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Neural Correlates of Prospective Memory: an EEG and ICA approach

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Gabriela Paz Cruz San Martín

Occupational Therapist
Master in Neuroscience

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Institute of Health and Wellbeing & School of Psychology
College of Medical, Veterinary and Life Sciences
University of Glasgow

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Abstract

Have you ever entered a room and wondered ‘What am I supposed to do here?’ or have you ever forgotten to turn off the oven, hang your clothes to dry or make a phone call. These examples illustrate the relevance of ‘prospective memory’ or ‘delayed intentions’ in our daily life activities. Prospective memory is the ability to remember to do something after a delay. This thesis addresses three questions relevant to understand maintenance and execution of intentions: Is attention required to retrieve delayed intentions? What does monitoring mean in the context of prospective memory? Is prospective memory a discrete memory system or it is based on already known attentional and memory mechanisms? To answer these questions, we used electroencephalography (EEG), in (traditional) non-movement and free-movement experimental paradigms. We explored the neural substrate of prospective memory across its different stages: (1) holding intentions during a delay, (2) detecting the right context to perform the delayed intention, and (3) retrieving the content of the intention (the action to be performed). Two types of prospective memory tasks were used: Event-based prospective memory (performing a delayed intention in response to an external cue) and time-based prospective memory (performing the intention at a particular time). Results indicate that: prospective memory always requires attention, at least in experimental contexts; monitoring involves different mechanisms depending on the particular features of the prospective memory task and; prospective memory is not a discrete memory system, but relies on well-established mechanisms for attention and executive control.

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Author's Declaration

I declare that this doctoral dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Introduction

Prospective memory is the ability to remember to do things at the appropriate time after a delay. To illustrate this imagine the following scenario: It's a weekday morning, and whilst taking a shower you remember the cat needs to be fed. You are running late, and after showering you eat breakfast, prepare a packed lunch and rush to the door. Just as you are about to leave you remember the cat, and fill its bowl with food.

This is a typical situation where prospective memory is required. We think about something we have to do but we cannot carry out the action at that time (thinking about feeding the cat while you are in the shower). Immediately after thinking about what we have to do, we get involved in a variety of different tasks that engage our attention (preparing breakfast or lunch) and we have to remember at the appropriate time (before leaving home) to execute the previously formed intention. In this example we have a happy cat, but it could also be the case that we remember half way to work that the cat has not been fed.

Prospective memory underlies many activities in our daily life and work environments; turning off the oven after 30 minutes, paying a bill, picking up children after school or closing an abdominal incision without leaving any surgical instruments inside the patient. Some of these tasks may seem simple, but failures are quite common, on occasions with impact on social dimensions (Brandimonte & Ferrante, 2008; Dismukes, 2008). Very occasionally prospective memory failures have disastrous consequences causing major accidents (Dismukes, 2008, 2012).

There is a wide range of situations and health conditions that affect prospective memory performance. Healthy individuals can forget to do things under demanding or distracting environments: for example, clothes can lie in the washing machine for hours on a busy day, or in a rush an email can be sent without an attachment. People affected by neurological or psychiatric conditions are more likely to experience prospective memory problems, resulting in disability and loss of independence (Boelen, Spikman, & Fasotti, 2011). The rehabilitation of prospective memory is therefore a key target for cognitive rehabilitation programs.

The ability to execute intended actions appropriately is critical for independent living. For this reason, prospective memory is an important topic to study from a clinical and theoretical perspective. The studies presented in this thesis aim to contribute to a better understanding of what cognitive resources are required for maintenance and execution of delayed intentions, in order to support the future development of interventions in rehabilitation contexts.

Currently there is no agreement between the different theoretical models that explain the mechanisms underlying prospective memory (Einstein et al., 2005; Guynn, 2003; Smith & Bayen, 2004). I address three issues in this thesis:

1. The main issue is related to whether retrieval of intentions can be spontaneously initiated (McDaniel & Einstein, 2000) or if attention is necessary to initiate the retrieval of intentions (Smith, Hunt, McVay, & McConnell, 2007). Yet, these different theoretical postures agree on that certain prospective memory tasks necessarily require sustained attentional to be successful. They do not agree that some prospective memory tasks can be performed spontaneously.
2. In the process of answering the first question, a second question arose. What do ‘monitoring’ and ‘spontaneous’ mean in the context of prospective memory literature?
3. Other issue relevant for the discussion is that sometimes prospective memory is treated as a discrete memory system (Crawford, Henry, Ward, & Blake, 2006; West & Krompinger, 2005; West & Wymbs, 2004), which may downplay the idea that prospective memory is based on already known attentional and retrospective memory mechanisms (Einstein & McDaniel, 2007; Knight, Ethridge, Marsh, & Clementz, 2010).

Across the development of this PhD work we have found different challenges in the study of prospective memory that can also explain the differences in the theoretical postures. Critical points include: (i) the terminology used to describe prospective memory processes, (ii) methodological approaches and techniques, (iii) the great variety of situations where prospective memory is required and (iv) fundamental differences between experimental and real-life prospective memory tasks.

Behavioural approaches have made a great contribution to the debate in prospective memory (Boywitt & Rummel, 2012; Guynn, 2003; Smith, 2010; Smith & Bayen, 2004). However, they are limited by their inability to explore the underlying neural activation patterns, which can be very informative regarding the nature of underlying cognitive processes, for example sustained versus transient processes (McDaniel, Lamontagne, Beck, Scullin, & Braver, 2013). Various methods have been used to study how the brain deals with delayed intentions. Functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) studies have shown activation of critical brain regions associated with prospective memory performance and their role during encoding and retrieval of delayed intentions (Burgess, Gonen-Yaacovi, & Volle, 2011; Burgess, Quayle, & Frith, 2001). Magnetoencephalography (MEG) (Martin et al., 2007) has shown involvement of parietal, frontal and hippocampal structures during prospective memory retrieval with higher temporal resolution than fMRI studies. On the other hand electroencephalographic (EEG) techniques have been used to examine the temporal dynamics observed during encoding and retrieval of prospective memory intentions (West, 2011).

Several advantages of EEG make it an attractive technique for the study of prospective memory. EEG is particularly suitable in situations that involve movement and displacement, which opens a window for the study of prospective memory failures in real life situations. Advanced and sophisticated methods to study behaviour using EEG are starting to be developed (Makeig, Gramann, Jung, Sejnowski, & Poizner, 2009). Perhaps, in the near future, we will be able to predict prospective memory performance and avoid undesirable consequences of prospective memory failures, but for that to become reality, we first need to better understand – or at least identify – the neural mechanisms or signatures of brain activity associated with good prospective memory performance.

We also used Independent Component Analysis (ICA), a mathematical method that separates the independent sources (ICs) that contribute to the whole brain activity detected at scalp electrodes level. ICA enables a focus on signals that are more sensitive to the cognitive processes of interest and increases the spatial resolution of the EEG (Makeig, Debener, Onton, & Delorme, 2004; Onton, Westerfield, Townsend, & Makeig, 2006).

In this thesis we used EEG and ICA to explore what cognitive resources are required for the maintenance and execution of delayed intentions. We propose that, to progress in the discussion of the issues enumerated previously, it is necessary to first define how the requirement of cognitive resources can be associated to four different stages of the prospective memory processing: (i) intention encoding, (ii) retention interval, (iii) retrieval of the intention and (iv) execution of the intention. Second, it is necessary to explore how manipulation of the task – particularly associated to the retrieval of the intention – can influence the prospective memory performance in its different stages, rather than in prospective memory performance as a whole.

In the first chapter of this thesis, we detail different mechanisms used to exert executive control across the different stages of the prospective memory process and how the intention retrieval, where the prospective memory task is embedded, can be manipulated in order to vary the requirement for executive control.

The second chapter describes the methodology used in the experimental part of the PhD work, including an updated review of the contribution of EEG to unresolved questions in prospective memory.

Chapters 3 to 6 detail each of the four experiments performed to answer the questions stated earlier in this introduction.

Chapter 3 corresponds to a behavioural pilot experiment exploring the sort of experimental manipulations that affect the requirement of monitoring during the different stages of the prospective memory process. This experiment consisted in a new behavioural paradigm that allowed comparison of two prospective memory tasks, a high-demand versus a low-demand one, in order to subsequently explore the requirement of attention under these two conditions using EEG. The results led to the experimental paradigm used for the EEG experiments presented in chapters 4 and 5.

Chapter 4 is an event-based prospective memory task, meaning that there is an external cue triggering the retrieval of the intention. The results contribute to the discussion of how differential attentional networks may be involved in different prospective memory paradigms, even when in terms of behavioural performance we may think that the experiment does not require much attention.

Chapter 5 corresponds to a time-based prospective memory task, meaning that the retrieval of the intention is self-initiated. The results show the involvement of the anterior cingulate cortex as a key region for the executive control of attention in time-based prospective memory paradigms, contributing to the idea that different attentional mechanisms are required depending on the type of prospective memory task.

Chapter 6 is an attempt to move towards more naturalistic prospective memory/EEG paradigms. We explored the feasibility of doing EEG experiments involving free-movement conditions, facing future development of paradigms to study neural processing of delayed intentions in real-life conditions.

The final chapter is an integrative summary, where we address the main issues mentioned in this introduction. Based on the experiments and results described in this thesis we deduce that attentional resources are required to retrieve a prospective memory intention, even in low demand situations, within the context of a laboratory short-term prospective memory task. In addition, the idea of ‘monitoring’ in prospective memory can involve different attentional mechanisms, depending on the particular features of the prospective memory task. The present work is consistent with the idea that prospective memory is not a discrete memory system, but a particular orchestration of executive functions, involving retrospective memory and executive control of attention. Maybe the best term to refer to this ability is prospective remembering or realisation of delayed intentions.

Chapter 1
Understanding prospective memory

1.1 What is prospective memory?

Prospective memory has been defined as the ability to execute an intended action after a delay (Burgess et al., 2001). Multiple cognitive processes are involved in the effective fulfilment of those actions, including memory, attention and executive functions (Einstein et al., 2005; Smith & Bayen, 2004). The present section details: how these cognitive processes participate in prospective memory tasks; the main theories that explain the involvement of attention and memory in prospective remembering; a new proposal that tries to unify the different theories and; a brief review of key brain areas relevant for prospective memory performance.

