); in the low memory load condition instead, we did not find any significant difference between offloading (89.91%) and no offloading (91.55%, $p = .99$) blocks. The main effect of *Memory Load* [$F_{1,56} = 0.110$, $p = .742$] failed to reach statistical significance.

The analysis on the percentages of confusions revealed an effect of both *Offloading* [$F_{1,56} = 15.452$, $p < .001$, $\eta_p^2 = .216$] and *Memory Load* [$F_{1,56} = 28.767$, $p < .001$, $\eta_p^2 = .339$], that was qualified by the significant *Memory Load*Offloading* interaction [$F_{1,56} = 10.874$, $p = .002$, $\eta_p^2 = .163$]. In the high memory condition, offloading blocks showed lower percentages of confusions (3.83%) compared to no offloading blocks (8.98 %, $p < .001$); in the low memory condition instead, no significant difference in the percentages of confusions emerged between offloading (1.75%) and no offloading (2.07 %, $p = .99$) blocks.

Regarding the ANOVA on the percentages of false alarms, the factors *Offloading* [$F_{1,56} = 0.580$, $p = .450$] and *Memory Load* [$F_{1,56} = 0.644$, $p = .426$], and the interaction *Memory Load*Offloading* [$F_{1,56} = 3.199$, $p = .079$] failed to reach statistical significance.

2.2. Off-task thinking

Results of the LMM on the off-task thinking levels revealed an effect of *Task Duration* [Wald $\chi^2_{(1)} = 8.965$; $p = .002$]: participants reported significantly higher levels of off-task thinking in the

second half (20.37%) compared to the first half (16.62%) of the task (see Figure 2). The factors *Offloading* [Wald $\chi^2_{(1)} = 0.149$; $p = .699$] and *Memory Load* [Wald $\chi^2_{(1)} = .110$; $p = 0.741$] instead were not significant.

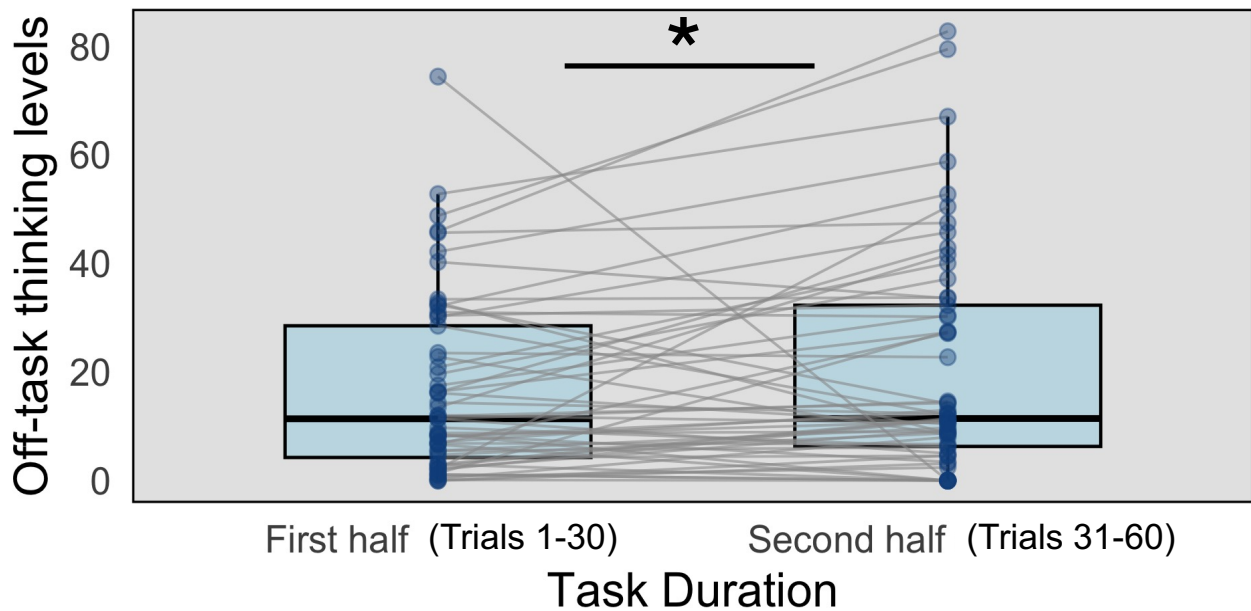


Figure 2. Levels of off-task thinking across task duration (first half: trials 1-30; second half: trials 31-60). Individual data points are jittered around each boxplot for clarity, while gray lines connect observations for each participant. * <.005

Regarding the LMM on the intentionality levels, none of the factors reached statistical significance (all $ps > .27$).

3. Discussion

In Study 4a, intention offloading effectively improved performance in the offloading task. However, contrary to our hypothesis, we did not observe any significant effect of intention offloading on either off-task thinking or levels of intentionality.

Participants reported an average off-task thinking rate of 18%. This percentage is relatively low compared to the average reported in other studies on off-task thinking using the same continuous measure (around 40%, e.g., Giordani et al., 2023). A possible explanation for this lower level of off-task thinking lies in the use of the Prolific online platform for participants' recruitment. In fact, Albert

& Smilek (2023) found that the use of Prolific is associated with lower levels of task disengagement compared to other online platforms, such as MTurk. The differences between platforms were explained by their distinct compensation policies: Prolific, in fact, allows researchers to use attention and comprehension checks to assess disengagement and deny payment. Moreover, Prolific policy may reduce disengagement by increasing the perceived risk of losing compensation or by selecting against participants more prone to task disengagement. These discrepancies could affect study outcomes, particularly when attention is a variable of interest.

It is worth noting, however, that the level of off-task thinking increased from the first to the second half of the task, replicating previous findings regarding the presence of a *time-on-task effect* (e.g., Brosowsky et al., 2021, 2023; Krinsky et al., 2017; Thomson et al., 2014; Zanesco et al., 2024). This effect has been observed in various task contexts, with some evidence indicating that mind-wandering increases faster in high-demand tasks (Krinsky et al., 2017), while other findings suggest that it is more prevalent in low-demand, routinized tasks (Blondé et al., 2021; Brosowsky et al., 2021; Van den Driessche et al., 2017). The time-on-task effect was attributed to the vigilance decrement, and linked to boredom and task disengagement, as engaging in off-task thinking should decrease attention to external stimuli. In the present study, it is plausible that although participants reported overall low levels of off-task thinking and relatively high accuracy, their attention levels declined over the course of the task, driven by decreased cognitive control (Thomson et al., 2015), boredom, and fatigue (Kurzban et al., 2013). This supports the hypothesis of a *competition* between attentional resources directed externally (task performance) or internally (off-task thinking). Offloading task-related intentions, however, was not sufficient to optimize the recruitment of attentional resources, balancing performance costs with engagement in off-task thinking.

Study 4b

Understanding the occurrence of off-task thinking during ongoing activities is crucial for predicting the occurrence of undesired attentional lapses. Relying solely on self-report techniques, however, can obscure real fluctuations in task engagement. Even though techniques like experience-sampling can periodically assess participants' attentional states and reveal a link between mind-wandering and various experimental manipulations (see Smallwood & Schooler, 2006, 2015 for reviews), in fact, these techniques are inherently subjective, not ensuring consistency of mind-wandering measurements across participants (Zheng et al., 2019; see also Kane et al., 2021). In contrast, physiological measures such as pupillometry offer additional insights into sustained attention and alertness (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Samuels & Szabadi, 2008; Szabadi, 2013), as they are directly related to the activity of the locus coeruleus norepinephrine (LC-NE) system.

The LC-NE system has been primarily linked to the regulation of the sleep-wake cycle and general arousal levels (Berridge & Waterhouse, 2003; Samuels & Szabadi, 2008; Szabadi, 2013), which in turn affect attentional focus. In particular, low LC-NE activity results in inattention and poor performance, while excessively high activity increases distractibility. Optimal performance occurs instead at moderate levels of tonic LC-NE activity, which would enable efficient phasic responses to task-relevant stimuli. Lenartowicz et al. (2013) suggested that LC-NE activity not only impacts focus but also affects the nature of attention lapses. Specifically, the combination of attention direction (internal vs. external) and arousal state influences the type of attentional lapse: external focus of attention with low arousal leads to external distraction, while internal focus with low arousal causes mind-wandering or mind-blanking. High arousal with internal focus instead is associated with exploratory mind-wandering, ruminations, or intrusive thoughts (Unsworth & Robison, 2018). Mittner et al. (2016) further supported this assumption, proposing the existence of three LC-NE states: *on-task* when attentional focus is entirely toward the environment, *off-task exploratory* for the highest

arousal levels, and *active mind-wandering* for optimal internal focus. Finally, a series of studies by Unsworth & Robison (2018) investigated the relationship between arousal levels, attentional states and mind-wandering using pupillometry during both the Stroop and the Psychomotor vigilance tasks. Their results suggested that different mind-wandering states are context-dependent and correspond to varying arousal and attentional focus levels. For example, in situations promoting external attention, on-task reports were associated with larger pupil diameters compared to mind-wandering, but this difference disappeared in situations promoting internal attention (e.g., participants are expected to give a speech). Additional evidence is awaited, however, to confirm the exact contribution of LC-NE activity in different forms of spontaneous cognition.

Another potential insight into the role of the LC-NE system in higher-order cognition comes from research in PM. In this regard, Moyes et al. (2019) used the pupillometry signatures to reveal insight into sustained monitoring vs. transient checking processes involved in an event-based PM task. The pupillary measures indicated a sustained monitoring effect in the PM vs. ONG condition, characterized by a continuous and consistent pupillary dilation throughout the trial - as opposed to a transient checking process time-locked to the PM target presentation. This effect was specific to category PM, i.e., when participants were required to detect target items within a predefined category (e.g., animals or colors) while performing another ONG (lexical decision) task (Moyes et al., 2019). However, it's not yet understood if the effects of offloading intentions on PM processes are also detectable at the physiological level.

Building on this background, Study 4b aims to explore the pupillometric signatures of the effect of intention offloading on two forms of thought: spontaneous – off-task thinking - and deliberate - PM. To achieve this, participants performed a PM task under two memory load conditions (high vs. low), while simultaneously recording their pupil diameter through an eye-tracker device. In half of the PM task blocks, participants offloaded their intentions by using external reminders to accomplish the PM instructions, whereas in the other half, they had to rely solely on their memory to retain the instructions. Similar to Study 4a, thought probes interrupted the PM task, prompting participants to

estimate their off-task thinking and intentionality levels. If intention offloading effectively preserves cognitive resources, this should be reflected in a decrease in pupil diameter in offloading blocks compared to blocks where participants rely solely on their memory. This difference should selectively occur in high vs. low-memory-load conditions, which demand a higher recruitment of cognitive resources. Moreover, if these preserved resources are redirected toward more adaptive forms of thinking, intention offloading should lead to higher levels of intentionality in thought.

1. Methods

1.1. Participants

Participants were recruited from the subject database of the Institute of Cognitive Neuroscience, with no previous history of psychiatric or neurological disease. They had normal or corrected-to-normal vision (i.e., contact lenses). A total of 68 participants (40 females; mean age = 31.86 years; range: 19–61), matched for gender balance ($\chi^2 = 2.97$, $p \geq .08$), took part in the study. The study was approved by the UCL Research Ethics Committee (ICN-VW-28-22-2023), and written informed consent was obtained from each participant prior to participation.

A statistical power analysis was performed with G*Power 3.1 software (Faul et al., 2007). We considered the probability to detect a main effect of Condition (PM vs. ONG) on the mean pupil size, based on the results of a previous study (Moyes et al., 2019). The power analysis indicated a minimum sample size of $N = 44$ participants to achieve a 95% power to replicate an effect of half this magnitude ($\eta_p^2 = .05$; $\alpha = .05$), in a within-subject comparison (correlation between repeated measures = 0.5). The experimental session lasted approximately 1 hour, for which participants received a payment of £9. The study protocol was pre-registered (<https://osf.io/gub4d/>) prior to data collection.