1.2 Cognitive functions across the four stages of prospective memory

Prospective memory is not an unitary, discrete memory system (Einstein & McDaniel, 2007), it rather represents a type of task that requires previously described memory systems in addition to attentional mechanisms (Smith, 2008) and executive functions (Martin, Kliegel, & McDaniel, 2003). The cognitive processes underlying prospective memory are classified into two components: prospective and retrospective. The prospective component corresponds to the detection of the right moment to execute the action and it is associated with attentional processes. The retrospective component refers to remembering the action to be executed and it is associated with retrospective memory processes (Einstein et al., 2005; Smith & Bayen, 2004). However, this classification is too broad to explain how attention, executive functions and memory are involved in prospective remembering: some prospective memory tasks require more attention or memory than others depending on the specific features of the task (McDaniel & Einstein, 2000). The requirement of memory, attention and/or executive functions will also depend on the stages in the prospective memory process. Prospective memory involves four different stages: intention formation, retention interval, intention retrieval and execution of intentions (Ellis & Milne, 1996; Fish, Wilson, & Manly, 2010; Kliegel, Mackinlay, & Jäger, 2008); (Kliegel, Jäger, Altgassen, & Shum, 2008).

1.2.1 Formation and encoding of intentions

This phase is highly related to planning skills (Kliegel, Mackinlay, et al., 2008; McDaniel & Einstein, 2000). At the moment an intention is created we can also plan the future actions that will lead us to the accomplishment of the intention, even though we do not always create detailed plans associated with intentions, or the plans are not adequate to accomplish the intention. Memory encoding (Addis, Wong, & Schacter, 2007; Poppenk, Moscovitch, McIntosh, Ozcelik, & Craik, 2010) and planning (Kliegel, Mackinlay, et al., 2008) seem to be the key cognitive functions at this stage.

1.2.2 Retention interval

A primary characteristic of prospective memory is that the intention must be retained and performed at a later point in time. During the retention interval we are engaged in another unrelated activity, which is known as ‘the ongoing task’ (in experimental paradigms) a term agreed after the First International Conference on Prospective Memory (Ellis & Kvavilashvili, 2000).

A general consensus is that the intention is not continuously kept in working memory (Ellis & Kvavilashvili, 2000) and that the ongoing task prevents the continuous rehearsal of it. So the subsequent question is: How do we maintain those intentions and retrieve them at the proper time? The mechanisms used to maintain an intention during the retention interval are still being studied.

The involvement of retrospective memory – where the intention is stored during the retention interval – seems to be clear (Kliegel, Jäger, et al., 2008; M. Martin et al., 2003). However, the question of whether attention is required during the retention interval is still a topic of debate (see section 1.6.1 in this Chapter). The main question is whether it is necessary to devote cognitive resources to maintaining the intention actively in memory (Guynn, 2008; Smith & Bayen, 2004) – by continuous or periodical checks on the uncompleted intention – or whether it is possible to have situations where the intention 'pops-up' spontaneously triggered by strong external cues (Einstein et al., 2005). If the latter were true, attention devoted to the prospective memory task would not be necessary during the retention interval. Section 1.4 details the different theories that support both positions.

1.2.3 Intention retrieval

Good prospective memory performance requires recollection of the intention in a specific context, which is encoded with the intention at the first stage of the prospective memory process. Specific features of a target event (a person, an environmental cue, a place, a specific time lapse, etc.) will indicate the right context to execute the intention. The nature of the target event has been used to classify prospective memory into different types of task (Ellis & Milne, 1996).

- Event-based tasks: the retrieval of the intention is prompted by an external cue: for example, post a letter when you see the box post.
- Time-based tasks: the retrieval should occur at a specific time or after a certain time period: for example, turn off the oven in 30 minutes.
- Activity-based tasks: the retrieval occurs associated to another task, for example taking medication after breakfast. The study of activity-based tasks is less common in the literature despite the fact that it has been mentioned as a distinctive type of event-based prospective memory task (Ellis & Milne, 1996).

Depending on the nature of the context, the intention retrieval can be more or less demanding. In the case of time-based tasks the execution of the intention relies on self-initiated processes. When we set the intention of 'taking medicine at 2pm', there are no external cues that will prompt the action, unless the task is transformed into an event-initiated task using an alarm. When an intention has been strongly associated with an external cue, the retrieval of the intention can imply the execution of well established sequences of action, and behaviour can be relatively easily triggered by the external cue rather than via self-generated conscious control (Gilbert, Gollwitzer, Cohen, Burgess, & Oettingen, 2009). Researchers agree that event-based prospective memory tasks will require fewer cognitive resources compared to time-based tasks (M. Martin et al., 2003). However, there is no consensus on whether the retrieval of intentions in event-based prospective memory tasks can occur spontaneously or if attentional processes are always required to recognise cues as prompts for intention retrieval (see section 1.6.2 in this chapter).

1.2.4 Execution of the intention and evaluation of the outcome

The execution of the intended action necessarily requires interrupting the performance of the ongoing task, and thus inhibition is a key cognitive function at this stage (Kliegel, Jäger, et al., 2008).

The 'Norman-Shallice model of action control' proposes that a Supervisory Attentional System (SAS) (Shallice, Burgess, Schon, & Baxter, 1989) inhibits behaviours irrelevant to the completion of a task and at the same time activates the necessary ones. The SAS does not lead directly to a response; instead, it provides additional activation or inhibition for schematas (well-established action or thought routines) (Burgess, Dumontheil, & Gilbert, 2007).

To evaluate the outcome of the action, we compare the result of our behaviour with the internal representation of goals (Shallice & Burgess, 1996). We detect an error when there is incongruence between the action and the internal state, so we can correct the performance towards the accomplishment of the goal. Strong executive control is required at this stage (Bettcher et al., 2011; Gracey, Evans, & Malley, 2009). Incorrect actions that do not contribute towards the accomplishment of goals can also be produced by incorrect formulation of intentions (Bettcher & Giovannetti, 2009). In this case, the problem is related to the planning and encoding of intentions, and there is a lower probability of detecting those errors, since we are acting according to the plan.

1.3 Is attention required to retrieve delayed intentions? Theoretical perspectives

While some say that prospective memory can be executed purely based on spontaneous processes (Multiprocess theory), others state that prospective memory necessarily requires some degree of strategic processes (Preparatory attention and memory processes theory). Thus, the point where these theories differ is whether prospective memory tasks can completely rely on automatic processes. In the present section we explain these two theories.

1.3.1 Multiprocess Theory

This theory states that retrieval can occur with or without the engagement of preparatory attentional processes (Einstein et al., 2005; McDaniel & Einstein, 2000), depending on the features of the prospective memory task. These features include: the importance of the prospective memory task, target distinctiveness, target-intention association, parameters of the ongoing task, planning and individual differences. It is important to highlight that this theory is described considering the case of event-based prospective memory tasks. Even though the theory can also be relevant to time-based prospective memory, it does not explicitly consider this.

Spontaneous retrieval is defined as the retrieval of an intention, triggered by an external target in the absence of preparatory attentional processes or a retrieval mode (executive resources) devoted to detecting the target to perform the intention; in other words, without the requirement of monitoring, it considers that occasional thoughts related to the prospective memory intention can occur during the retention phase. According to this theory, spontaneous retrieval can occur through association between the target cue and the intended action during planning, which has been called ‘reflexive-associative theory’ (Einstein et al., 2005) or it can also be the result of spontaneous recognition, when there is high focality of the prospective memory target (Einstein & McDaniel, 2007).

In contrast, monitoring would be required under non-routine situations where novel responses are required (Burgess et al., 2007; Shallice et al., 1989). In these cases, the Supervisory Attentional System (SAS) (Shallice et al., 1989) would monitor the environment until a prospective memory cue is encountered, after which it would switch attention from the ongoing to the prospective memory task by means of providing additional activation or inhibition for schematas (action routines) to execute the correct behaviour according to the situation.

1.3.2 Preparatory attentional and memory processes (PAM) theory

This theory is based on event-based prospective memory tasks, similarly to the Multiprocess Theory. The authors refer to prospective memory as 'delayed intentions'; this is relevant to understanding this theory, since it is supported by a careful definition of the concepts involved (Smith, 2008). It defines intentions as actions that result from a previously formulated plan, and thus it necessarily implies some requirement for executive control. Under this definition, all intentions are prospective, as they will be performed after the formulation of the plan, but some of them will be acted immediately after the formulation (without necessarily having been conscious of the process) and others will have to be stored and performed after a delay, which is the case of prospective memory tasks or delayed intentions.

Smith (2008) does recognise the existence of automatic processes in delayed intentions, but when there is no previous plan to act or if the action relies purely on reflexive movements, that action would not be an intention. Thus, by definition, all delayed intentions require some degree of cognitive control. When the plan for action is created, the intention is in the focus of the attention. However, if for any reason the intention cannot be immediately performed, the focus of attention is occupied by the ongoing task. During the ongoing task, some of the limited attentional resources (Smith & Bayen, 2004) must be devoted to evaluating the environment to recognise the prospective memory cue that will prompt the retrieval of the intention. Once the cue has been detected, the previously created intention returns to the focus of attention, allowing performance of the action. This does not imply that we require constant engagement of preparatory attention, but that it is required at some point and to some degree.

This theory has been validated through two main approaches: first, the idea of 'cost' (Smith, 2010; Smith et al., 2007), and second through a multinomial mathematical model (Smith & Bayen, 2004).

The 'cost' is measured by comparing the performance of the ongoing task (control condition) with the performance of the same ongoing task plus the holding of the intention. The reaction time and accuracy of the ongoing task should be the same as in the control condition if no attention is required by the prospective memory task during the retention interval, but affected if prospective memory involves processes drawing on our limited attentional resources (Smith & Bayen, 2004). A number of experiments show an interference between the performance of the ongoing task and the holding of intentions (Guynn, 2003; Marsh, Hicks, Cook, Hansen, & Pallos, 2003; Smith et al., 2007), suggesting that in some situations prospective memory requires cognitive resources to be withdrawn from the ongoing task. However, the results are controversial (Scullin, McDaniel, & Einstein, 2010; Smith, 2010; Smith et al., 2007).