1.2. Design

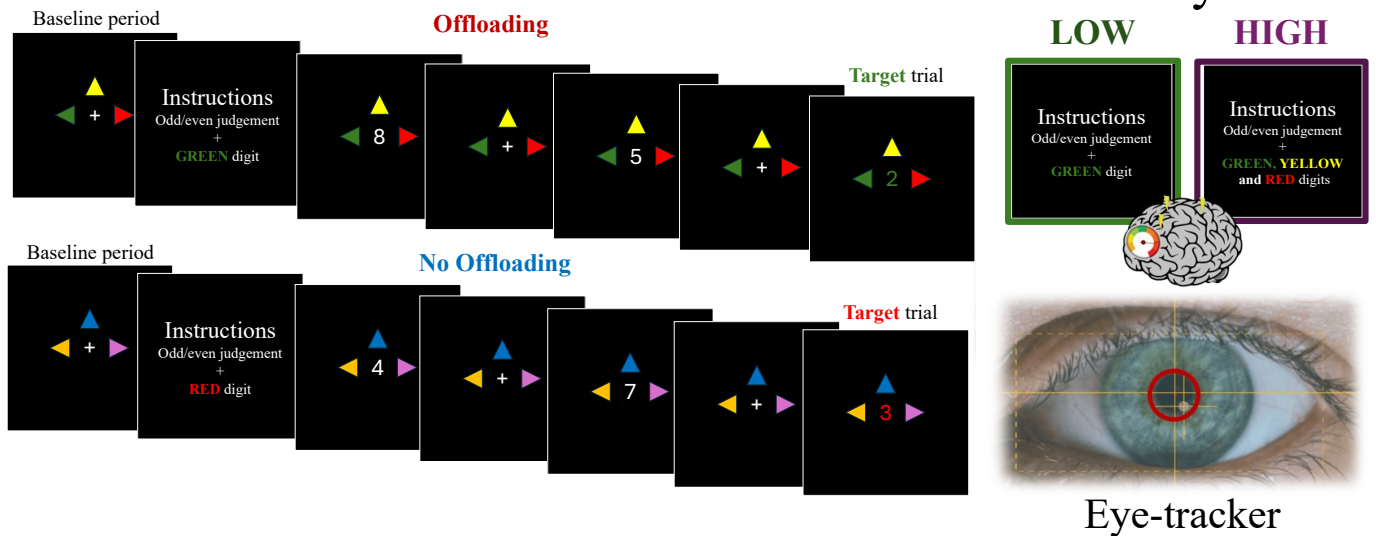
1.2.1. Prospective Memory task and concomitant off-task thinking assessment

The PM task involved 40 blocks in total. In each block, participants were presented with a stream of digits (1-9). The ONG task required them to perform an odd/even judgement in response to each digit, by pressing “Z” or “M” keys. At the beginning of each block, participants received delayed intentions (see Figure 1a). Specifically, they were asked to monitor the appearance of colored digits, which required withholding the response to the ONG task and pressing directional keys instead (e.g., left, right or up arrows). In the low load condition, participants were required to monitor for 1 target color, while the high load condition involved monitoring 3 target colors (e.g. press the left arrow when you see a red digit, the up arrow for the green digit, and a right arrow for the yellow digit).

In half of the blocks, the task also included a possibility for *intention offloading* (see Figure 3a): before the beginning of the trial, the participant could press another key, i.e., the spacebar, to stamp on the screen a reminder of both the target colors (e.g., red, green and yellow) and the corresponding directional keys (right, left and upper arrows) to be remembered. Then, both the target colors and the response keys (i.e., colored arrows) remained on the screen for the entire length of the intention offloading blocks, with no need to rehearse them.

The colored arrows were displayed on the screen in both offloading and no offloading conditions. However, to prevent participants from using the previously learned response key-color associations in the no offloading blocks, they appeared in two different color sets (e.g., *red, green and yellow* or *orange, purple and blue*). In the offloading blocks, the colors of the directional keys always matched the color of the target numbers – thus acting as *reminders* - whereas in the no offloading blocks they did not match (e.g., colors of target digits were green, red and yellow but arrows were colored in purple, orange and blue) and, thus, participants were instructed to ignore them. The assignment of color sets to the two categories (**1. Targets + real reminders**; **2. Ignored reminders only**) was counterbalanced between participants.

a) Prospective Memory task



b) Thought probes

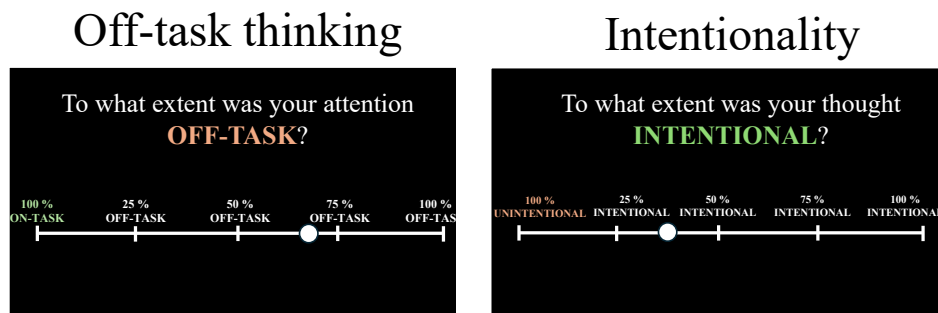


Figure 3. Panel *a*) illustrates the Prospective Memory (PM) task, where participants were presented with a stream of digits and made odd/even judgments while monitoring for the appearance of target – colored - digits. In the Offloading condition (top row, in red), participants could rely on the three colored digits displayed on the screen to execute the delayed intention. In the no Offloading condition (bottom row, in green), the colored arrows on the screen differed from the target colors, requiring participants to rely solely on their memory. Moreover, participants monitored for the appearance of either one (low memory load) or three (high memory load) targets. Panel *b*) depicts some examples of thought probes that interrupted the PM task to assess participants' off-task thinking and intentionality levels using continuous scales. An eye-tracking device continuously recorded pupil diameter and gaze direction throughout the task.

Prior to each block, a stimulus - composed of a fixation point (+) surrounded by the colored arrows for that block – appeared on the screen for 3 seconds (i.e., *baseline period*, see Figure 1a). This stimulus was chosen to approximate the size of task stimuli (digits) and was included to record a *baseline* measure of pupil diameter. The baseline recording, in fact, was intended to be subtracted

from the data collected during the subsequent block to improve data quality by controlling for the natural fluctuations in pupil size throughout the experiment (see also Mathôt & Vilotijević, 2023; Reimer et al., 2016). In an earlier version of the task, the baseline period followed the presentation of instructions for the current block. However, to avoid the pupil diameter being influenced by the cognitive load of recently reading the instructions, in a new version, this baseline period was shifted to precede the instruction block. Pupillometry analyses (see below) were conducted exclusively on data from this revised version of the task.

To control for *order effects* the block sequence was fully randomized for each participant, ensuring that each condition appeared exactly 10 times throughout the task. Moreover, all conditions were equally likely to precede or follow one another, minimizing *carryover* effects between blocks. Each block was composed of 14-20 trials. Since we were interested in characterizing the behavioral and physiological profile of the - sustained - monitoring process for the PM targets, the target digit consistently appeared in the final trial of all blocks. The block length, however, was randomized (14-20 trials), so that participants could not predict when the target occurred. Refer to the following paragraph for a more extensive description of the stimuli used in each trial.

Off-task thinking was measured through the *probe-caught* method (Schooler et al., 2011; Smallwood & Schooler, 2006): 12 thought probes interrupted the PM task, with one probe occurring per block (see Figure 3b). A first screen probed participants to estimate the percentage to which, immediately before the probe, their thoughts were *on-task*, i.e., focused on performing the task, *off-task*, i.e., focused on something unrelated to task execution (like the own thoughts, feelings about the experiment, or some other distraction in the environment) or somewhere in between, by using a slider with continuous measure ranging from – “100% on-task” to – “100% off-task”. In a second screen, they had to estimate the percentage to which their off-task thoughts were intentional, i.e., they have deliberately engaged in thinking about something unrelated to the task, unintentional, i.e., something popped up into their minds without deciding to do it deliberately, or somewhere in between, by using a slider with continuous measure ranging from - “100% unintentional” to – “100% intentional”.-

Participants were prompted with a maximum of one thought probe per block. To avoid appearing too close to the block instructions, the thought probe could only interrupt the task after the 10th trial of each block. After the thought probe, the current block was interrupted – without target appearance - and the task proceeded with the next block. Thought probes were randomly allocated so that 3 out of the 12 probes corresponded to each cell in the 2x2 experimental design, with the additional constraint of having at least one block as time interval between them.

1.3. Equipment and stimuli

Pupil diameter was continuously recorded binocularly at 120 Hz using an Tobii Pro SDK eye tracker (<https://developer.tobiipro.com/index.html>) positioned approximately 50 cm from the participant (see Gibaldi et al., 2017 for empirical validation of pupillometry data from this device). Participants used a chin rest to ensure immobilization during the experimental procedure. Stimulus presentation and data collection were conducted on a PC running Psych toolbox (3.0.19) with MATLAB R2020a, in conjunction with the *Tobii Pro SDK Toolbox* for MATLAB (<https://www.developer.tobiipro.com/matlab/matlab-getting-started.html>).

In each trial, a stream of digits (1-9) – surrounded by arrows - was presented in randomized order, interspersed by a fixation point. Stimuli were presented for 2 seconds, with an inter-trial interval (*fixation point*) of 1 second. Stimuli were displayed on a 22-inch monitor located approximately 50 cm from the participant, with a refresh rate of 60Hz, in black 36-point Helvetica font on a dark grey background.

1.4. Procedure

The experimental session took place in a quiet environment, free from potential external distractions. The lighting conditions of the testing room were controlled (dimly lit room with the window blacked out).

After calibrating the eye tracker, participants completed a brief practice session consisting of 4-6 trials -randomly allocated - of the ONG task only, followed by 4-6 trials each of the PM task in the low load condition (1 target), in the high condition (3 targets) and a practice block (4-6 trials) in the offloading condition. In the first three blocks, participants could only proceed to the next block after achieving a minimum task accuracy of 70%; otherwise, they had to repeat the current practice block. After these blocks, participants practiced responding to thought-probe questions. Participants were told that – since the task is long and boring - it would have been perfectly normal for them to experience off-task thinking. They were also instructed on the multitude of off-task experiences (e.g., task-related thoughts, external distractions and internal thoughts) that might characterize their endogenous activity, and on the difference between intentional and unintentional forms of thought. The main experiment began immediately after the practice session.

Each experimental block included a pre-block baseline interval lasting 3 seconds, followed by the instructions for that block. The use of fixed stimulus presentation times ensured that any differences in response time across conditions did not affect visual stimulus features, which could otherwise confound pupillometry measurements.

In all blocks, participants had to continue doing the ONG task (odd/even judgement), plus additional PM and Offloading instructions. In the low load condition, they were instructed: “*In the next block, keep in mind to press the LEFT directional key when you see a [target color] digit*”. In the high load condition, they were told: “*In the next block, keep in mind to press the LEFT arrow if you see a [target color 1] digit, the UP arrow if you see a [target color 2] digit and the RIGHT arrow if you see a [target color 3] digit*”. In the Offloading condition, instructions were: “*In this block, arrows will act as REMINDERS, helping you remember the association between the response keys and the target color(s)*”. Finally, the no Offloading condition comprised: “*In this block, arrows will be in different colors from the target; thus, we simply ask you to IGNORE them*”. Participants were instructed to maintain fixation on the digits at the centre of the screen, rather than looking at the arrows.

1.5. Data analysis

Participants were excluded from the analyses if: their accuracy in the non-offloading condition deviated by more than three Median Absolute Deviation (MAD) units compared to other participants, or their accuracy in the offloading condition exceeded this threshold. We also excluded participants who consistently reported the same value on the off-task thought-probe measure throughout the task, showing zero variance across trials. For the pupillometry analyses, trials were removed if the gaze coordinates deviated by more than 0.15 units from the screen center (as defined by the Active Display Coordinate System; for further details, see <https://developer.tobiipro.com/commonconcepts/coordinatesystems.html>) or if pupil diameter data for a given trial were missing or unrecorded.

For the behavioral data, we calculated accuracy for the ONG task (ONG accuracy) as the proportion of correctly identified (odd/even) digits over the total ONG trials, and for the PM task (PM accuracy) as the ratio of correct target identifications to the total number of target trials. To test the effect of Offloading and its timing during each block, we run a Linear Mixed Model (LMM) on the ONG accuracy levels, with *Memory Load* (high vs. low), *Offloading* (Offload and no Offload) and *Block Duration* (first 10 trials, after trial 10 of the block) as fixed effects and *Participant* as random effect. Another LMM was performed on the PM accuracy, with *Memory Load*, *Offloading* and *Task Duration* (first and second half of the entire task duration) as fixed effects and *Participant* as random effect.

Regarding off-task thinking, we performed a LMM with *Task Duration*, *Memory Load* and *Offloading* as fixed effects and *Participant* as random effect. The same analysis was then run on thought intentionality levels.

Pupil diameter at each time point was calculated as the average of the left and right eyes: a total of 120 observations were recorded per trial. For each trial, we calculated the mean pupil diameter by averaging the right and left eye pupil diameters across valid gaze points (see above). For observations

where data from one eye were missing, we considered the remaining eye. The mean pupil diameter was computed separately for each trial, excluding any missing or invalid data (i.e., NaN and anomalous values). To account for the natural fluctuations in pupil size throughout the experiment (see above, but also Mathôt et al., 2018), we normalized pupil size measures by subtracting the last 50 ms (Mathôt & Vilotijević, 2023) of the baseline pre-block recording from each trial's pupil size measure within the subsequent block for each participant. Due to a variation in the methodology (presenting the baseline period before rather than after the presentation of instructions for each block), the pupillometry analyses were conducted on a subsample of participants (47).

First, to examine potential intention-related effects on pupil diameter, we conducted a LMM on normalized pupil diameters from no Offload blocks only, with *Memory Load* as fixed effect and *Participant* as random effect. To assess the effect of offloading on pupil diameter, we then analyzed the entire normalized pupil size dataset using LMM, with *Memory Load*, *Offloading* and *Block Duration* as fixed effects, and *Participant* as random effect.

Finally, we validated self-report (probe-caught) measurements against more objective behavioral and physiological measures. To do so, we considered Reaction Times (RTs) and normalized pupil size measures within a time window of 9 seconds (i.e., 3 trials; see also Christoff et al., 2009; Franklin et al., 2013) preceding each probe. These two measures were then used, for each thought-probe block, as predictors in a multiple linear regression to model self-reported off-task thinking levels expressed by participants.

The analyses on behavioral and pupillometry measures were pre-registered, excepting the variable *Block Duration*, which we will consider exploratory. Similarly, the analyses on PM accuracy and the validation of thought-probe measures against RTs and pupil diameters were not included in the pre-registration and remain exploratory.

2. Results²⁰

2.1. Behavioral results

The LMM on ONG accuracy levels revealed an effect of *Block Duration* [Wald $\chi^2_{(1)}=8291.12$; $p < .001$], as participants showed higher accuracy levels (mean= 0.94; st.dev. = 0.22) in the first half of the block compared to the second half (mean= 0.64; st.dev.= 0.48). There was also a significant interaction *Offloading*Memory Load* [Wald $\chi^2_{(1)}=3.90$; $p = .048$]: in the no Offload blocks, accuracy levels were significantly lower in the high (3 targets; mean= 0.82; st.dev. = 0.39) vs. low (1 target; mean= 0.83; st.dev. = 0.38, $p = .01$) memory load conditions, while no significant differences ($p = .83$) between high and low memory load conditions emerged in the Offload blocks. The effect was further qualified by the significant interaction *time*Load*Offloading* [Wald $\chi^2_{(1)}=8.29$; $p = .004$]: In the first half of the block (before trial 10), no significant differences in accuracies were observed across conditions (all $ps \geq .96$); these differences emerged instead in the second half of the block (after trial 10), where in the no-Offload blocks, accuracy was lower in the high (mean= 0.63; st.dev.= 0.48) vs. low-load (mean= 0.65; st.dev.= 0.48; $p = .04$) condition, while in the Offload blocks accuracy levels did not change regardless of load (all $ps \geq .43$; see Figure 4).

²⁰ For Supplementary Results, see Appendix D.

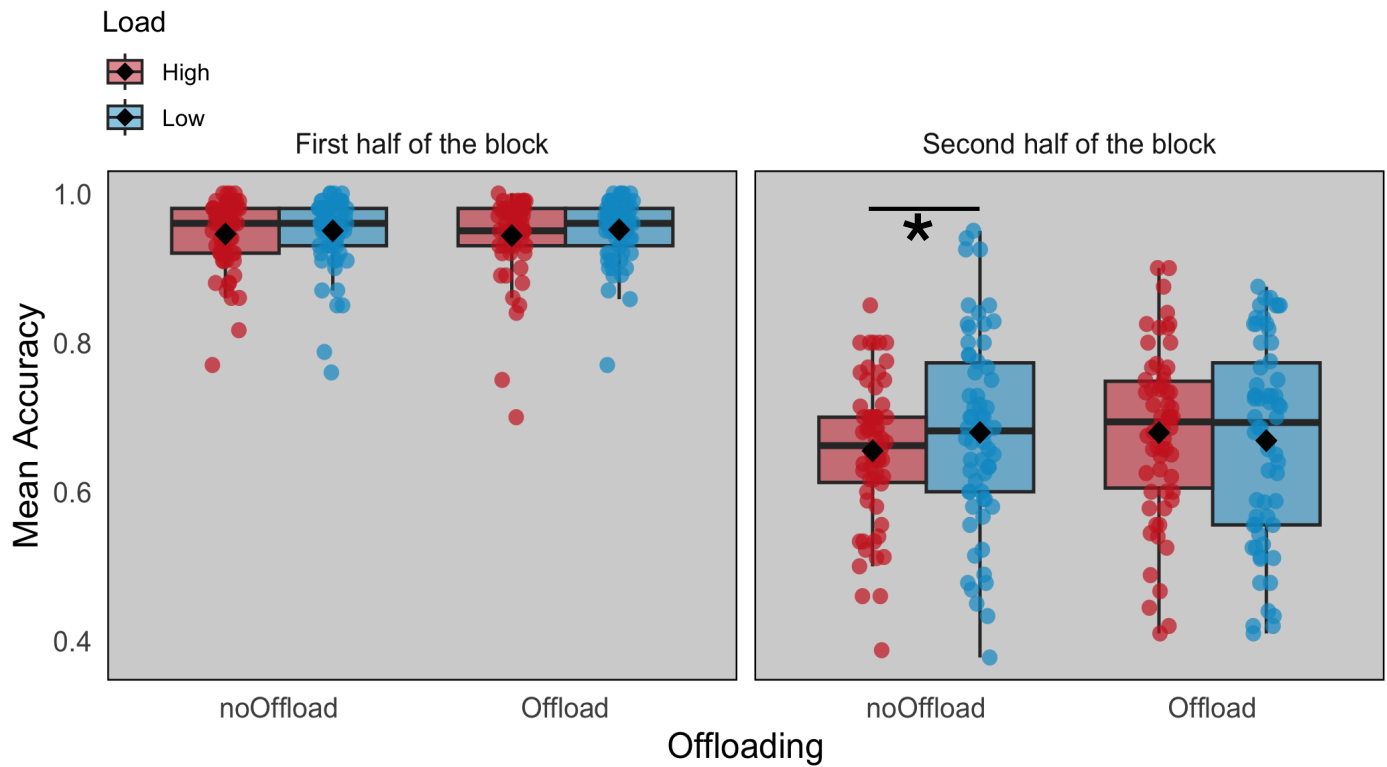


Figure 4. Mean ONG accuracy by Offloading (noOffload on the left, Offload on the right), Task Duration (first half vs. second half of the block) and Memory Load (High in red, Low in blue). Black diamonds represent group means, and individual data points are jittered for clarity. $* < .005$

The results of the LMM on the PM accuracy yielded a main effect of *Task Duration* [Wald $\chi^2_{(1)} = 8.29$; $p = .004$], with the first half of the task showing higher PM accuracy levels (mean = 0.35; st.dev. = 0.47) compared to the second half (mean = 0.28; st.dev. = 0.45). There was also a significant *Load*Offloading* [Wald $\chi^2_{(1)} = 6.48$; $p = .01$] interaction, that configured in the significant triple interaction *Load*Offloading*Task Duration* [Wald $\chi^2_{(1)} = 6.61$; $p = .01$]. In the no Offload blocks, PM accuracy levels in the low memory load condition were significantly higher for the first (mean = 0.38; dev.st. = 0.49) vs. second half (mean = 0.25, dev.st. = 0.44; $p = .04$) of the task, while no time-on-task differences emerged in the high memory load condition (all $ps \geq .99$) nor in the Offload blocks (all $ps \geq .30$; see Figure 5).

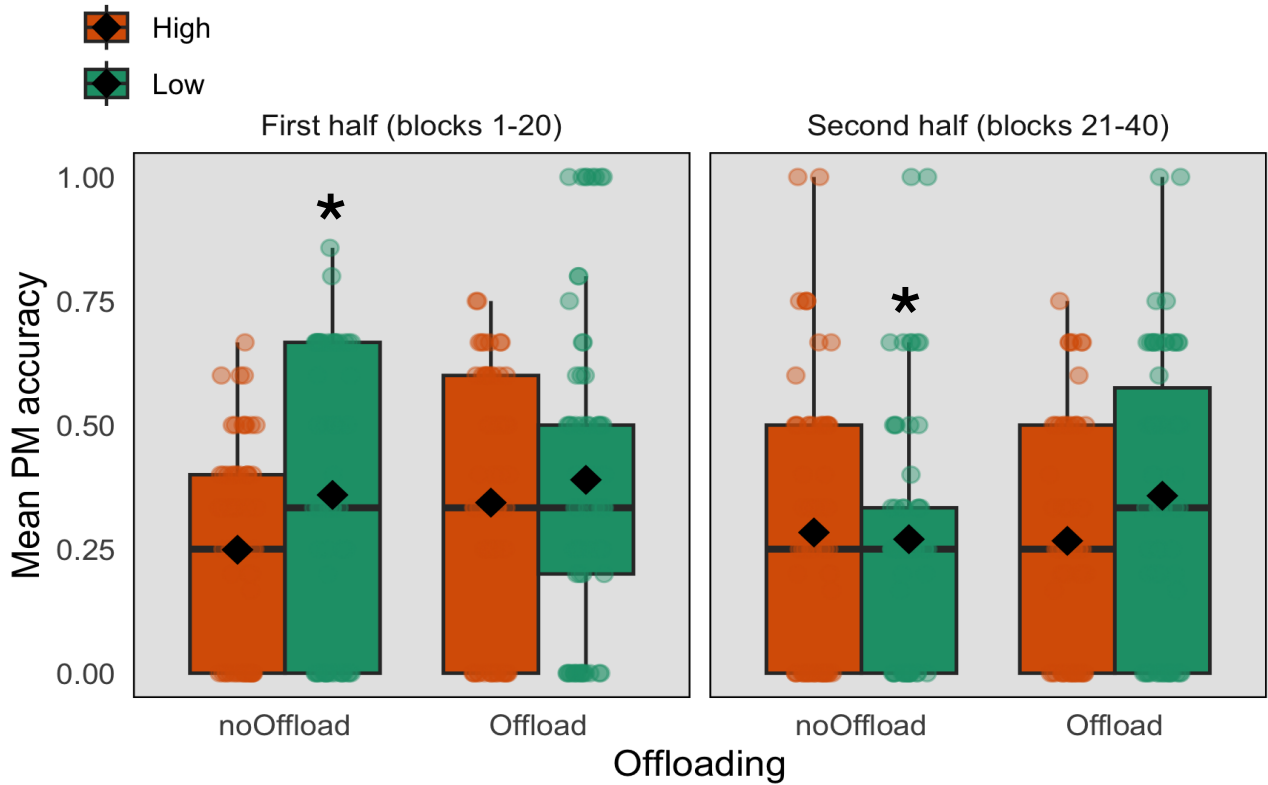


Figure 5. Mean PM accuracy by *Offloading* (noOffload on the left, Offload on the right), *Task Duration* (first half: blocks 1-20; second half: blocks 21-40), and *Memory Load* (high in orange, low in green). Black diamonds represent group means, and individual data points are jittered for clarity. * $<.005$

In this section, we observed distinct behavioral patterns based on both Memory Load and Offloading. For ONG accuracy, offloading effects emerged selectively in the final part of each block: in no-Offload blocks, accuracy was lower under high compared to low memory load, whereas no such difference was observed in Offload blocks, where accuracy levels remained stable across conditions. Regarding PM accuracy, offloading effects appeared in the second half of the task, where no-Offload blocks showed a decline in accuracy under low memory load, a pattern not observed instead in the Offload blocks.

2.2. Pupillometry results

The LMM on the normalized pupil size data – selectively for the no Offload blocks – revealed a significant effect of *Memory Load* [Wald $\chi^2_{(1)} = 11.79$; $p < .001$], indicating that pupil diameters were

larger in the high (mean= -0.07; st.dev.= 0.41) vs. low (mean= 0.11; st.dev.= 0.38) memory load blocks (see Figure 6).

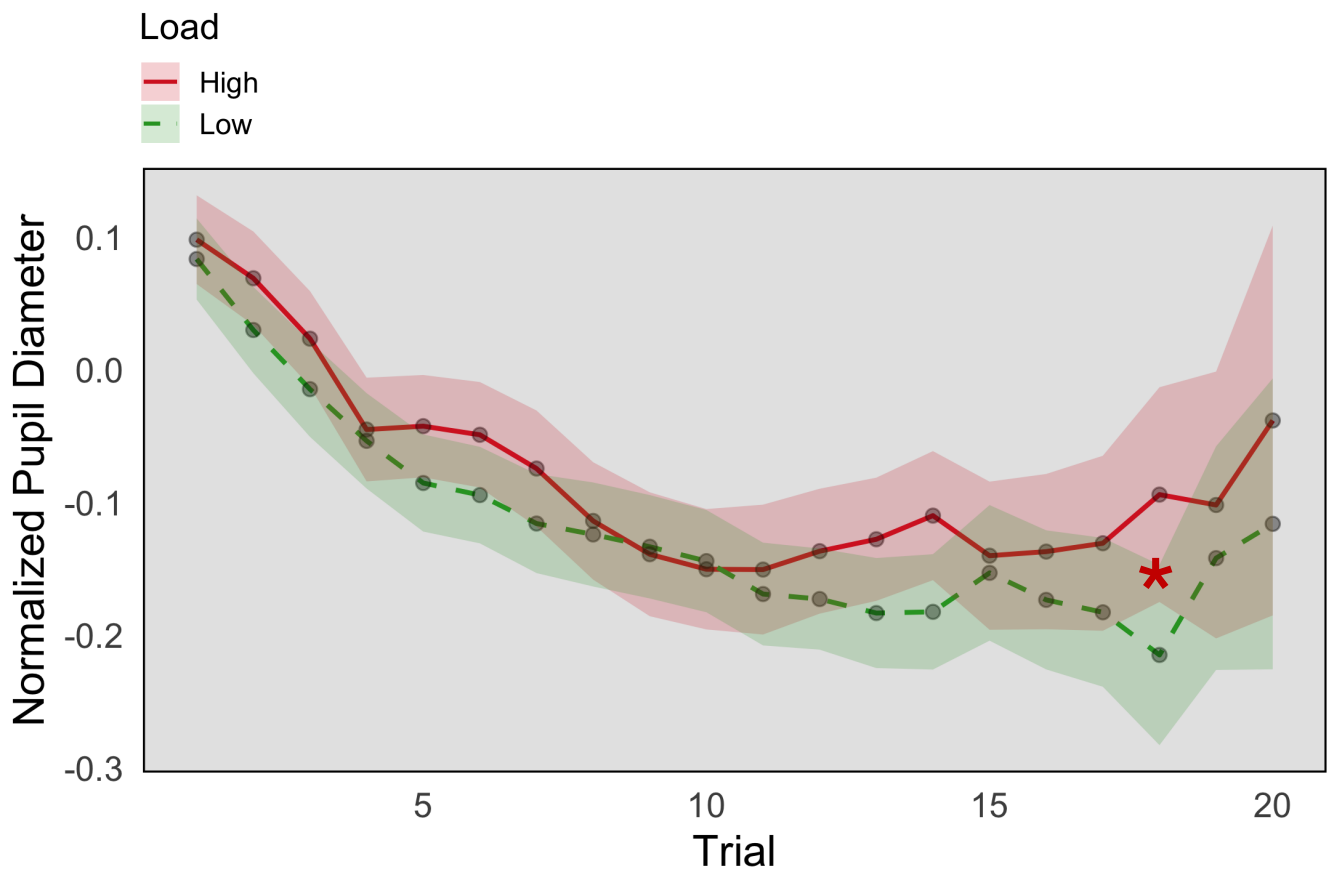


Figure 6. Averaged normalized pupil diameter trajectories across all participants and blocks over 20 trials (one block), comparing the two memory load conditions: low (dashed green line) and high (solid red line). * <.005.