The multinomial mathematical model corresponds to a statistical model popular in cognitive psychology (Batchelder & Riefer, 1999) used to identify which cognitive processes are involved in particular experimental tasks. In this case, two cognitive processes are involved: preparatory attention and memory processes. The multinomial model can only be used for categorical data, where the categories are all the possible responses in a particular experimental task, for instance, target, non target and prospective memory responses. This model represents all the possible interactions and responses as a tree, with each branch representing different interactions of the cognitive processes (model's parameters) that will finish in the expected response (probability parameters). The interactions and the expected response are built based on theoretical assumptions of how the cognitive processes used in the model interact. If the estimations given by the model (probability parameters) match the result of actual experiments, the theoretical assumptions used to create the model (model's parameters) are confirmed (See Batchelder, 1999 for a review). In summary, this theory states that the only way of achieving a prospective memory response is through monitoring processes, which are not necessarily conscious (Smith, 2010) and it is based on the idea that the prospective component involves the requirement of limited attentional resources.

1.4 What does monitoring mean in prospective memory tasks? Theoretical perspectives

1.4.1 Guynn's Monitoring Theory

This is the only theory that incorporates time-based prospective memory tasks to some extent. It does not detail the mechanisms by which monitoring occurs, but it contributes to the discussion of how monitoring may operate. It does not discuss whether it is possible or not to have spontaneous – automatic or reflexive – prospective memory; it rather focuses on the cases of tasks that do require monitoring, the point in which both of the theories explained above converge. This theory states that there are two components that relate to monitoring: 'Retrieval Mode' and 'Target Checking'.

The idea of a retrieval mode is taken from studies in retrospective memory (Guynn, 2003; Guynn, 2008) and it is defined as a mental state or 'set' that allows the retrieval of information, and which does not imply that the retrieval will be successful (Tulving, 2002). In the field of prospective memory, retrieval mode is defined as a mental state that keeps the intention active in mind, thus allowing recognition of a prospective memory cue or of the appropriate context to perform the intention (Guynn, 2008). According to Monitoring Theory, the retrieval mode is more or less continuous, and it is necessary to allow intention retrieval. It may operate through the 'intention superiority effect', a phenomenon referring to a better retrieval when the information stored is relevant for the performance of a future action (intention), in contrast with the case of storing information that will not be required in the near future (Goschke, 1993). The original conceptualization of 'retrieval mode' in episodic memory involves several processes (Lepage, Ghaffar, Nyberg, & Tulving, 2000), such as holding a piece of episodic information 'in the back of the mind', treating contextual information as retrieval cues, stopping irrelevant processes at the moment of retrieval and becoming conscious of the retrieval-result. It is interesting how all these aspects of episodic memory retrieval are consistent with concepts in prospective memory retrieval. Although ‘retrieval mode’ is associated with episodic memory, it is rather associated with the executive component of episodic memory retrieval.

The other component of this theory is ‘Target Checking’, which would be more intermittent and operates by checking the environment for the occurrence of the prospective memory event: for instance, checking for a specific cue in the case of event-based prospective memory and checking a clock in the case of time-based prospective memory task.

Experimental evaluation of this theory examines the impairment of an ongoing task (in terms of accuracy and reaction time) compared to the performance of the same task without the prospective memory task embedded (control condition), the same concept of ‘cost’ used by the PAM theory (section 1.3.2). To examine the difference between retrieval mode and target checking, the tasks are performed in two different modalities: block and alternated design (Guynn, 2003). In the block design, the control task goes before the experimental task. Alternate design combines execution of control task with experimental task. When the control task is alternated with the experimental task, the retrieval mode should be active, but no target checking would be needed. Thus, assuming that monitoring relies on limited cognitive resources, the performance in the ongoing task is (a) better when the control task is performed previous to the experimental task (block design), (b) intermediate in the control alternated block and (c) worst in the experimental block (Guynn, 2003; M. J. Guynn, 2008).

As far as we know, this is the only theoretical account for monitoring in prospective memory. Studies using fMRI (Burgess et al., 2008) have elucidated the role of the prefrontal cortex in prospective memory and goal directed behaviour. However, these findings have not been used to articulate a theory of what monitoring involves in prospective memory. In section 1.6, we present our account for what monitoring involves in prospective memory tasks.

1.5 Understanding the contradictions among theories in prospective memory

The questions as to whether prospective memory tasks can rely only on automatic processes, and what monitoring means in the context of prospective memory, have different responses depending on the theoretical framework that is being used to answer them (Multiprocess, PAM or Monitoring theory). However, each of these theories highlights unresolved questions that may be explaining the discrepancies among them. It may be the case that theories in prospective memory are not contradictory, but rather focus on different aspects of prospective memory processing. Understanding unresolved questions within each theory and the key points that may explain discrepancies between these theories is relevant for the theoretical proposal developed in this thesis.

1.5.1 Unresolved questions within theories of prospective memory

The Multiprocess Theory (Einstein et al., 2005; McDaniel & Einstein, 2000) states that there are two components – a retrospective or memory-based component, and a prospective or attentional component – that make a task either automatic or strategic, depending on the situation. However, while this theory describes the multiple factors that influence the requirement of strategic resources (or attention-demanding processes), it does not make a direct link with either component. Under the Multiprocess Theory, ‘attention demanding processes’ are associated with monitoring the environment for the occurrence of the prospective memory cue that signal the moment to execute the intention. However, the nature of these attentional processes is not described (McDaniel & Einstein, 2000). The attentional component seems to entail multiple cognitive processes (Shallice & Burgess, 1996; Stuss, Shallice, Alexander, & Picton, 1995). For example, attentional control may be involved in monitoring the environment during the retention phase – by shifting attention between external stimuli and goal representations – or it may be involved in the modulation of processing of environmental task stimuli relevant for the prospective memory task (Knight et al., 2010). The attentional component described in this theory may also involve other mechanisms that are not necessarily defined as attention, but require cognitive control, such as the activation or inhibition of motor schemata to perform the intended action. In addition, automatic processes can support the different components of prospective memory, for example spontaneous memory retrieval (Hall, Gjedde, & Kupers, 2008) or attention directed by salient environmental stimulus. This does not mean that prospective memory retrieval can be automatic, but that some stages in the prospective memory process can rely on rather automatic processes. We propose that cognitive processes occurring at different stages of the prospective memory process – encoding of the intention, retention interval, retrieval (including detection of the right moment to perform the action and recalling the action to be performed) and implementation of the intention – are also associated with what can be defined as automatic or strategic cognitive processes in prospective memory. In other words, the degree to which memory and attentional processes are involved can be understood in relation to the four stages of the prospective memory process.

As already noted, the PAM theory also defines two separate parameters: preparatory attentional processes and retrospective memory processes. The two parameters are used in the mathematical multinomial model of event based prospective memory to predict performance (Smith & Bayen, 2004). However, the theory does not extend to time-based prospective memory tasks and they recognise the lack of clear measures for studying how different manipulations of a task can affect the two underlying processes (Smith, 2008). In addition, the use of 'cost' to evaluate the requirement of strategic processes has been controversial (Einstein & McDaniel, 2010) and the use of the multinomial models to probe the requirement of strategic attentional processes is designed for very specific experimental paradigms that allow limited number of responses, so it may not capture all the cognitive processes underlying the task (Batchelder & Riefer, 1999).

In a recent publication, Scullin et al, (2013) updated the Multiprocess Theory, calling it the Dynamic Multiprocess Framework. This new version of the theory expanded its assumptions to naturalistic situations, where long retention intervals occur, for example, in remembering to attend an appointment in a week. Under this view, monitoring is required only when people enter a context in which prospective memory cues are expected. Spontaneous retrieval of intentions prompted by environmental cues would be one of the mechanisms that reminds people that it is time to monitor the environment for the execution of the intention. This new version of the theory brings closer the different theoretical postures, since the PAM theory also states that we do not require constant engagement of monitoring (preparatory attention), but that it will be required at some point and in some degree (Scullin, McDaniel, & Shelton, 2013; Smith & Bayen, 2004).

On the other hand, the Monitoring Theory proposes two components of monitoring: ‘Retrieval Mode’ and ‘Target Checking’. It may be argued that both processes imply the requirement of executive functions and may be explained in terms of the supervisory Attentional System (see section 1.6.1). But perhaps the main issue with this theory is the concept of ‘cost’ and the block and alternated design used to test it (Guynn, 2003). The problem with this design (described in the previous section) is that Guynn (2003) assumes in her theory that the different elements of monitoring can be summed arithmetically or linearly, which is not necessarily the case. This is the problem of ‘pure insertion’ (see chapter 2) and it assumes that in the case of having two cognitive processes underlying monitoring, there is no interaction between them, which is unlikely if we consider that both components of monitoring may be part of the same Supervisory Attentional System. Separating the two processes in a behavioural paradigm is very difficult, and more evidence to validate this model is needed (Hertzog, 2008).

1.5.2 Key points to consider in the discussion of prospective memory, attention and monitoring

Critical aspects to be considered in this discussion are: terminology, methods and real-life versus experimental conditions.

Regarding the terminology, a wider definition of ‘intention’ is necessary to account for situations in which purely automatic processes are sufficient to execute an action (Smith, 2008). These situations could also fall into reflexive actions or habits (for instance, taking medication) and not necessarily be considered as prospective memory tasks. In addition, the Multiprocess theory uses the term ‘spontaneous retrieval’ to reference the absence of preparatory attention. This may be confusing when talking about prospective memory as a whole process, because retrieval can be explained in terms of at least two different phases: detection of the right moment to execute the intention and the recall from memory of what the intention to be performed is (see section 1.6.2 for more detail). Both of them may require memory and attention to different extents. ‘Spontaneous’ references the idea that non preparatory attention is needed; however, as other attentional mechanisms can be involved, this term can lead to a misunderstanding. The terms, ‘transient’ versus ‘sustained’ cognitive processes or ‘internally’ versus ‘externally’ driven processes, may be more appropriate for this discussion, in relation with specific prospective memory stages and not treating prospective memory as a unitary process.