Results of the LMM on the overall normalized pupil size data yielded a main effect of *Block Duration* [Wald $\chi^2_{(1)}=265.48$; $p < .001$], as pupil diameter tended to significantly decrease from the first (mean= -0.08; st.dev. = 0.40) to the second half (mean= -0.17; st.dev.= 0.42) of each block. This effect was qualified by the significant interaction *Block Duration*Offloading* [Wald $\chi^2_{(1)}=7.55$; $p = .006$]: in the first half of the Offload vs. no Offload blocks, pupil sizes did not change significantly ($p = .07$), whereas in their second half, Offload blocks showed significantly lower pupil diameters (mean= -0.20; st.dev. = 0.42) compared to no Offload (mean= -0.15; st.dev.= 0.41; $p < .001$) blocks (see Figure 7).

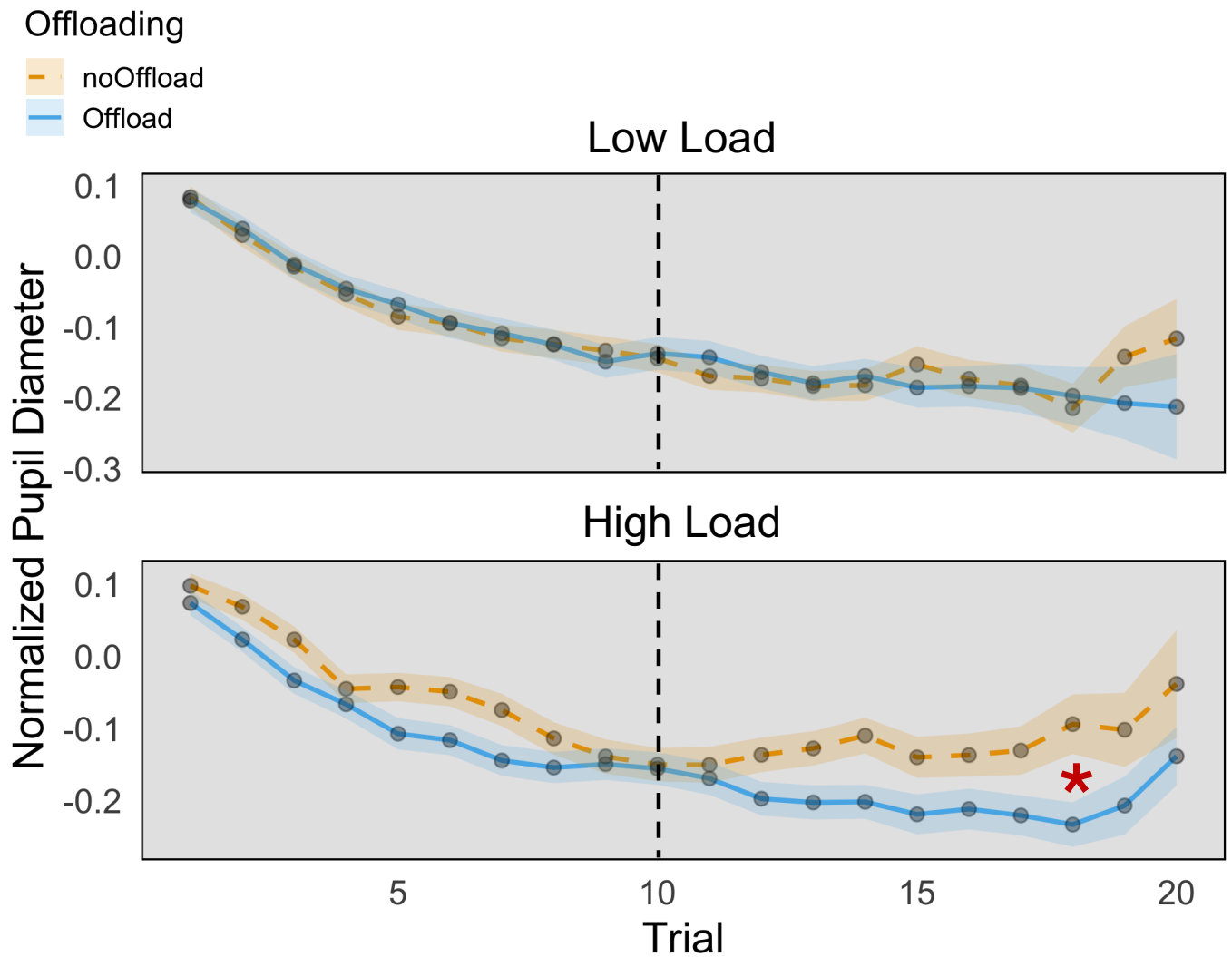


Figure 7. Averaged normalized pupil diameter trajectories across all participants and blocks over 20 trials (one block), comparing the two memory load conditions: low (top panel) and high (bottom panel). In both panels, data are further divided into the two offloading conditions: Offload (solid blue line) and no Offload (dashed orange line). Shaded areas represent the standard error of the mean. The vertical dashed line at trial 10 indicates the midpoint of the block, emphasizing differences in pupil dynamics between the first and the second half of each block. * <.005.

This set of analyses revealed that both memory load and offloading affected pupil diameters. First, participants exhibited larger pupil diameters under high compared to low memory load. Second, pupil diameter remained stable during the first part of each block, regardless of memory load condition, but in the second part of Offload blocks it decreased significantly.

2.3. Off-task thinking

The LMM on the off-task thinking levels yielded a significant interaction *Task Duration*Offloading* [Wald $\chi^2_{(1)} = 4.04$; $p = .04$]: in the Offload blocks, participants showed significantly lower off-task thinking levels in the second half of the experiment (mean= 38.06; st.dev.= 27.48) compared to the first (mean= 42.38; st.dev.= 28.22; $p = .036$; see Figure 8), whereas in the no Offload blocks, they did not exhibit significant differences in off-task thinking levels between the first half and the second half of the experiment ($p = .99$) The remaining factors were not significant (all $ps \geq .07$).

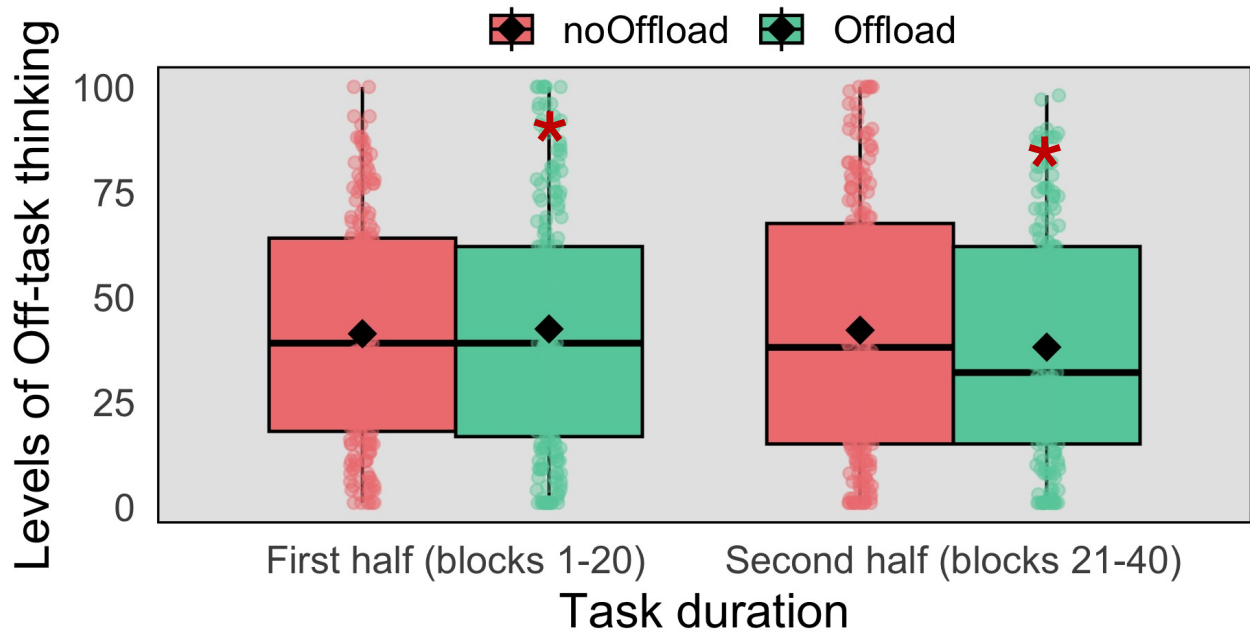


Figure 8. Levels of off-task thinking across task duration (first half: blocks 1-20; second half: blocks 21-40), separated by Offloading conditions (noOffload in red, Offload in green). The black diamonds represent means, while individual data points are jittered around each boxplot for clarity. * $<.005$

Regarding the LMM on the intentionality levels, all factors failed to reach statistical significance (all $ps \geq .15$).

The multiple linear regression model predicting off-task thinking based on RTs and normalized pupil diameters revealed a significant overall effect ($F_{2,12} = 4.09$, $p = 0.017$), even if the

model explained only a small proportion of the variance in off-task thinking levels (adjusted $R^2 = 0.0051$). RTs were a significant positive predictor ($\beta = 5.689$, $SE = 2.687$, $t = 2.118$, $p = 0.034$), indicating that slower RTs were associated with higher levels of off-task thinking. Normalized pupil diameter instead was a significant negative predictor ($\beta = -3.288$, $SE = 1.656$, $t = -1.985$, $p = 0.047$), suggesting that larger pupil diameters were related to higher levels of on-task engagement (see Figure 9).

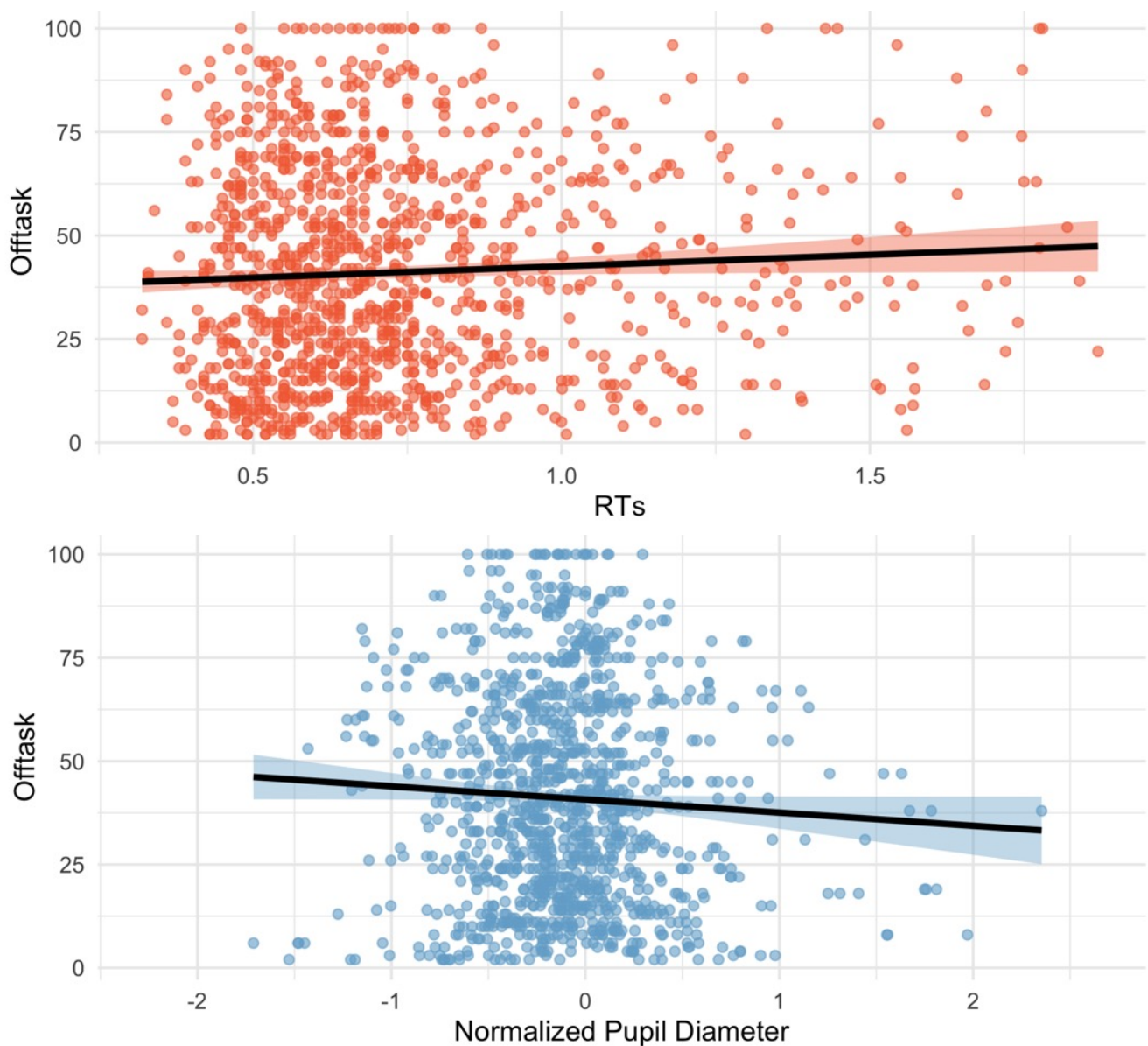


Figure 7. Scatter plots with regression lines illustrating the relationship between off-task thinking levels and the two predictors: Reaction Times (RTs, top panel) and Normalized Pupil Diameter (bottom panel). The top panel shows a positive association between RTs and off-task thinking, indicating that slower RTs correspond to higher off-task thinking levels. The bottom panel reveals a negative association between Normalized Pupil Diameter and off-task thinking levels, suggesting that larger pupil diameters are related to increased on-task engagement. Shaded areas represent 95% confidence intervals.