The methods used to study automatic prospective memory and the idea of cost (how prospective memory affects the performance of the ongoing task) are based on an assumption that is not commonly discussed in prospective memory research. This is related to the linear interpretation or elemental arithmetic modelling of the cognitive process. The idea of monitoring has been measured based on the assumption that we have limited cognitive resources to perform a task, so if attention is required for prospective remembering, there is a cost reflected in an impaired performance of the ongoing task, measured in terms of accuracy and/or reaction time. The concept of cost is controversial (Scullin et al., 2010; Smith, 2010; Smith et al., 2007), as even when an ongoing task is using most of our available attentional resources, what little resources are left may be enough to identify a prospective memory cue, meaning that a behavioural cost in the ongoing task may not necessarily show, or if it shows, it may not be related to preparatory attention but to other cognitive resources i.e., selecting the appropriate motor schema to make a response. In other words, devoting attention to the prospective memory task may not necessarily be reflected in an impaired performance of the ongoing task. That is why the use of imaging methods to complement behavioural paradigms is so important.

The final point that may explain the discrepancy between theories is related to the differences between prospective memory in real life conditions and in experimental paradigms, in addition to the high variety of situations that involve prospective memory. One question that arises from the discussion of automatic versus strategic prospective memory is whether the conditions reproduced to study automatic prospective memory in the laboratory can be applied to real life situations. Many of the tasks used to support automatic prospective memory have been performed in a laboratory environment. Tasks that do not require monitoring in the laboratory are extremely simple and controlled, and it is difficult to find these conditions in real life environments, where we face unpredictable situations and there are many factors involved. Additionally, the temporal scale of experimental prospective memory tasks is usually short, which increases the probability of having participants constantly engaged in a retrieval mode, even when there is no conscious effort to enter a retrieval mode. In real life situations, successful prospective remembering is not guaranteed even when we have carefully planned a salient event-based prospective memory task. Our attention can be completely captured by thoughts or by the ongoing task, thus even in the case of a very salient/focused target we may not notice it; for instance, we may plan to put a sticky note on the windshield of the car to reminds us about something, but be completely swamped by thoughts or by seeking directions and do not notice the sticky note.

In summary, the term ‘automatic’ is not appropriate for the discussion in prospective memory, which involves different stages and cognitive processes. We think that the best approach is to study internally versus externally driven processes, which also matches with the terms used in the literature of attention (Corbetta, Patel, & Shulman, 2008; Shomstein, 2012) and goal-directed behaviour (Gilbert et al., 2009). In addition, the different stages in prospective memory are based on different cognitive processes, which can be more or less cognitively demanding depending on the stage and type of prospective memory task. This should also be studied in more naturalistic contexts. Research using imaging methods is recently moving towards the study of brain dynamics under natural situations (Gramann, Ferris, Gwin, & Makeig, 2014; Gramann, Jung, Ferris, Lin, & Makeig, 2014). The following sections detail how executive control of attention may be associated with different stages in the prospective memory process and with different types of prospective memory tasks.

1.6 Integrating theories of attention, monitoring and memory to understand prospective memory: An original proposal

Monitoring has been used as a general term in the prospective memory literature to refer to the cognitive resources required to perform prospective memory tasks. But usually, when tasks are tagged as resource demanding, there is no clear agreement of what this really means. In fact, monitoring appears to be a complex system composed of different processes that support the maintenance and execution of intentions. It may be argued that monitoring in prospective memory can be characterised by different concepts of the Supervisory Attentional System (SAS) (Shallice & Burgess, 1996; Stuss et al., 1995), memory storage mechanisms (Basak & Verhaeghenb, 2011) and the dorsal and ventral attention system (Corbetta & Shulman, 2002). But the specific forms of monitoring would be different depending on the prospective memory task condition and on the prospective memory stage (i.e. retention interval or response retrieval).

The extent to which supervisory functions are required by a task will determine whether the task is more or less demanding. Supervisory functions may include different types of executive functions, such as planning, executive control of attention, attentional shifts and inhibition. Each of them is relevant at different stages of the prospective memory process (Kliegel, Mackinlay, et al., 2008). We will define monitoring during the retention interval of prospective memory as ‘executive control of attention’ and propose that the features and mechanisms required for monitoring will differ, depending on the context and particular features of the task, i.e. time-based versus event-based prospective memory tasks (Figure 1-1). Other supervisory components may be required as well, and these can also be translated into effortful or self-initiated cognitive processes, for example, inhibition of an ongoing task, selection of the appropriate responses or compensatory adjustment in the behaviour. These cognitive functions are also considered as ‘monitoring’ in the literature of cognitive control (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gehring & Knight, 2000). The requirement of the different monitoring mechanisms would be associated with the concurrent contextual demands (Figure 1-1, B).

This thesis studies the cognitive resources required during the retention interval (or intention maintenance) and the intention retrieval, acknowledging that executive control can also be required during intention formation and intention execution. The Supervisory Attentional System (Burgess et al., 2007; Burgess & Shallice, 1996) may be involved differentially in both stages. For instance, during the retention interval, we may require some degree of attention to detect the context for performance; whereas during intention retrieval, we may require supervisory resources to recall the intention (what is the action to be performed) and give a response.

1.6.1 Executive control during the retention interval phase

Cognitive resources at the retention interval stage are aimed at maintaining the intention actively in memory. This process is not necessarily conscious but it requires some degree of supervisory control (Okuda, Gilbert, Burgess, Frith, & Simons, 2011). We propose that monitoring at this stage corresponds to the mechanisms that control the focus of attention between an internal cognitive state (goal representations) and external task stimulation (Burgess et al., 2007; Corbetta et al., 2008).

During the retention interval we may need to periodically recall the intention (to keep it active in memory) and to monitor the environment for the prospective memory context that will signal the right moment to execute the intended action. Recall of the intention during the retention interval is different from recall of the intention during the retrieval phase, where the context to perform the intention has been identified and the recall leads to execution of the intention. We propose that the recall of the intention during the retention interval can be one of the mechanisms to maintain the intention active in mind.

Different mechanisms would result in recall of an intention: Recall of the intention can be externally initiated by environmental cues, for example, to remember something you have to do when you hear a particular word in a conversation. It can also be internally initiated, as is the case of time-based prospective memory tasks, when you decide to check the clock in case it is time to perform an intended action.

The intention can also be ‘spontaneously’ recalled during the retention interval, maybe based on memory association or cues that we do not consciously perceived (Einstein & McDaniel, 2007).

The idea of checking on the intention (regular recall) to maintain it actively in ‘memory’ is similar to the concept of energizing as a mechanism of the supervisory attentional model (Stuss et al., 1995). ‘Energization’ has been defined as a function of the supervisory attention system that is in charge of maintaining activation of behavioural schemata in order to sustain a specific selected response over prolonged periods of time, for example sustaining attention tasks. ‘Energizing’ might support prospective memory tasks by maintaining neural activation associated with lower level perceptual or motor schemata required for detecting occasional stimuli or performing occasional motor acts (Stuss & Alexander, 2007). The mechanisms proposed in this section are schematised in Figure 1-1A and exemplified in the green shaded area of Figure 1-1 from C to D.

1.6.1.1 Redirecting the focus of attention

The Supervisory Attentional Gateway (SAG) – the mechanisms underlying the Gateway Hypothesis (Burgess et al., 2007) – suggests that attention can be directed either toward an internal cognitive state (the intention) or toward the ongoing task.

It may be argued that directing attention towards internal cognitive states (goal representations or the context associated with the intention) helps to maintain the intention active in mind (Burgess et al., 2007). The requirement for strategic maintenance of the intention is relative to the features of the prospective memory task. In the case of a long retention interval, it is not necessary to maintain continuous activation of the intention (for example, to stop by the supermarket tomorrow after work). But when the moment for execution is close, we may need to increase activation of the intention (when getting ready to leave work, remembering that we have to stop at the supermarket on the way home).

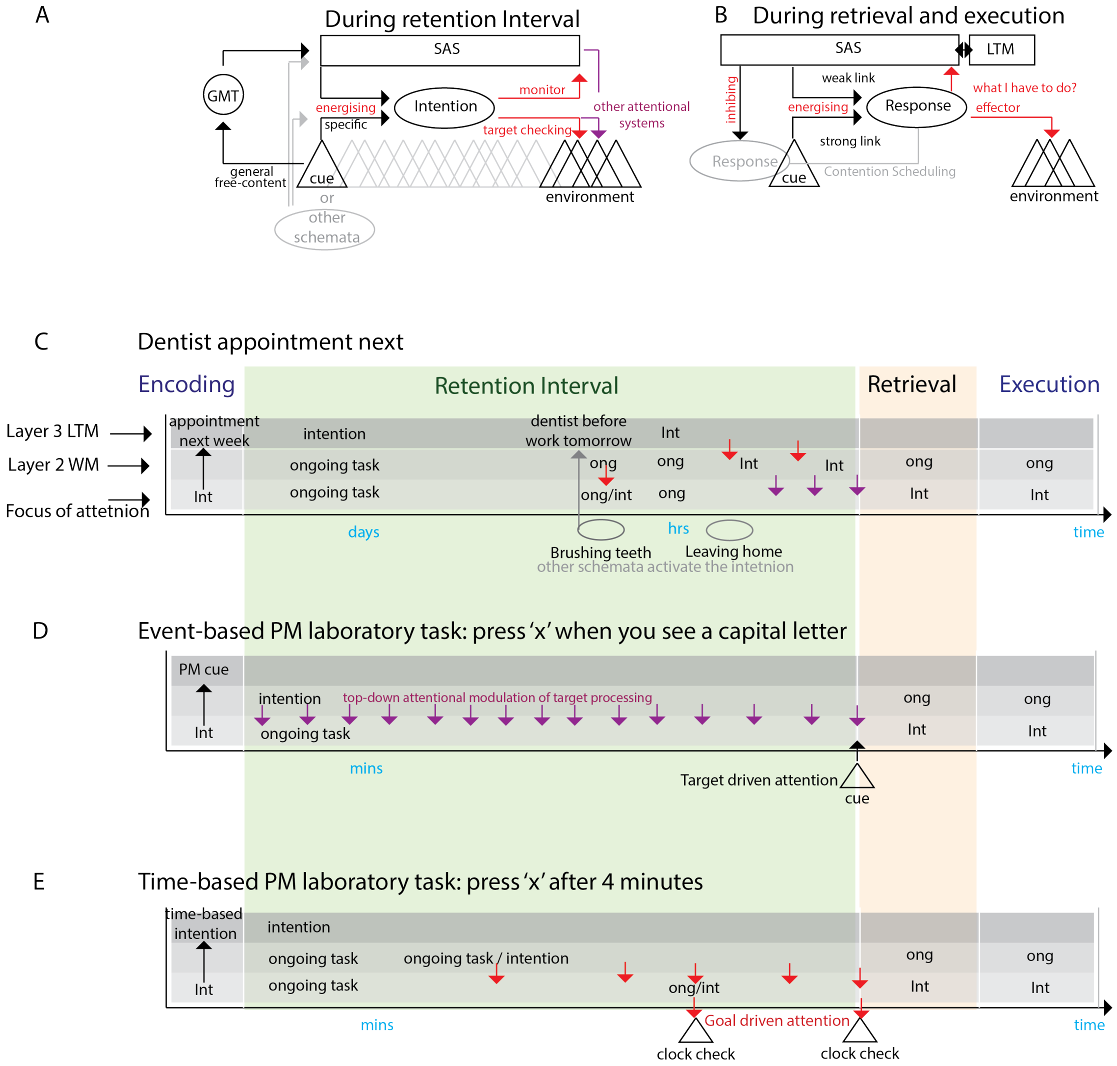


Figure 1-1. Executive control during the retention interval and retrieval of the intention. An original model based on the integration of concepts of a supervisory attentional system (SAS) (See Stuss et al., 1995; Shallice and Burgess, 1996), monitoring (Guynn 2003) and working memory (Basak & Verhaeghenb, 2011). During the retention interval, (A) the intention is kept active in mind by either top-down (SAS) or bottom-up (cue) modulations. Other schemata may also activate the intentions, for example, remembering a dentist appointment while brushing your teeth. GMT stands for Goal Management Training, a strategy to increase monitoring in rehabilitation contexts, which in turn activates intentions. GMT may be associated to external cues (Manly, Hawkins, Evans, Woldt, & Robertson, 2002). If the intention is active, the environment will be monitored for the occurrence of the right moment to perform the intention. During the intention retrieval (B), the supervisory attentional system (SAS) acts by inhibiting the response for the ongoing task and selecting the correct motor schema for the prospective memory response. The response can be also recalled by direct association between the external cue and the intention, and thus with less participation of the SAS (the case of strong link cue-intention). LTM stands for Long Term Memory, which stores the content of the intention to be retrieved. (C-D) Examples of how the supervisory attentional system (SAS) may operate in three types of prospective memory tasks. The intention is kept in one of the three layers of the three-embedded-component memory system (Oberauer, 2013). When the intention is created, the intention is in the focus of attention. Then, during the retention interval, the intention transits between the second and third layer, though it may occupy the first layer again if new plans need to be created in order to fulfill the intention (C). Finally, during the intention retrieval, the intention again occupies the focus of attention. Int: Intention, ong: ongoing task.

1.6.1.2 Relationship between attention and memory during maintenance of intentions

As noted in section 1.2, executive control of attention and memory seem to be the critical cognitive functions required during the retention interval. But what is the relationship between them? One way to think about the relationship between the Supervisory Attentional Gateway theory and retrospective memory is to think about the three layers model of working memory (Basak & Verhaeghenb, 2011).

The ‘Three-embedded-component framework’ developed to explain working memory (Basak & Verhaeghenb, 2011; Oberauer, 2013), offers a model that can also be used to understand how we maintain intentions during the performance of an ongoing task. It suggests that there are at least three layers in memory, where we store information that can be more or less accessible to conscious attention. The first layer is the zone of immediate access, where the focus of attention is located. The focus of attention can hold a limited number of items, and when its maximal capacity has been reached those items pass onto the second layer, where items are readily available but not immediately accessible. Working memory uses these two levels of storage, and retrieves items by switching the focus of attention between them, bringing ‘to mind’ the information required by the task. The third level corresponds to items that are not needed by the ongoing task but that may be required at a future point. Storage at this level is strategic (not driven by overflow of information from the other levels), which makes sense considering that we do not need to keep information active in mind if we will not need it relatively soon. Experimental research in working memory shows that items stored in the third level do not interfere with processing of the ongoing task (Basak & Verhaeghenb, 2011), suggesting that maybe this third level uses long term memory mechanisms rather than being part of working memory itself. These results are consistent with models of prospective memory, which suggest that mechanisms used to store the intention are similar to those of long term memory (LTM) (Addis et al., 2007; McDaniel & Einstein, 2000; Poppenk et al., 2010; West & Ross-Munroe, 2002). Experimental tasks developed to study the three-layer-model are different from prospective memory tasks, the main difference being that in those paradigms items allocated to the third level of storage are explicitly requested for recall after a delay – as in retrospective memory paradigms – while in prospective memory the retrieval of the intention is cued by the context and not specifically requested. More research is needed to explore the extent to which this model of working memory could also explain prospective memory processes.

When we bring the intention to the focus of attention, we actively look for the target that will indicate the moment for retrieval (a cue in event-based prospective memory and a clock in the case of time-based prospective memory). This would be similar to the theory proposed by Guynn (2003) of Retrieval Mode plus Target checking (see section 1.4.1), with the difference that, we propose that Retrieval Mode and Target Checking are actually an expression of the same mechanism, but operating at different levels: Retrieval Mode would correspond to the expression of 'keeping the intention in the back of the mind' and it would comprise the case of moving the content of the intention from the third to the second level of storage. Target Checking would correspond to moving the focus of attention between the second and the first level of storage. If this is true, the two mechanisms 'Retrieval Mode' and 'Target Checking', are not independent of each other, and thus they cannot be studied using categorical designs as proposed by Guynn (2003).

It is possible that some mechanisms of cognitive control, maybe the Supervisory Attentional System (SAS), as it is schematised in the Figure 1-1, are involved in the control of attention and in deciding when intentions are maintained in 'hold' mode or transformed into action. More research is needed to clarify this issue, this thesis intend to give evidence to the model. This initial proposal plus other mechanisms for control of attention will be resume in the last Chapter of the present thesis (Page 217).

1.6.1.3 Internally initiated recall of intentions during the retention interval

Retrieval Mode and Target Checking would interact in different ways depending on whether the prospective memory task is event- or time-based (Figure 1-1 B, middle and bottom panel). As noted earlier, a mechanism of monitoring would be based on attentional shifts between internal states and the tasks. The shifts of attention can be driven by external stimuli or self-initiated processes. For instance, in the case of the time-based prospective memory task, when alarms are not available, we have to maintain regular checks on our time perception. We propose that these internal checks on the passage of time will be performed every time we recall the intention, for example to turn off the toaster in two minutes in order to avoid burning the bread; if we forget about the toaster, we will probably stop checking the time.

Another mechanism that can be interpreted as ‘self-initiated’ is when a behavioural schemata being performed triggers recall of intentions, for example remembering a dentist appointment while brushing your teeth (Figure 1-1 B).

1.6.1.4 Externally initiated recall of intentions during the retention interval

Different mechanism of monitoring would be required when the prospective memory task is stimulus oriented (associated with an external cue), rather than internally initiated (check internal states). In event-based prospective memory tasks, it is necessary to evaluate the stimuli presented in the ongoing task to be ready to respond when the prospective memory cue is detected. In this case, the SAS may operate during the retention interval in a more continuous fashion (when the intention is active in mind); for instance, attentional resources would be devoted to examine environmental cues that would indicate the moment for the action, by means of top-down attentional modulation that favours early processing of target events. Top-down modulation of attention has been tested in a number of experimental paradigms in attention literature (Hillyard & Anllo-Vento, 1998; Katsuki & Constantinidis, 2013) and in a less extent in prospective memory (Knight et al., 2010).

Similar mechanisms can apply in real life situations, when we are somehow aware that we are relatively close to the right moment for the execution of the intention (and we enter the retrieval mode). For instance, think of the hypothetical case in which you are told to pick up someone you do not know from the airport. You know that the person will be wearing a red jacket; the red colour will easily draw your attention and thus many other red things will pop out when you are searching for the red-jacket person. In the case of prospective memory, a similar example can be used if your intention is to post a letter in the (red) post-box. If you encode the colour as an important feature to detect the post-box, you will probably be ‘more sensitive’ to the colour red.

1.6.2 Executive control during the intention retrieval phase

As noted in section 1.2, classification of prospective memory tasks is based on the context for intention retrieval: when the proper moment to execute an intention is given by the occurrence of a specific event or cue, then it is an event-based prospective memory task; whereas if the retrieval context is given by a specific time, then it is a time-based prospective memory task. Both types of prospective memory tasks have in common that an intention has to be executed in the future when a specific context occurs.

The following section details different mechanisms attributed to event- and time-based prospective memory tasks, leading to the idea that the requirement for executive control during the intention retrieval will change depending on the type of prospective memory task. The mechanisms proposed in this section are schematised in Figure 1-1, B and exemplified in the light-orange region of Figure 1-1 from C to D.