In this section, results showed that intention offloading significantly reduced off-task thinking levels in the second vs. first half of the experiment, whereas no such time-related differences were found in the no-Offload blocks. Additionally, we validated the self-reported thought-probe measures of off-task thinking, showing that both RTs (positively) and pupil diameter (negatively) - recorded during the 9-second pre-probe interval – predicted the on-task vs. off-task levels reported by participants.

3. Discussion

This study aimed to investigate the behavioral and physiological effects of intention offloading on both externally (PM) and internally directed (off-task thinking) cognition. Our findings demonstrated that intention offloading affected behavior, improving both ONG accuracy - particularly in the second half of each block under high memory load - and PM accuracy - especially in the latter half of the task under low memory load. Pupil diameters were larger in the high vs. low memory load condition. Offloading also influenced physiological patterns, selectively reducing pupil diameter the second half of each block (i.e., around the time of PM target appearance). Moreover, offloading significantly reduced off-task thinking levels from the first to the second half of the task. Contrary to our expectations, however, offloading had no effect on the intentionality of thought. Our findings reveal that offloading intention – promoting a higher availability of cognitive resources – facilitates the coexistence, instead of competition, between externally and internally directed cognition.

3.1. The effect of offloading and memory load on behavior

First, ONG accuracy decreased more in the high vs. lower memory load condition, especially in the second half of the no offload blocks. This effect likely stems from the so-called *PM cost* (F. Anderson et al., 2019; R. E. Smith et al., 2007; Strickland et al., 2017): under high vs. low memory load, participants must allocate more cognitive resources to the sustained monitoring of delayed intentions, resulting in a worse behavioral ONG performance. This decline in ONG accuracy became more pronounced toward the end of each block (after trial 10), likely due to participants anticipating the execution of the prospective intention and diverting cognitive resources to monitoring for the PM target appearance. Notably, this PM cost— i.e., a decrease in ONG accuracy—was eliminated in the offloading blocks: when participants could rely on external reminders, they likely allocated more cognitive resources to the ONG task, maintaining relatively higher ONG accuracy, though still lower than in the first half of the block. This effect aligns with the *multiprocess framework* (McDaniel & Einstein, 2000) indicating that, under certain circumstances, presenting an external cue (in this case, the arrows on the screen indicating the PM instructions) can trigger the spontaneous retrieval of PM intentions without incurring any PM-related costs during the ONG trials.

The more pronounced effect of offloading on ONG accuracy in the high vs. low memory load condition (three vs. one target to be remembered) replicates previous findings on the selective benefit of offloading under increased cognitive load (Gilbert, 2015). This phenomenon can be attributed to the role of *metacognition*, i.e., the capacity to monitor and regulate one's own cognitive processes and abilities (Dunlosky & Metcalfe, 2008; Flavell, 1979; Sachdeva & Gilbert, 2020b; Scott & Gilbert, 2023). Individuals, in fact, typically engage in a metacognitive assessment of their memory performance: they tend to set more external reminders in situations where they perceive their memory abilities to be insufficient. In the current study, it is likely that such metacognitive assessment led to rely on external reminders more when it was deemed necessary, i.e., under high memory load (see also Arango-Muñoz, 2013; Weis & Wiese, 2019).

Second, PM accuracy decreased significantly in the second half of the task under low vs. high memory load, but, again, intention offloading reduced this effect. This indicates that intention offloading affected both the *retrospective* component of PM—i.e., the *content* of the delayed intention - and the *prospective* component – i.e., remembering that something needs to be done (Cohen et al., 2001; Gilbert, 2015). The effect of offloading on the content of delayed intentions is consistent with previous studies (e.g., Landsiedel & Gilbert, 2015; see also Gilbert, 2015) demonstrating that intention offloading affects brain regions (i.e., medial rostral PFC) associated with storing the content of intentions, while leaving relatively unchanged the neural activation of those (i.e., lateral rostral PFC) linked to content-free retrieval (i.e., remembering that *something* needs to be done). Notably, in our study the external reminders not only referenced the specific *content* of delayed intentions (i.e., the association between the cues - distinct colors - and the directional arrows to press), but also the content-free aspect of remembering that delayed intentions had to be performed (i.e., pressing directional keys in response to colored digits). For these reasons, it is plausible that our PM task also emphasized the prospective component of PM, helping to maintain relatively stable PM accuracy throughout the task.

3.2. *The effect of offloading and memory load on pupil diameter*

Crucially, we found preliminary evidence of decreased pupil diameter in the offload vs. no offload blocks. This was consistent with behavior, as occurred especially towards the second half of each block, i.e., in proximity of PM target appearance. Demonstrating a physiological effect of offloading is particularly notable, because it confirms that intention offloading effectively reduces the amount of cognitive resources required to monitor for PM target appearance. Pupil diameter, in fact, has been convincingly demonstrated as a physiological index of arousal (Grujic et al., 2024; Maier & Grueschow, 2021; Bradley, 2008). Pupil dilation, in particular, has been related to the activity of the sympathetic activity (Mathôt, 2018), that activates more under conditions of increased mental elaboration. Accordingly, several studies (Chen & Epps, 2014; Foroughi et al., 2017; Oliva,

2019; Querino et al., 2015; van der Wel & van Steenbergen, 2018; Wahn et al., 2016, 2017) have demonstrated that changes in pupil diameter occur in response to experimental manipulations that modulate attentional load, reflecting the allocation of cognitive resources. Particularly, Moyes et al. (2019) proposed different behavioral profiles for sustained monitoring versus target checking in PM tasks, and showed how an increase in pupil diameter can be considered a physiological index of sustained monitoring of the PM target. Building on this view, our findings suggest that intention offloading reduced the need for sustained monitoring of the delayed intentions, as pupil diameter tended to constrict more compared to when participants needed to rely on their memory solely. This could be interpreted as evidence for a transient checking – as opposed to a sustained monitoring - mechanism, that leads individuals to concentrate more on the ONG activity and to respond transiently when the PM target approaches, thus preventing the consumption of cognitive resources. More research is needed, however, to clearly differentiate patterns of pupillary responses to stimuli in offload vs. no offload conditions at the single-trial level.

Our findings revealed that in no offload blocks, pupil diameters were larger under high vs. low memory load conditions. This reinforces the view of pupil diameter as an index of sustained monitoring for delayed intentions. In this regard, the study by Moyes et al. (2019) had participants perform a lexical decision (ONG) task: pupil diameters increased selectively in the category (non-focal PM instructions, where PM and ONG tasks require separate cognitive processes; Cantarella et al., 2023; Cona et al., 2013) PM task, i.e., when participants were required to detect target items within a predefined semantic category, compared to when they had to keep in mind to press a special key upon encountering a particular word (focal PM instructions). Here, we replicate their findings, demonstrating that our non-focal PM instructions - monitoring for colored digits (PM task), while performing an odd/even judgement (ONG task) – increased pupil diameters sustainedly more under high memory load conditions. The detection of sustained PM processes with pupillometry further confirms previous cognitive and computational models on event-based PM (Gilbert et al., 2013; Guynn, 2003), suggesting the presence of a “*monitoring*” node that can be activated sustainedly

during task performance, enhancing the ability of incoming stimuli to trigger activity in “*target detection*” nodes and potentially leading to a PM response (i.e., retrieval of PM intentions).

3.3. The effect of offloading on off-task thinking and reliability of thought-probe measures

The present study provides preliminary evidence that offloading intentions decreases off-task thinking levels, particularly in the second half of the task. This contrasts with the well-documented time-on-task effect (Study 4a, but also Brosowsky et al., 2023; Krinsky et al., 2017; Thomson et al., 2014; Zanesco et al., 2024), where off-task thinking levels typically increase as cognitive control declines and fatigue sets in. In the offloading blocks, in fact, this pattern was reversed: participants engaged in more off-task thinking in the first half of the task, but significantly less in the second half. One possible explanation for this shift from internally to externally directed cognition lies in the redistribution of cognitive resources. Time-on-task effects, in fact, are often attributed to a decline in cognitive control (Krinsky et al., 2017; Thomson et al., 2014; Zanesco et al., 2024) due to the depletion of cognitive resources required for higher-level executive functions over time. The presence of external reminders may have allowed participants to preserve these cognitive resources, making them more available for use until the end of the task and thus reducing task disengagement. The evidence that participants had higher PM accuracy for offload vs. no offload blocks in the second half of the task aligns with this perspective.

Alternatively, participants in the no-offload blocks might have engaged in continuous, often unaware, monitoring of the PM intentions to be accomplished, which in turn could have increased the occurrence of off-task - albeit task-related - thoughts. By contrast, relying on external reminders (in offload blocks) might have reduced the need for constant monitoring of the intentions, enabling participants to concentrate more on the ONG task. Based on previous PM research (Rummel et al., 2017), Dupre et al. (2023) had already investigated the effect of offloading on future-oriented (PM-related) thinking, showing that offloading intentions had no effects on both task-related (i.e., referred

to both the ONG and the PM tasks) and task-unrelated (i.e., mind-wandering) thoughts. However, it should be worth mentioning a few methodological differences that might explain the discrepancies between their findings and our results. First, the fact that the PM task length, that in our case was 1 hour rather than 25 minutes (Dupre et al., 2023): in the present study, the effect of offloading emerged selectively in the second half of the task and task duration is, in fact, a crucial factor in determining the occurrence of off-task thinking, likely due to boredom and task-disengagement (Study 4a, but also Thomson et al., 2015; Westgate & Wilson, 2018; Wolff & Martarelli, 2020). Second, our Study 4b treated off-task thinking as a natural cognitive process that typically happens during long and boring tasks (see the Methods section), while Dupre et al., (2023) emphasized the importance of PM intentions. The different emphasis given to on- vs. off-task, in task instructions, may account for the tendency – or not- to report being off-task (Nagamatsu et al., 2013; Weinstein, 2018), as well as the recruitment of cognitive resources directed to PM performance (McDaniel & Einstein, 2007; Walter & Meier, 2014). Lastly, the present study conceptualized various forms of mind-wandering (including internal thoughts, external distractions and task-related thoughts) under the same category of off-task thinking, whereas the study by Dupre et al. (2023) differentiated between categories of off-task (clearly referred to task-unrelated, internal thoughts) and on-task (ONG- and PM-related thoughts) thinking. Future research could help clarify, then, which type of thinking (e.g., *unspecifically* task-related thoughts like “*I have to concentrate more*”; see also Rummel et al., 2017), if any, is affected more by offloading intentions.

Finally, our analyses revealed that both slower RTs and lower pupil diameters were significant predictors of self-reported off-task thinking levels. The observed relation with more objective – behavioral and physiological - measures provides a critical validation of self-reports as a meaningful tool for studying mind-wandering (see also Kane et al., 2021; Weinstein, 2018). Moreover, the convergence of behavioral (RTs) and physiological (pupil diameter) data with subjective self-reports demonstrates that participants could accurately introspect on their attentional state. Accordingly, previous research had shown that as cognitive resources are diverted from the primary task,

participants become less responsive to external stimuli, resulting in slower reaction times (Smallwood & Schooler, 2015). This view supports the *attentional decoupling* hypothesis (Kam & Handy, 2013; Schooler et al., 2011; Smallwood et al., 2007, 2011).