1.6.2.1 Mechanisms of event-based prospective memory tasks

The retrieval phase in response to cues seems to be composed of at least four sub-phases (Knight et al., 2010; Marsh et al., 2003): (i) d*etection of the cue* is the very first stage in the retrieval phase and means that a cue is ‘recognised’ as a possible prospective memory target; (ii) *verification* means that the cue is evaluated to confirm that it meets all the features of the prospective memory target; (iii) *response retrieval* corresponds to recall of the content of the intention; and the final sub-phase is (iv) c*oordination* of the intended response with the response required by the ongoing task. The temporal dynamics of these phases are very fast and, depending on the nature of the task, they may be more or less detectable. Thus it may be difficult to clearly identify these sup-phases in behavioural terms, but electroencephalographic studies have been able to show brain activity associated with each of the different stages (Knight et al., 2010; West, 2011). fMRI (Simons, Scholvinck, Gilbert, Frith, &

Burgess, 2006) and behavioural studies have also shown evidence of cue detection (Cohen, Dixon, Lindsay, & Masson, 2003), verification and intention retrieval as different cognitive processes (Marsh et al., 2003).

The distinction between the four sub-phases may be difficult to determine in behavioural terms. It may be argued that cue detection, verification and response retrieval overlap in certain conditions, for example when the target cue is highly salient and tightly associated with the intention to be performed. McDaniel et al. (2004) suggests that the retrieval can be triggered without previous recognition of a prospective memory cue. We propose that cue detection is always a necessary first step, occurring in a temporal scale of milliseconds, and thus it is not necessarily a conscious or ‘effortful’ process.

Cue detection is mediated by attentional processes that can be externally or internally driven, the salience of the cue can be increased in a way that less top-down attentional resources are required, thus cue detection is more externally driven (Cohen, West, & Craik, 2001). Distinctiveness of a cue is not just defined by its physical salience. Schmidt (1991) defines ‘category distinctiveness’, as the case in which the distinctive item belongs to a different conceptual category; “For example, embedding the name of an animal in a list of names of countries leads to better recall and recognition of the animal name than does embedding the name in a list of other animal names” (Schmidt, 1991, p. 529). McDaniel et al. (2004) proposes that another way in which a cue can drag attentional resources is by discrepancy, meaning that the target event requires processing that is different form that required by the ongoing events (see Lee and McDaniel, 2013).

It may be argued that verification of the cue can be skipped if the cue detected is tightly associated with the intention to be performed, as is proposed by the reflexive associative theory (McDaniel, Guynn, Einstein, & Breneiser, 2004). This theory describes the mechanisms by which an intention can be retrieved with minimum or absent requirement for executive control. Less is required of the SAS in situations where intention retrieval can be undertaken by strong cue-intention associations. In those cases, behaviour would be relatively easily triggered by sensory input rather than via self-generated conscious control (Gilbert 2009). In contrast, complex situations will require the Supervisory Attention System (SAS) to select the correct schema appropriate for response (i.e., activate or inhibit schemes).

In summary, the evidence demonstrates that ‘retrieval of intentions’ is not a single process. First, it is necessary to recognise a cue as a suitable context for retrieval (a colleague in the corridor) and then to assess if the context is appropriate for task performance (i.e. verify if the colleague is the person you have to give a message to) and what the action to be performed is (what is the actual message). These sub-phases may be more or less distinguishable and accessed by conscious control – for example, detecting a cue (a colleague in the corridor using a characteristic hat that this colleague always wears) and immediately retrieving the intention (remember the message).

1.6.2.2 Mechanisms of time-based prospective memory tasks

As far as we know, retrieval of time-based prospective memory tasks has not yet been studied. Research has focused on the retention interval or maintenance of the time-based intention, rather than retrieval of the intention itself. It may be argued that the mechanisms corresponding to detection of the correct context for performing the time-based intention (retrieval phase) are similar to those described for intention maintenance. Whereas mechanisms for intention retrieval (once the context for retrieval has been identified) are similar with the mechanisms for ‘response retrieval’ and ‘response coordination’ in event-based prospective memory tasks, requiring more executive control or participation of the supervisory Attentional System (SAS).

Researchers agree that frontal lobe structures support strategic monitoring, but both ‘frontal lobes’ and ‘strategic monitoring’ are rather general terms to explain how time-based prospective memory operates. More research is needed to define what is the role of the different frontal regions activated during time-based prospective memory tasks (Okuda et al., 2007), what the temporal dynamics of these activations are, how they interact with other brain areas and how research in time-based prospective memory fits with research in time estimation.

Time estimation seems to be an important component in time-based prospective memory tasks, even though it is not considered a central element (Cona, Arcara, Tarantino, & Bisiacchi, 2012). It may be the case that the most demanding aspect of retrieval in time-based prospective memory is detection of the right moment to execute the intention, since it requires monitoring and mechanisms associated with time estimation. Block (2006) proposes a theoretical framework for time-based prospective memory tasks that draws on elements from established models of time estimation. The core of this proposal is the 'internal clock theory', which proposes that there is an internal clock that, after a start signal, produces a steady stream of pulses that are stored in an accumulator until a finish signal. The final count is stored in memory and becomes a representation of the time interval. The 'attentional counter theory' (Block, Hancock, & Zakay, 2010) extends this theoretical model, proposing that attention influences time estimation, in the sense that the accumulator only updates the counts when attention is directed towards the passage of time. The paradigms used by Block (2010) differ from the classical paradigms in time estimation, where the explicit focus of the task is to keep track of time. In real-life activities, time estimation usually is required during the performance of a non-related additional task and it is not the primary focus of the performance. Thus, new paradigms to study time estimation are very similar to time-based prospective memory tasks.

One of the main focuses of research in the field of time estimation relates to how time estimation is affected by simultaneous tasks that also require allocation of attention. The evidence shows that the more demanding the non-temporal or secondary task, the more affected is the time estimation. This result leads to the idea that time estimation requires executive control of attention. Models of time estimation continue to be extended to explain complex situations (more similar to real-life), including variables such as learning processes of time estimation and knowledge transfer to similar situations, thus reducing the requirement for attentional processes for accurate time estimates (Taatgen, van Rijn, & Anderson, 2007). More research is needed to generate and integrate evidence from studies in prospective memory and the well-developed body of literature in time estimation (Block & Zakay, 2006).

1.7 Neural correlates of prospective memory

Memory and executive functions are the central cognitive functions required for prospective memory. The brain structures most associated with these functions are the frontal (Gilbert & Burgess, 2008) and temporal lobes (Squire, 1992). Regions in parietal lobes, associated with goal-directed and stimulus-driven attention (Asplund, Todd, Snyder, & Marois, 2010), may also participate in prospective memory tasks. The following review will be focused on these three regions. However, to understand how the brain works in complex situations, it is necessary to adopt an integrated approach, that considers not only specific regions of the brain but, also how different brain areas interact to allow the emergence of complex cognitive functions (Thompson & Varela, 2001). The last section of this chapter reviews that approach.

1.7.1 Frontal lobe

Prefrontal cortex is a large region in the human brain that contains several sub-regions that have been associated with a number of cognitive functions grouped under the term executive functions (Gilbert & Burgess, 2008). Regulation of behaviour is considered to rely on frontal lobe structures, such that clinical reports often describe people with frontal lobe damage becoming a completely different person (Garcia-Molina, 2012). The rostral prefrontal cortex (RPFC) or Brodmann's area 10 (BA 10) is probably the largest single architectonic region of the frontal lobe (Burgess et al., 2008), and it is crucial for prospective memory performance (Burgess, Scott, & Frith, 2003; Gilbert et al., 2009; Okuda et al., 2011).

The Gateway Hypothesis (Burgess et al., 2007) referred to earlier suggests that BA10 acts as an attentional gateway, directing attention between external stimuli and internal representations. Medial activation of BA10 reflects attention oriented towards external stimuli, provided by the environment or the task being performed and experienced through the body sensors. In contrast, lateral activation reflects attention oriented towards mental representations, such as the state of goals. For instance, lateral BA10 is activated during the maintenance of an intention throughout the performance of an ongoing task (Simons et al., 2006), and also in tasks where people orient attention towards goals (internal representation) rather than task stimuli (Gilbert et al., 2009). This evidence suggests that lateral BA10 is activated when the retrieval of intended intentions relies on internal processes rather than external stimuli. However, the attentional focus between the prospective memory task and the ongoing task (both stimulus-oriented) can be automatically regulated without the participation of lateral regions of BA10 (Okuda et al., 2011). Activation of BA10 does not necessarily reflect conscious control of attentional resources, and in some conditions self-initiated processes (or monitoring of the internal state) are not essential for the performance of a prospective memory task.

Time-based prospective memory tasks show particular activation in frontal areas, besides activity in BA10. Okuda et al. (2007) found activation in the superior frontal gyrus (including BA 10), anterior medial frontal lobe and anterior cingulate cortex, with differential involvement of these areas reflecting processing demands associated with different time-based prospective memory tasks.

Rubia & Smith (2004) concluded that the areas particularly relevant for prospective time estimation are the inferior frontal cortex (IFC), the supplementary motor area (SMA) – relevant not only for motor timing functions – and the dorsolateral prefrontal cortex (DLPFC), the latter being well known for its participation in working memory tasks (Owen, 1997). The DLPFC has been associated with ‘online’ maintenance of time estimation; according to Rubia (2004), it may act as an ‘accumulator’ that stores contextual information associated with the passage of time, and this may be the neural substrate of the ‘internal clock’ described in time estimation theories (Graf & Grondin, 2006). Activation in the anterior cingulate gyrus has been consistently found in different types of time estimation studies (Okuda et al., 2007; Pouthas, Garnero, Ferrandez, & Renault, 2000; Rubia, 2006; Rubia & Smith, 2004). This brain region is also part of the midline attentional system (Corbetta et al., 2008) and more than specific timing functions, it may be supporting cognitive control of attention (Carter, Botvinick, & Cohen, 1999; MacDonald, Cohen, Stenger, & Carter, 2000).

1.7.2 Parietal lobe

The superior parietal cortex and the Temporo-Parietal Junction (TPJ) have been shown to be part of the dorsal and ventral attentional system respectively, the first associated to goal-directed attention and the second to stimulus-driven attention.

The superior parietal cortex is involved in enhanced processing of stimulus features that are relevant for the performance of the task (top-down attentional modulations) (Corbetta & Shulman, 2002; Shomstein, 2012), a possible mechanism for monitoring in event-based prospective memory tasks (top-down attentional modulation). In turn, activity in the TPJ has been associated with shifts in attention produced by external stimuli containing features relevant for task decisions (Corbetta & Shulman, 2002; Posner & Dehaene, 1994). Activity in this area has been found in experiments that use highly salient (unexpected) external cues that drag attention towards the stimulus, i.e., for externally initiated recall of intentions in prospective memory tasks.