Several studies have associated a decrease in pupil diameter with subsequent probe-caught measures of off-task thinking (e.g., Gouraud et al., 2018; Grandchamp et al., 2014; Konishi et al., 2017). By contrast, in other studies an increase of pupil diameter co-occurred with self-reported mind-wandering (M. S. Franklin, Broadway, et al., 2013). Resonating with a recent theory (Unsworth & Robison, 2018) and the *context-regulation hypothesis* (Smallwood & Schooler, 2015), thus, it is plausible that different task demands produce distinct physiological effects, with easier tasks being more likely to trigger increased internal mental elaboration (i.e., *active mind-wandering*; Unsworth & Robison, 2018). Reduced pupil diameter, for example, has been considered a physiological index of intrusive, past-oriented thoughts (Huijser et al., 2020; Konishi et al., 2017). The fact that, in our study, self-report off-task thinking measures were probe-caught, thus reflecting unaware mind-wandering episodes (Schooler et al., 2011; Smallwood, Schooler, et al., 2011), aligns with this view. Our findings suggest that as participants' attentional focus unconsciously waned (e.g., *mind blanking* or *exploratory mind-wandering*; Unsworth & Robison, 2018), decreased pupil diameters reflected this disengagement, offering a real-time physiological measure of off-task thinking. The use of normalized pupil data in our analysis adds further reliability to this measure, accounting for individual variability and highlighting the robustness of pupil diameter as an indicator of attentional lapses.

However, we failed to find any effect of intention offloading on the intentionality levels in participants' thoughts. A possible explanation for this may lie in the PM task difficulty (as indicated by the relatively low PM accuracy levels; see Methods section). Recent evidence (Seli, Konishi, et al., 2018) suggests, in fact, that more intentional forms of thought are typically elicited during easier tasks. Moreover, given that off-task thinking in this study was plausibly more unintentional, using a scale that measured intentionality levels (from 0 to 100) may have masked potential alternative effects of offloading on this measure (e.g., less unintentional thinking in offload blocks).

Conclusions

In the current work, we hypothesized that the intention offloading could decrease the intentionality levels required in tasks involving external attention, thereby allowing for more intentional forms of internal attention. To do so, we manipulated both memory load and offloading across two experiments that allowed for the concomitant assessment of both externally (event-based PM) and internally (off-task thinking) directed cognition. In Study 4a, offloading significantly improved PM performance, but had no effects on off-task thinking; by contrast, in Study 4b offloading affected both PM performance and off-task thinking. In both studies, however, we did not find any offloading effect on intentionality levels in participants' thoughts. Taken together, these results reveal that, under certain circumstances, offloading intentions is effective at redistributing cognitive resources between external and internal cognition, promoting an increase in task performance and concomitant decrease in task-disengagement, both of which are reflected in pupillary signatures.

Further studies are needed to clarify the contribution of external reminders in the adaptive management of cognitive resources, including more nuanced approaches to investigate the neural – other than physiological – correlates of intention offloading. The use of a combined fMRI-pupillometry methodology (e.g., Fietz et al., 2021; Groot et al., 2021; Satterthwaite et al., 2007), for example, might allow to track the simultaneous effects of offloading on both physiology and neural network activations. It may also be worth investigating which types of off-task thinking—such as internal thoughts, external distractions, and task-related thoughts—are more affected by offloading. This could help clarify whether intention offloading reduces the need to monitor delayed intentions (task-related thoughts) or if instead it primarily impacts task-unrelated content.

There is a critical need to manage the vast complexity of both internal and external stimuli that compete in capturing our attention in today's world (especially in fields such as medicine and aviation). Such advancements in research could help contribute to a better understanding of how

individuals adaptively allocate cognitive resources in complex environments and whether intention offloading effectively impacts this mechanism.

General Discussion

We are immersed in a complex reality, rich with stimuli, yet equally intricate is the diversity of forms our thoughts can take. Building on this premise, the present PhD thesis explored various forms of thought and their relationship with the external reality that surrounds us. Overall, despite this variety in the phenomenology of human thought, a unified perspective emerges, characterizing them as part of a single *continuum*—ranging from more spontaneous (mind-wandering; Chapters 1 and 2) to deliberate, goal-directed forms (MTT; Chapter 3 and PM; Chapter 4). The present findings, therefore, will be interpreted through this integrative approach, which has recently emerged as part of a collective effort to develop an integrative taxonomy of various forms of thought (e.g., [Christoff et al., 2016](#); [Kvavilashvili & Rummel, 2020](#); [Seli et al., 2018](#)). This perspective is particularly valuable as it enables the simultaneous consideration of different aspects of thought and how they interact with the surrounding environment.

Throughout the 4 Studies, this PhD thesis aimed to explore *a)* the neural bases of external versus internal attention (thought); *b)* the cognitive and physiological mechanisms underlying spontaneous and deliberate thought and *c)* the use of internal or external strategies to promote more adaptive forms of thought. However, three unifying *themes* emerged, to which the obtained results unanimously converge. In this General Discussion, I will examine these themes in turn, attempting to help the reader identify a unifying *thread* within the extensive and heterogeneous body of information presented thus far.

I. vmPFC: the brain's supervisor of spontaneous and deliberate thought

Theme 1 pertains to the role of the vmPFC in both spontaneous and deliberate thought. In the introductory Chapter, in fact, we explored various studies delineating the importance of the vmPFC in the initiation and maintenance of mental events, which constitute the *building blocks* of human thought in both spontaneous and deliberate thought (see paragraph 3.1.2. of the Introduction section). In this PhD thesis, we demonstrated that disrupting vmPFC activity—either by inhibiting its function

through non-invasive brain stimulation techniques (*Chapter 1*) or as a consequence of brain damage (*Chapter 3*)—significantly alters human thought. Specifically, Chapter 1 shows that inhibiting mPFC activity decreases future-oriented spontaneous thinking, while Chapter 3 reveals that selective damage to the vmPFC disrupts the temporal progression of memory structures in event construction, hindering access to specific mental events. These findings align with recent theoretical models that attribute to the vmPFC the role of a *supervisor* (Ciaramelli & Treves, 2019; McCormick, Ciaramelli, De Luca, et al., 2018) in the activation and maintenance of personal semantic knowledge to support the temporal unfolding of an extended mental event (in both spontaneous and deliberate thought). Hypothetically, we could describe this vmPFC-mediated impairment as a partial, degraded activation of *schematic* structures, which compels the hippocampus to generate a rudimentary sketch of the mental event in the absence of appropriate higher-level monitoring. Similarly, they support the view of the vmPFC as an *integrative hub* (D’Argembeau, 2020) between higher-order and event-specific mental representations to contextualize them within a coherent life-narrative.

Inhibiting the mPFC activity (*Chapter 1*) or a damage to the vmPFC (*Chapter 3*), however, selectively affected future-oriented thought. In the former case, future-oriented spontaneous thought (mind-wandering) decreased; in the second case, future-oriented deliberate thought (MTT) exhibited more backward transitions towards superordinate memory structures, preventing access to specific events. This highlights the centrality of the vmPFC in future-oriented cognition, confirming previous extensive research on this field (e.g., [Benoit et al., 2014](#); [Bertossi et al., 2017](#); [Ciaramelli et al., 2021](#); [Verfaellie et al., 2019](#)). As we have seen in the Introduction (paragraphs 1.3.2. and 2., but also [Bar, 2007](#); [Kvavilashvili & Rummel, 2020](#)), the ability to mentally represent what is about to happen in the future is essential for human survival. Considering that episodic, semantic and hybrid forms of prospection (i.e., simulation, prediction, intention and planning; see [Szpunar et al., 2014](#)) interact flexibly with one another to support prospective cognition, future research could further investigate the functional outcomes of these interactions (e.g., *Chapter 4*, but also [Kvavilashvili & Rummel, 2020](#)).

Moreover, future research might explore the neural dynamics underlying the contribution of the vmPFC in spontaneous and deliberate thought. At the single-region level, studies adopting an EEG resting state measure in vmPFC patients could determine additional evidence for altered connectivity patterns (e.g., neural oscillations; see also [Florin & Baillet, 2015](#)), which may provide further insights into how vmPFC damage impacts both spontaneous and deliberate thought dynamics (e.g., in the initiation and/or maintenance of spontaneous thought or in MTT). At the neural-network level (see also paragraph 3.4. of the General Introduction), the mPFC could be considered as a node within a broader network (the DMN) that interact closely with other large-scale neural networks (e.g., the FPCN and the Salience Network), exerting altogether varying degrees of constraint over thought (Christoff et al., 2016). In this view, we could anticipate, for example, that the MTL subsystem of the DMN (comprising the vmPFC and the hippocampus; see subsections, Study 3, but also [Andrews-Hanna et al., 2010](#)) - typically involved in thought generation - deactivates more in response to either deliberate or automatic constraints on thought. By contrast, the midline core of the DMN could activate more with increasing levels of automatic constraints on thought (Christoff et al., 2016). In this regard, computational models are particularly informative, as they allow exploration of the neural dynamics between distinct brain regions (e.g., the vmPFC and the hippocampus) within the same (e.g., the DMN) and/or across different neural networks (e.g., FPCN), providing simulations of how these regions interact to generate mental events (e.g., [Ryom et al., 2024](#)). Further insights could arise from investigating the neuro-modulatory influences exerted by midbrain mechanisms like the LC-NE system (Chapter 4, but also [Mittner et al., 2016](#); [O'Callaghan, Walpola & Shine, 2020](#)) on thought.

Understanding the neural mechanisms that support various forms of thought - ranging from spontaneous to deliberate - might help better identify thought-flow impairments in clinical contexts (e.g., anxiety and depression, making thought flow more rigid and constrained; [Buschmann et al., 2018](#)), as well as the dynamics of thought that instead promote more beneficial outcomes (e.g., creativity; see paragraph 1.5. of the General Introduction, but also [Baird et al., 2012](#); [Beaty et al., 2014](#); [Mooneyham & Schooler, 2013](#)).

II. *External and internal attention: a double-edged sword for human thought*

Theme 2 explores the dynamics of competition and/or coexistence between internal (to endogenous experience) and external (to the environment) attention. In Chapter 1, we framed the external environment as a source of *distraction* (see the subsection 1.1., but also [Kam & Handy, 2013](#); [Schooler et al., 2011](#)), allowing for an investigation into the neural mechanisms that facilitate the human capacity to orchestrate attentional resources between internal (spontaneous thought) and external (salient environmental stimuli) attention, where these two sources competed between each other. By contrast, Chapter 4 conceived the external environment as a valuable *resource* (see paragraph 2.2.1., but also [Gilbert et al., 2023](#); [Risko & Gilbert, 2016](#)) that enables individuals, as cognitive agents, to offload their mental contents (i.e., PM intentions) in the environment, thus allowing them to strategically orchestrate their attentional resources over time. These findings substantiate that the external environment, depending on the circumstances influencing the distribution of cognitive resources, can either facilitate or hinder human thought.

Exploring the allocation of attentional resources across internal and external sources offers a promising avenue for research. In this regard, recent theories (Ralph et al., 2020; Taatgen et al., 2021) have explored the relationship between mind-wandering and external distractions through the lens of cognitive resource *competition*. One example is the *resource-availability model* (Taatgen et al., 2021), suggesting that when a task-related goal requires numerous cognitive resources (i.e., mental operators), but not all are actively engaged, there is a higher likelihood that the individual will be distracted by external stimuli in the environment. This framework helps clarify the circumstances (i.e., recruited but unused cognitive resources) that determine distractions, interfering with task-related goals. By contrast, the conception of *distributed* (“embodied”, “extended” or embedded”) cognition (Clark & Chalmers, 1998; Kirsh, 2010), that coincides with the increasing reliance on technological aids, offers an alternative view of *co-existence* (and, hopefully, cooperation) of internal and external sources that interact dynamically to enhance human capabilities. The most optimistic

scenario - i.e., when externally and internally-directed cognition *cooperate* to achieve higher-order goals - can occur especially in contexts like creative thought, where internal processes (i.e., memory retrieval and simulation) inform external actions (e.g., theatrical improvisation), and vice versa (Dixon et al., 2014). This complex but adaptive mechanism plausibly requires a simultaneous *metacognitive assessment* mechanism that ensures the real-term monitoring of one's own cognition (i.e., increasing cognitive flexibility; Preiss, 2022).

Investigating how to effectively distribute human cognitive resources in complex environments may promote more effective learning strategies, paving the way for rehabilitative and educational interventions (e.g., Mrazek et al., 2020). It may also contribute to the development of new external devices, and individuals with attentional deficits (e.g., Attention Deficit Hyperactivity Disorder; ADHD) could benefit from their use to enhance their quality of life and autonomy. Similarly, research on cognitive strategies may shape information technology, making technological devices like computers and smartphones more accessible and intuitive for interacting with human thought. This may be leveraged in specific settings like businesses to optimize productivity and management of human resources. Finally, understanding how sustained attention in automated environments can affect the allocation of cognitive resources may inform sectors like aviation (e.g., Servais et al., 2023) and medicine where – given the high involvement of complex decision-making and problem-solving situations – a lack of cooperation between internal and external attention might have catastrophic consequences.

III. Promoting adaptive thinking: internal and external strategies

Theme 3 focuses on the use of strategies to promote more adaptive forms of thought. Interestingly, as shown in the present PhD thesis, this can be achieved both *internally*—by activating relevant the self-schema and mental representations of the future (*Chapter 2*)—and *externally*, allowing individuals to offload their intentions into the external environment (*Chapter 4*). The

activation of internal mental representations in Study 2 selectively increased the frequency of spontaneous internal thoughts, making their content more self-related and future-oriented (adaptive thought; see Study 2, but also [Baird et al., 2011](#); [Smallwood et al., 2011](#); [Stawarczyk et al., 2013](#)). By contrast, the impact of external reminders in the environment (i.e., intention offloading; Study 4) reduced the off-task (spontaneous) thinking levels, improving behavioral performance and decreasing pupil diameter while monitoring a future intention (deliberate thought). Despite their opposite effects on thought, both studies support the use of strategies—whether internal or external—that promote more adaptive forms of both spontaneous and deliberate thought.

The literature already proved both internal and external strategies as effective in shaping human thought. As previously mentioned, in fact, [Smallwood et al. \(2011\)](#) has revealed that a brief period of self-reflection (internal strategy) was capable of affecting the directionality of spontaneous thought during a subsequent task, rendering it more future-oriented. Additionally, there is evidence that enhancing attentional abilities (e.g., through mindfulness training; [Mrazek et al., 2013](#)) reduces mind-wandering levels. Another wave of research - driven by the assumption that the dimensions of time, space and motion are inherently intertwined ([Casasanto & Boroditsky, 2008](#); [Oliveri et al., 2009](#)) – has shown that directing attention to the left or right steers the content of self-generated mind-wandering towards the past or the future, respectively ([Vannucci et al., 2019](#)) and that the direction of - backward and forward - illusory motion generates mind-wandering episodes aligned with this directionality (past and future; [Liefgreen, Dalton & Maguire, 2020](#)). Regarding deliberate thought, [Anelli et al. \(2016, 2018\)](#) demonstrated instead that shifting spatial attention (leftward or rightward), through the use of prismatic adaptation, can direct MTT toward the past or the future.

Non-invasive brain stimulation techniques offer innovative approaches to shape human thought by targeting brain activity. In Chapter 1, we have demonstrated that inhibiting the mPFC activity decreases spontaneous – especially future-oriented - thought. The recent meta-analysis by [Nawani et al. \(2023\)](#), in this regard, concluded that the mPFC might represent a suitable target for

brain stimulation to modulate spontaneous thought. Given the negative association between PPC activity and spontaneous thought generation, the PPC might also serve as a potential target for future brain stimulation studies – including transcranial magnetic stimulation; TMS – to reduce mind-wandering in psychiatric disorders such as ADHD and major depressive disorder (e.g., see [Konjedi & Maleeh, 2017](#); [Lanier, Noyes & Biederman, 2021](#); [Chou et al., 2020](#)). Based on the same principle, and supported by the evidence that depressed individuals experience reduced episodic future thinking (e.g., [Hallford et al., 2020, 2022](#)), future studies may target key brain regions (such as the dmPFC; [Dunlop et al., 2020](#); [Gupta et al., 2024](#)) at the crossroads wherein large-scale neural networks (e.g., the FPCN, the DMN and the Salience Network; see the paragraph 3.4.) with aberrant patterns of functional connectivity in depression overlap, with the aim of restoring these dysfunctional thought patterns – and hopefully alleviating depressive symptomatology (see also [Aupperle et al., 2024](#) for an alternative approach employing neurofeedback modulation for future-thinking).

Interacting with a complex external environment enables the exploration of innovative ways in which modulating human thought in real-world settings. Nowadays, in fact, our external environment is increasingly *digital*, and this creates new opportunities to store a large amount of information, creating digital records of our memories that, of course, may affect the modalities and the quality of their recall. In this regard, a very recent theoretical framework ([Hutmacher et al., 2024](#)) reviewed how the creation of an immense amount of recorded information in digital formats (e.g., pictures, videos, posts on social networks) can shape autobiographical memory. In the *digital age*, in fact, autobiographical remembering is conceived as an iterative process that combines internal mental representations with external information provided by technology devices. For instance, we are exposed to myriads of stored data (that are intentionally recorded – e.g., photos - or instead passively captured– e.g., location data) which we can actively curate (i.e., *curation stage*; re-structuring the stored content over time; [Hutmacher et al., 2024](#)), prioritizing access to some information over others. At the same time, we can keep our memories private, but also share them publicly - on social networks – creating personal archives of our lives that will likely contribute to the generation of new *life themes*.

All these factors make autobiographical memory a *dynamic* – instead of unitary - process that relies not only on our cognitive abilities, but also on the format and quality of information stored externally.

In conclusion, this PhD thesis aimed to broaden the research focus on human spontaneous and deliberate thought by exploring its phenomenological, neural, and physiological correlates. Taken together, the present findings contribute to: *a*) distinguishing the neural correlates of internal and external attention (Study 1); *b*) identifying the cognitive and physiological mechanisms underlying spontaneous (Study 2) and deliberate (Studies 3 and 4) thought, *c*) demonstrating that both internal (i.e., activating relevant mental representations; Study 2) and external (i.e., intention offloading; Study 4) strategies can foster more adaptive forms of thought.

Let us revisit the image of myself on a crowded subway of a crowded city, immersed in the equally overwhelming flow of my thoughts. The effort to understand the large-scale features of human thought, as well as the variety of internal and external factors influencing its unfolding over time, allows us not only resist being swept away by the chaos of our minds and environments but also fully leverage the opportunities they both offer. In other words, this new perspective could lead to viewing myself not just as immersed in the crowd - of the subway, or the multitude of my thoughts - but as an *active* agent within that complexity, drawing inspiration from it to build more creative forms of thinking. This understanding, if anything, might help us feel a little less overwhelmed by the crowded – internal and external - complexity in which we are immersed.

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Appendix A

Supplementary Materials

Study 1.

The role of posterior parietal cortex and medial prefrontal cortex in distraction and mind-wandering

1. Supplementary Methods

1.1. Working Memory Task

Before starting the experimental sessions, all participants were evaluated on their working memory capacity, an aspect of executive functioning linked to mind-wandering (Levinson et al., 2012; Smallwood & Schooler, 2006; Teasdale et al., 1995), with a 3-back task (Zimmerman & Fimm, 2002). The task required to monitor a series of 100 digit stimuli (from 1 to 8), and signal whether the number currently presented matched the number presented 3 trials earlier. Each number was presented for 2 s, followed by a fixation cross lasting 1.5 s.

1.2. Mind Wandering Questionnaire

Following the working memory task, participants were administered the Italian version of the Mind Wandering Questionnaire (MWQ; Mrazek et al., 2013), which assesses the self-reported frequency of attentional shifts from an external activity towards the inner world (e.g., ‘while reading, I find I haven’t been thinking about the text and must therefore read it again’). The MWQ was originally designed to assess attention and distraction in university students, and therefore it was particularly suited to our sample. The questionnaire consisted of 5 items, whose response range was from 1 to 6. The total score ranges from 5 to 30, with higher scores indicating a higher propensity towards mind-wandering.

2. Supplementary Results

2.1. Relation between mind-wandering and visual search

We investigated whether mind-wandering influenced performance on the visual search task. We focused on the pre-tDCS session, as the different tDCS stimulation delivered to participant groups may alter the relation between mind-wandering and visual search. For each individual, we computed the median thought intensity reported at the VAS in association with thought probes, and divided trials into those attracting low vs. high levels of off-task thought using a median-split. Then, for each thought probe trial and individual, we computed the mean RTs and accuracy relative to the 15 visual search trials preceding the thought probe (collapsing across trial types). We then compared RTs and accuracy associated with trials preceding high vs. low intensity off-task thought trials across participant groups, using paired-sampled t tests. Participants were less accurate ($M = 0.98$, $SD = 0.02$; $M = 0.99$, $SD = 0.02$; $t_{64} = -1.95$; $p = 0.03$) and faster ($M = 622$ ms, $SD = 71$; $M = 629$ ms, $SD = 69$; $t_{64} = -1.68$; $p = 0.049$) in visual search trials that preceded reports of high vs. low levels of off-task thought, compatible with a tendency towards more impulsive responding. Because mind-wandering affected speed and accuracy in opposite ways, no significant difference was detected on the iRTs for trials preceding reports of high vs. low off-task thought ($p = 0.15$).

3. Supplementary Tables

	Past		Future		Present		Atemporal	
	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>	<i>pre-tDCS</i>	<i>post-tDCS</i>
Sham group	48 (62)	50 (58)	55 (85)	159 (124)	75 (90)	78 (78)	49 (83)	87 (98)
PPC group	70 (75)	43 (64)	72 (64)	109 (104)	53 (76)	70 (86)	63 (94)	78 (90)

mPFC group	64 (103)	81 (95)	81 (87)	112 (97)	65 (66)	58 (73)	80 (102)	95 (90)

Supplementary Table 1. Mean mind-wandering scores (and SD) for internal thoughts by temporal focus, participant group, and visual search condition. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

Appendix B

Supplementary Materials

Study 2.

Face the future!

How the Self and Time shape mind-wandering

1. Supplementary results

1.1. Levels of Boredom

Since the assumption of normality was violated, we performed a Kruskal-Wallis ANOVA on levels of boredom reported by subjects during the CRT task with Time and Person as between-subjects factors. There were no statistically significant differences in levels of boredom across groups when categorized by both Time [$H = 0.820$; $p = .365$] and Person [$H = 0.602$; $p = .438$]. This indicates that any effect of the activation of Self-schema or the future cannot be explained as a result of having elicited different boredom levels.

1.2. Levels of off-task thought

This analysis allowed us to check for differences among groups in the levels of off-task thought (i.e., the degree to which, immediately before the probe, their attention was *on-task* or *off-task*; see the *Methods* section). Since these values violated the assumption of normality (as assessed with the Shapiro-Wilk test), we ran a Kruskal-Wallis ANOVA on the levels of off-task thinking, with Time and Person as between-subject factors. We did not find any significant difference among groups in their levels of off-task thought both for probe-caught off-task thoughts (Person: [$H = .019$; $p = .890$]; Time: [$H = .496$; $p = .481$]) and probe-caught mind-wandering only (Person: [$H = .678$; $p = .410$]; Time:

[$H= 2.044$; $p = .153$]). These findings indicate that activating the Self-schema or a representation of the future time did not affect the intensity to which participants experienced off-task thought.

1.3. Number of thought-probes

To ensure equal chances for groups to report their unaware mind-wandering episodes, we conducted a Kruskal-Wallis ANOVA on the total number of probes they received during the CRT task, with Time and Person as between-subject factors. The analysis did not find any significant effect both for Time [$H= 0.924$; $p= .336$] and Person [$H= 0.723$; $p= .395$], demonstrating that the groups received a comparable number of thought-probes throughout the task.

1.4. Behavioral performance – CRT task

To evaluate whether groups differed in their behavioral performances, Kruskal-Wallis ANOVAs with Time and Person as between-subjects factors were conducted on the mean reaction times (RTs) and accuracy values at the CRT task. We found no statistically significant effects on RTs both for Time [$H= 0.039$; $p= .844$] and Person [$H= 0.586$; $p= .444$]. The analysis also failed to reveal significant effects of Time [$H=2.685$; $p= .101$] and Person [$H= 1.178$; $p= .278$] on the mean accuracy values. Taken together, these findings indicate that all groups were comparable in their behavioral performance at the CRT task.

Appendix C

Supplementary Materials

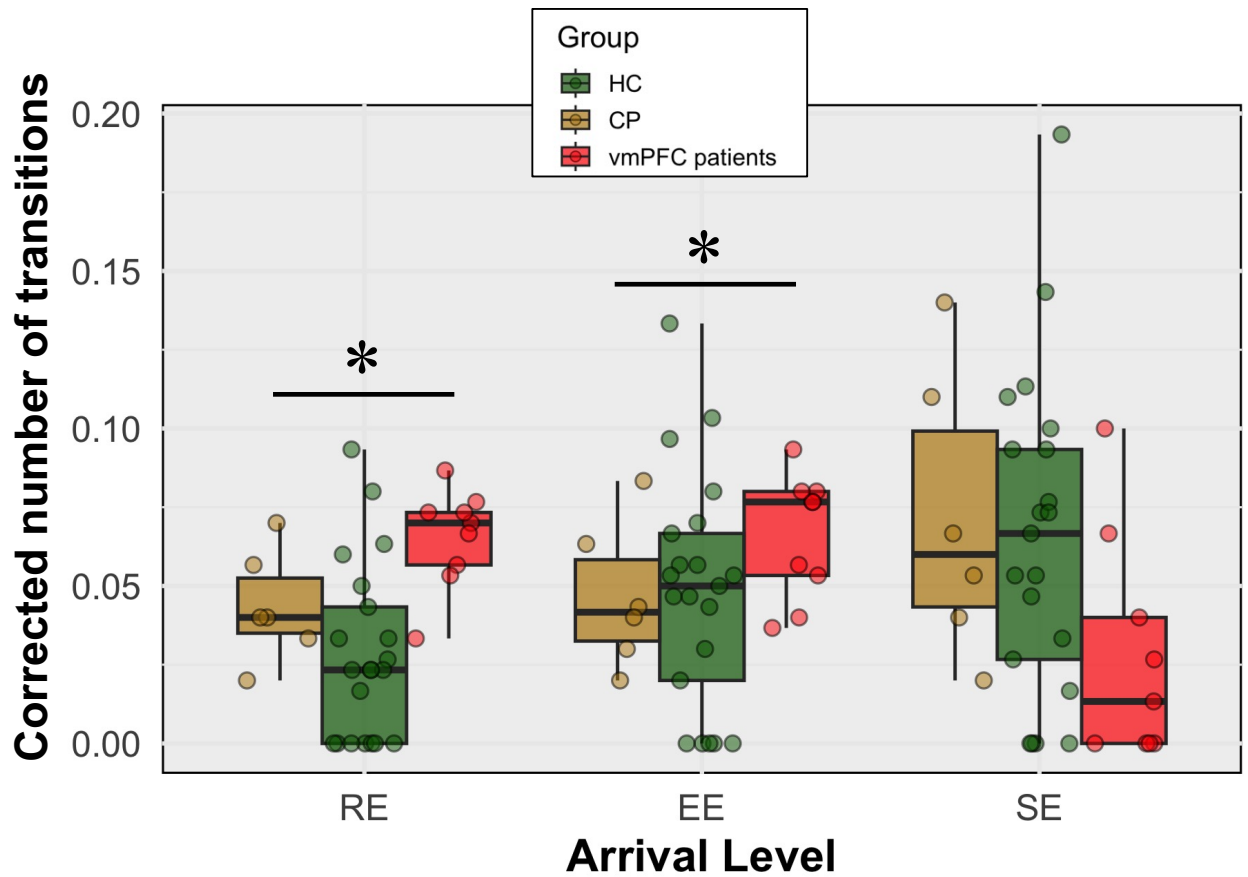
Study 3.