1.7.3 Medial temporal lobe

The medial temporal lobes (MTL) host one of the structures most studied in the neuroscience of memory: the hippocampal formation (Benfenati, 2007; Eichenbaum, 2001; Squire, 1992), which has a central role in the encoding of declarative memory. Specific events and facts are encoded and represented in the hippocampus. It is not just past event representations that are mediated by the hippocampus, but also the ability to imagine future events (Addis et al., 2007; Poppenk et al., 2010), necessary for prospective memory tasks during the creation and encoding of intentions.

The hippocampus has a role not only in encoding and storage of future intentions, but is also in retrieval. The hippocampus (Cohen & O'Reilly, 1996) and temporal lobes (Reynolds, West, & Braver, 2009) contribute to the identification (recognition) of stimuli or contexts associated with an intention.

1.7.4 Network approach

The prefrontal cortex has been the most studied brain structure in prospective memory research (Burgess et al., 2008; Burgess et al., 2011). This is understandable if we think that one of the big questions in the field is the degree of executive control required to execute delayed intentions. However, it is also clear that it is not the only brain region involved. Activation of the parietal lobe and the anterior cingulate cortex has been reported in fMRI prospective memory studies (Reynolds et al., 2009; Simons et al., 2006). Temporal structures are also relevant, since they are responsible for episodic memory, which is also required for prospective memory performance (Addis et al., 2007; Poppenk et al., 2010).

Cohen (1996) offers a theoretical framework for understanding how the hippocampus-prefrontal cortex relationship contributes to prospective memory. He suggests that an important function of the prefrontal cortex is the representation and maintenance of contextual information that can be used to mediate an appropriate behavioural response. In turn, the hippocampus would be responsible for storing specific episodes or events in relation to particular cortical states associated with those contexts. Patterns of activities would originate in the prefrontal cortex in response to incoming information; this primary cortical input would go to the hippocampus, where if an input pattern closely resembled a previously stored one, it would trigger the recall of that pattern. Some EEG studies describe temporal dynamics of prospective memory (West, 2011) (see the review of EEG and prospective memory in the following section), but no studies have tested Cohen's model or effective neural connections in prospective memory tasks.

We know that activation of different brain areas during task performance is not a random or isolated phenomenon (Klimesch, 1999; Thompson & Varela, 2001). However, explaining co-activation patterns and building information processing theories based on fMRI studies is limited because of the low temporal resolution of this technique. It is necessary to complement the theoretical models with other techniques with higher temporal resolution, such as EEG or MEG (Sauseng & Klimesch, 2008), with clinical evidence (Brandimonte & Ferrante, 2008) and everyday performance (Hanlon et al., 2012). As far as we know, the relationship between activation of BA10 and activation of fronto-temporal (Eichenbaum, 2000) and fronto-parietal (Katsuki & Constantinidis, 2013) networks has not yet been explored. Whether prospective memory shares common networks or activation patterns with memory and attention, or it follows differential principles, is a question without a clear answer so far.

Chapter 2
EEG methods in the study of prospective memory in laboratory contexts

Behavioural prospective memory paradigms have been very important for studying the neuropsychology of prospective memory, by examining cognitive functions that are directly observable (Burgess et al., 2006). Various paradigms have studied performance under different prospective memory task conditions, which may vary in the type of prospective memory cue used (Cohen, Dixon, Lindsay, & Masson, 2003), the ongoing task demands (Einstein, McDaniel, Williford, Pagan, & Dismukes, 2003) or the motivation for performance (Walter & Meier, 2014). The results from behavioural paradigms give rise to new questions that are more difficult to answer based only on behavioural measures. These questions are associated with brain mechanisms that support the observable behaviour, for example, what are the attentional mechanisms operating during maintenance of the intention. The present chapter details how imaging methods, particularly electroencephalography, contribute to the study of prospective memory in experimental conditions.

2.1 Prospective memory in the laboratory

2.1.1 Prospective Memory task design

To study prospective memory in experimental conditions, paradigms must meet basic criteria, in order to emulate prospective memory as it is encountered in daily life. The following table summarises the basic features of prospective memory tasks.

Table 2-1. Main features of a prospective memory paradigm.

Intention Creation	In experimental contexts, the experimenter usually creates the intended intention through the task instructions. The intention refers to execution of an action after a delay and in a particular circumstance. The particular circumstance is signalled by a cue in event-based studies (Burgess et al., 2003) and by a certain amount of time in time-based studies (Graf & Grondin, 2006). See Figure 2-1 for examples.
Intention Maintenance and Ongoing task	Once an intention has been created and encoded it is necessary to retain the intention over a delay period in order to perform the task at a later moment in time. During this retention interval, the participant is involved in an ongoing task, meaning that the intention cannot be continuously rehearsed. The ongoing task must not be easily performed at ceiling levels to maintain engagement in the performance (Figure 2-1, D), simulating the demands of everyday tasks (Einstein et al., 2003).
Retrieval Context	The retrieval of the intention is signalled by the occurrence of a specific context associated with the intention, for instance a particular cue or a time lapse. The intention is not explicitly prompted for execution and no immediate feedback is given to the participant regarding errors.
Minority of experimental trials	The prospective memory task applies to a minority of the experimental trials (Burgess et al., 2003; Einstein et al., 2005; Gilbert et al., 2009). Meaning that during the experiment, participants mainly perform an ongoing task and only a minority of the trials (10% in the present thesis) correspond to the prospective memory task, with the aim of emulating real life prospective memory situations, where something non-routine has to be done after a delay.

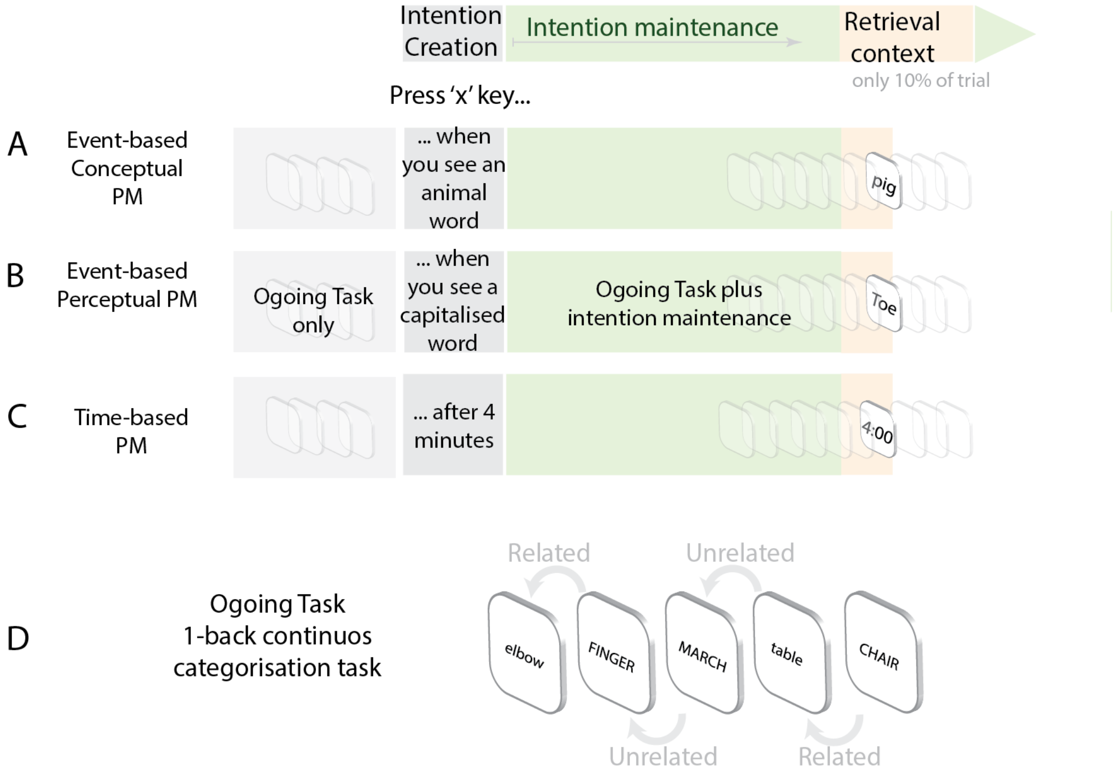


Figure 2-1. Experimental design. The figure represents the general experimental design used in this thesis. Intention Creation, Intention Maintenance and Retrieval context are highlighted in different background colours. Prospective memory tasks are classified according the retrieval context: (A) shows an event-based prospective memory task when animal words signal the retrieval of the intention. In (B) the retrieval is signalled by perceptual information of the cue, an upper case letter and, in (C) the retrieval is self-initiated after the person considers that 4 minutes have passed. The intention to retrieve is to stop performing the ongoing task and press the 'x' key when a particular retrieval context is encountered. All prospective memory tasks are embedded in an ongoing task, schematised in (D). Prospective memory trials (retrieval context) correspond to only 10% of the trials.

2.1.2 Categorical and parametrical designs

Traditional prospective memory experiments use a categorical design, meaning that two conditions are contrasted, for instance the (i) Baseline – which is the ongoing task prior to the introduction of the intention – and (ii) the ongoing task whilst maintaining the prospective memory instructions, see in Figure 2-1 'Ongoing task only' and 'Ongoing task plus Intention Maintenance'. The risk of this kind of design is that it assumes ‘pure insertion’ (Price & Friston, 1997), meaning that the involved cognitive states are independent of each other and can thus be inserted or removed without any interaction between them.