The temporal unfolding of memory structures following vmPFC damage

1. Supplementary results

1.1. The temporal progression of memory structures: forward transitions

The analysis on the corrected number of forward transitions starting from PS yielded a significant main effect of *group* [Wald $\chi^2_{(2)} = 26.19$; $p < .001$] and an interaction *arrival level * group* [Wald $\chi^2_{(4)} = 26.87$; $p < .001$], with the vmPFC patients' group showing a higher number of transitions from PS to RE compared to HC ($p < .001$), and more transitions from PS to EE than HC ($p = .002$), with no differences in these transitions between HC and CP (all $ps \geq .63$; see *Supplementary Figure 1*); groups did not differ significantly instead in the number of transitions from PS to SE (all $ps \geq .53$). The factor *time period* [Wald $\chi^2_{(2)} = 6.34$; $p = .042$] was also significant and configured in the significant interaction *time period * arrival level* [Wald $\chi^2_{(4)} = 10.65$; $p = .031$]: participants expressed overall more transitions from PS to EE in the future compared to the remote ($p = .044$), but not the recent past ($p = .99$), with no differences in the remaining transitions (all $ps \geq .32$).



Supplementary Figure 1. Corrected number of transitions starting from personal semantics (PS) by *group* (healthy controls, control patients and vmPFC patients) and *level of abstraction* (repeated events, extended events and specific events). Error bars indicate standard error of the mean. * $p < 0.05$.

The analysis on the corrected number forward transitions starting from RE showed no significant effects [all $ps \geq .05$]. Similarly, in the analysis on the corrected number of forward transitions starting from EE to SE, none of the factors reached statistical significance [all $ps \geq .19$].

1.2. Ratings

We conducted repeated-measure ANOVAs on the events' ratings (emotional valence, importance and relationship with personal goals), with *group* (HC, vmPFC patients and CP) as between-subject factor, and *time* (remote, recent past and near future) as within-subject factor.

1.2.1. Emotional valence

We found a main effect of *time* [$F_{2.66} = 18.696$; $p < .001$; $\eta_p^2 = .362$], suggesting that imagined future events (mean = 4.5; $p = .049$) were rated as more positive than events that happened in the recent past (mean = 3.5; $p < .001$) and the remote past (mean = 3.0; $p < .001$). The factor *group* [$F_{2.33} = 2.457$; $p = .101$] and the interaction *time*group* [$F_{4.66} = 1.082$; $p = .373$] instead were not significant.

1.2.2. Importance

The analysis yielded a main effect of *time* [$F_{2.66} = 9.441$; $p < .001$; $\eta_p^2 = .222$], revealing that events in the remote past were rated as less important than events in the recent past ($p = .002$) and events in the future ($p < .001$). The factor *group* [$F_{2.33} = 0.502$; $p = .610$] and the interaction *time*group* [$F_{4.66} = 1.624$; $p = .179$] failed instead to reach statistical significance.

1.2.3. Relationship with personal goals

We found a main effect of *time* [$F_{2.66} = 4.937$; $p = .010$; $\eta_p^2 = .130$], whereby imagined future events were rated as significantly more related to participants' personal goals, compared to events in the recent past ($p = .017$) and remote past ($p = .026$). The factor *group* [$F_{2.33} = 1.826$; $p = .177$] and the interaction *group*time* [$F_{4.66} = 1.071$; $p = .378$] were not significant instead.

2. Supplementary Tables

Names of people (Acquaintances, friends, relatives)	Sum 0/6
Name or surname	0/1
Job or role/ relationship (parent, friend, colleague, partner, acquaintance, etc).....	0/1
Name or surname	0/1
Job or role/ relationship (parent, friend, colleague, partner, acquaintance, etc).....	0/1
Name or surname	0/1
Job or role/ relationship (parent, friend, colleague, partner, acquaintance, etc).....	0/1
Places	Sum 0/6
Name.....	0/1
Address or geographical location (area, neighborhoods).....	0/1
Name.....	0/1
Address or geographical location	

(area, neighborhoods).....	0/1
Name.....	0/1
Address or geographical location	
(area, neighborhoods).....	0/1

Personal address	Average 0/4
Full address (street, house number).....	0/1
City.....	0/1
Type of residence.....	0/1
Details (floor and/or other characteristics).....	0/1
Full address (street, house number).....	0/1
City.....	0/1
Type of residence.....	0/1
Details (floor and/or other characteristics).....	0/1
Full address (street, house number).....	0/1
City.....	0/1
Type of residence.....	0/1

Details (floor and/or other characteristics).....	0/1

School/ work	Average 0/4
Typology..... City..... Address or geographical location (area, neighborhoods) Institution name	0/1 0/1 0/1 0/1
Typology..... City..... Address or geographical location (area, neighborhoods) Institution name	0/1 0/1 0/1 0/1
Typology..... City..... Address or geographical location (area, neighborhoods) Institution name	0/1 0/1 0/1 0/1

Supplementary Table 1. *Scoring protocol for the Personal Semantic Interview.* The scoring procedure involved assigning a score for each of the 4 categories explored during the Personal Semantic Interview. Each new item of information was given a score of 1. For the *people* and *places* categories, the scores for each piece of information were summed, while for the *address* and *work* categories, the scores were averaged across the items mentioned. Each section allowed for a maximum of 3 items identified by the participant. At the end, the scores for each category were summed to obtain a comprehensive index, with a maximum score of 20.

Appendix D

Supplementary Materials

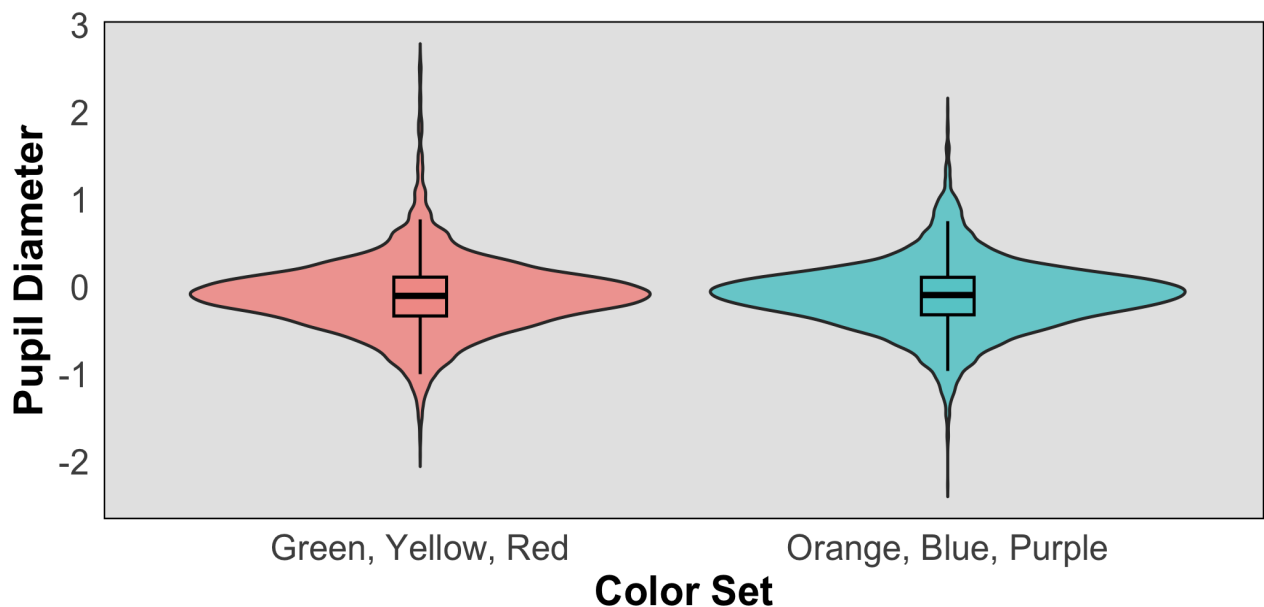
Study 4.

Freeing the Mind with External Reminders: Intention Offloading decreases Pupil Diameter and Off-task thinking levels

1. Supplementary results

1.1. Color sets of stimuli

To ensure that the two different color sets of stimuli did not affect participants' pupillary responses, we conducted a linear mixed model (LMM) on normalized pupil diameters, with *color set* (green, yellow, red or orange, blue, purple) as a fixed effect and *participant* as a random effect. The factor color set was not significant [Wald $\chi^2_{(1)} = 0.70$; $p = .40$], confirming that the use of one or the other color set did not affect pupil diameters differently (see Supplementary Figure 1).

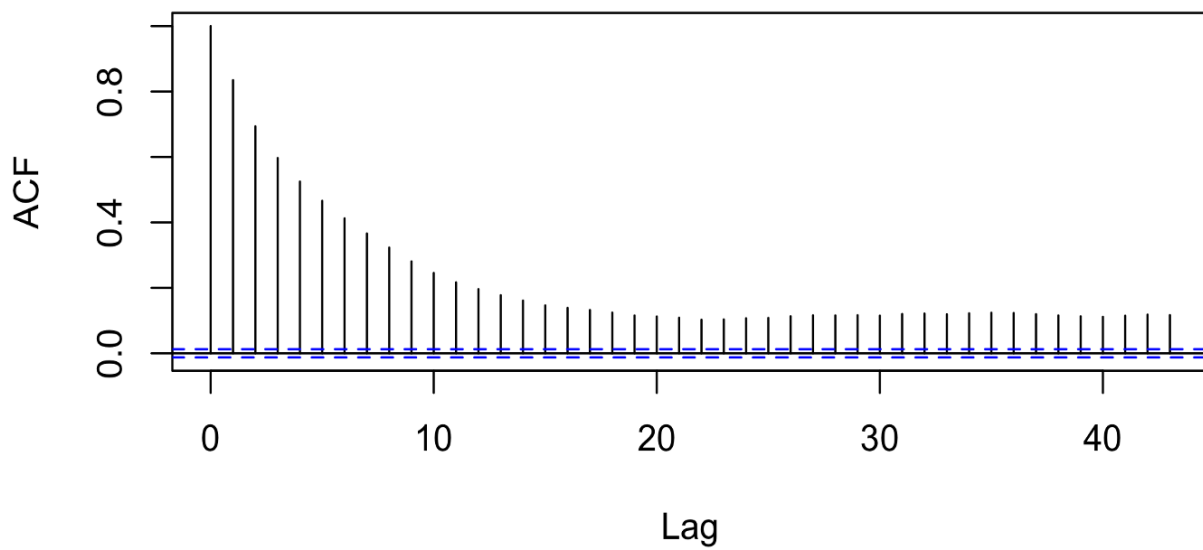


Supplementary Figure 1. Violin plot displaying normalized pupil diameters by color set (green, yellow, red and orange, blue, purple). The boxplot within each violin represents the interquartile range (IQR) with the median indicated by the central line.

1.2. Autocorrelation function

Pupil diameters tend to change gradually: it means that the pupil diameter measured at one point in time is often related to the measurements recorded shortly before or after a given time-point (van Rijn et al., 2019; Vogels et al., 2018). To account for this temporal dependence, we fitted an autocorrelation function to the successive normalized pupil diameter measures over trials (see Supplementary Figure 2). To examine the effects of load and offloading on pupil diameter, we repeated the LMM on normalized pupil diameter and implemented an AR(1) autocorrelation structure, with *Memory Load* and *Offloading* as fixed effects and *Participant* as random effect. The autocorrelation parameter ($\Phi = 0.82$) indicated a strong temporal dependence between successive pupil measurements. The analysis revealed a significant main effect of *Offloading* [Wald $\chi^2_{(1)} = 5.23$, $p = .022$], with pupil diameters being smaller in the offloading condition. Additionally, we found a significant interaction *Memory Load* * *Offloading* [Wald $\chi^2_{(1)} = 7.88$, $p = .005$], indicating that in offload blocks pupil diameters decreased more under high vs. low memory load condition, while this difference did not emerge in the no offload blocks.

These findings suggest that consecutive normalized pupil measures were correlated; however, the selective effect of offloading on pupil diameter on high vs. low memory load conditions remained significant even after accounting for this temporal dependence.



Supplementary Figure 2. Autocorrelation function (ACF) plot showing the relationship between normalized pupil diameters across successive trials. The y-axis represents the autocorrelation coefficient (ACF), while the x-axis indicates the lag (the number of trials separating each pair of data points). The initial high autocorrelation values gradually decline as the lag increases, confirming a temporal dependence between pupil measurements in nearby trials. The dashed blue lines represent the 95% confidence interval, with values outside these bounds indicating statistically significant autocorrelations.

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