The categorical design can be improved by using ‘Conjunctions’, which is to minimise the pure insertion problem by isolating the same process or component in two or more separate tasks, for example, by designing two different tasks that are thought to rely on the same processes and then comparing similar patterns of activation between them. Some researchers use conjunction designs to study the neuroanatomical correlates of prospective memory (Gilbert et al., 2009; Simons et al., 2006). A similar alternative is the use of factorial designs (Price & Friston, 1997), which study main effects and interactions between two or more independent variables or cognitive processes of interest. The difference between conjunction and factorial designs is that conjunctions do not study the interactions among the main effects of independent variables. An example of factorial design is the pilot study of the present thesis (Chapter 3). We studied cue detection and intention retrieval in prospective memory paradigms creating four conditions; (i) cue detection with minimal demands on intention retrieval, (ii) intention retrieval with minimal demands on cue detection, (iii) high demanding cue detection and intention retrieval and, (iv) neither cue detection or intention retrieval are present (baseline) (see Figure 3-1). In the result section of Chapter 3 we explored the interaction between ‘cue detection’ and ‘intention retrieval’. Chapters 4 and 5 can be considered together as a conjunction design. In the experimental design of those chapters we used the same ongoing task to explore the interference produced by different types of prospective memory tasks, (Figure 1-2, from A to C). Under the assumption that similarities and differences between the ‘ongoing task plus intention maintenance’ of the different task conditions will give us information about the processes involved in maintenance and retrieval of prospective memory intentions, to avoid directly comparing data from different session days we used the ‘ongoing task only’ as a baseline for each of the experimental sessions.

The parametrical design consists of varying the stimulus parameter of interest on a continuum, relating the neural signal to these parameters and testing these relations using mathematical modelling (Price & Friston, 1997). The main difference between categorical and parametrical analysis is that a parametrical design treats a cognitive process as a dimension or attribute that can be expressed to a greater or lesser extent and not as something that is present or not. A parametric design, where time is the parametric variable, seems to be a good approach to study time-based prospective memory, where time is the parametric variable (see Figure 5-8).

2.2 Why use EEG to study prospective memory

Electroencephalography (EEG) is a non-invasive tool that measures electrical brain activity (excitatory and inhibitory post-synaptic potentials) produced by macroscopic neuronal patches on the scale of 1 square centimetre (Makeig, Debener, et al., 2004). It provides high temporal resolution and directly measures neuronal activity, as compared to more indirect methods such as functional Magnetic Resonance Imaging (fMRI), which measures changes in blood flow reflecting metabolic changes related to neuronal activity (Gramann et al., 2011). Its temporal resolution is in the range of milliseconds, which is important if we consider that neural processes underlying cognitive functions are also in the range of milliseconds. Research in the area of neuroscience has shown that cognitive operations emerge by means of fast and transient neuronal synchrony. For instance, perception is related to high frequency synchrony, in the order of 25 Hz (Rodriguez et al., 1999; Thompson & Varela, 2001) and communication between cortical regions can be as fast as 40ms (Varela, 2006). Slower rhythms are also relevant to understanding memory, attention, executive functions and other cognitive operations (Sauseng & Klimesch, 2008). EEG measures electrical activity of neural populations that are synchronously activated during cognitive processing and gives us information about the temporal timing of this neural activity.

Besides its high temporal resolution, another advantage is that the devices used for EEG recordings are relatively light and portable, making EEG suitable for experiments under real world conditions (Makeig et al., 2009), opening a window to the study of “embodied cognition”, which appeals to the idea that cognition is shaped by the body and the person’s interaction with the environment and not from the brain as an isolated system or ‘machine’ (Thompson & Varela, 2001). This is highly relevant if we think that current experimental paradigms for imaging methods (fMRI, PET, EEG) require minimizing the complexity of task materials and participant responses, which is far from conditions faced in real-life situations. Furthermore, EEG has the benefit of being relatively easy to apply and its relative low cost makes it suitable for application in large and diverse clinical groups.

Despite the relevance of EEG studies in cognition, this method is usually not considered as ‘imaging’ due to its low spatial resolution and because most EEG analysis has been done in the time-domain (Gramann et al., 2011) using Event-related potentials that have dominated the literature in psychology. To deal with the spatial limitations of EEG, spatial filtering algorithms can be used. One example of this is the Independent Component Analysis (ICA) method, which separates data recorded by multiple channels into component activities, which are maximally statistically independent from each other in terms of their time course. Based on the model’s assumptions, ICA is able to locate the source of these independent components, which are projected onto the scalp. To increase the spatial resolution of EEG, it is recommended that accurate head models warped to 3D localization of electrode positions are used, or ideally an individual’s magnetic resonance (MR) image (Akalin Acar & Makeig, 2013), which are not always available in EEG laboratories.

Why is this so relevant for the study of prospective memory? As noted earlier, prospective remembering is critical for the successful performance of daily activities (Boelen et al., 2011; Kliegel, Mackinlay, et al., 2008). Failures of prospective memory in daily life are common (Dismukes, 2012) and more likely after brain injury (Boelen et al., 2011). EEG can give information about the neural mechanisms underlying prospective memory and it can also support theoretical models that try to explain how prospective memory works (West, 2011). In addition, new analysis methods allow exploration of communication between brain areas during cognitive processes with high temporal resolution (frequencies, dipole location, synchrony, coherence, effective connectivity). But maybe the most exciting scope of EEG research is the potential application of sophisticated EEG systems to study prospective memory using ecological tests and naturalistic paradigms, a field in which traditional imaging techniques do not yet have access. Recent developments in EEG are making it possible to examine brain function in real life situations, portable EEG systems are already available in the market. However, we need new methods to process and analyse brain signals acquired in real life conditions, plus development of new theoretical frameworks to interpret complex results. The emerging field of Brain Computer Interface (BCI) uses information obtained through electroencephalography to monitor cognition and predict behaviour. Studying how the brain deals with delayed intentions in real life situations will be possible in the near future, and a step towards this is made in the experiment described in Chapter 6 of this thesis.

2.3 Event Related Potentials: the approach most widely used to study electrophysiology of cognition

Event-Related Potentials (ERPs) became the first functional brain imaging method to study human cognition (Makeig & Onton, 2011) and have become the predominant method for human experiments since the 1960's when the first studies using computer averaged potentials started to appear (Luck, 2005). This method is based on averaging the EEG signal locked to the presentation of a stimulus, under the assumption that averaging a large number of event-locked activities – segmented into time windows called epochs – cancels out unrelated activity, leaving a single average response window dominated by activity consistently related to the presentation of a particular stimulus type.

The waveforms produced by the averaged brain signal have been widely described and associated with a number of sensory, perceptual and cognitive functions (Hillyard, 1993). Early evoked potentials were used to examine integrity of the auditory system. The first voltage deflections (originating in the brainstem) can be observed as early as 1-10 ms (Hillyard, 1993). Activity from the primary and secondary auditory cortex can be detected from 50 ms after stimulus onset. ERP components that vary according to attentional and cognitive processes can be shown from as early as 100 ms (Hillyard & Anllo-Vento, 1998). Perceptual discrimination processes can be observed around 200-300ms. Other later components (between 300 to 700 ms) have been associated with memory encoding and retrieval (Hillyard, 1993).

Usually these modulations (voltage deflections) are named using the polarity and the approximate time when they are observed. For example, N2 is the name given to a negative deflection around 200 milliseconds. Despite the fact that polarity is used to name ERP components, it does not have any particular relevance in terms of neurophysiology (Otten & Rugg, 2005). The only truly meaningful sign is the direction of current flow in the originating cortical patch: either into the cortex or out of the cortex. However, since the cortex is intricately folded, without a complete source estimation (MR image-based individual subject head models) it is not possible to tell the real direction of the deflection and thus polarity is arbitrary.

The ERP technique works based on two basic assumptions (Makeig & Onton, 2011). First, cortical processing of sensory event information follows a fixed spatiotemporal sequence of source activity, meaning that the brain response (measured as potential deviations in the scalp) is very similar every time a particular stimulus is presented. Second, the time-locking event of interest does not affect the EEG activity going on in other brain areas not directly involved in the processing of the event and it does not affect artifacts produced by non-brain structures either. Basically, the ERP approach treats the brain as a ‘linear system’. Methods beyond linear modelling are outside the focus of this thesis.

2.4 Event related potentials and prospective memory

Paradigms used to study prospective memory using ERPs follow two approaches: One approach studies ERP modulations that are different from those generally related to target processing and memory retrieval, such as the N2, P300 and the old-new effect (West, 2011). The other approach studies the requirement of executive control of attention in prospective memory by manipulating different task variables (Cona et al., 2012; Knight et al., 2010; West, 2007).

The first approach contributes to the question of whether prospective memory corresponds to a distinctive cognitive function that relies on mechanisms different from memory retrieval, i.e. attention and executive functions. The second approach contributes to the discussion of theories still under debate, such as the role of attentional resources in achieving a prospective memory response or whether retrieval can occur without executive resources devoted to the prospective memory intention.

2.4.1 Are mechanisms in prospective memory different from attention, memory retrieval and executive functions?

In relation to the first approach, most studies have used computerised event-based prospective memory tasks, where a specific event prompts the retrieval of the intention. Thus the study of ERPs modulations associated with prospective memory tasks has been related to: detection of prospective memory cues (modulations around 200 and 300ms) and retrieval of the intended responses (modulations starting at 400ms). Thus, one of the issues in prospective memory and ERP research is to elucidate whether these modulations reflect mechanisms particular to prospective memory tasks, or if they correspond to ERP modulations already described in the literature of visual attention (N200), memory retrieval (old/new effects) or decision making, context updating and maybe other executive functions (P300). For example, are occipital ERP modulations of target detection in prospective memory tasks different from target processing in the context of other tasks? Literature in the field describes three main ERP modulations associated with prospective memory performance: two associated with the detection of prospective memory cues (N300 and frontal positivity) and one with the retrieval from memory, execution of the intention and maybe contextual updating (parietal positivity).

The N300 and frontal positivity modulations have been associated with detection of prospective memory cues. The N300 is characterised by a negativity over occipital-parietal regions, beginning 200 ms after stimulus onset, with maximum amplitude observed around 300 - 400 ms (West, Herndon, & Crewdson, 2001). The scalp distribution of the N300 resembles the distribution of the N2, which has been associated with activity in visual associative areas. However, the latter has not been associated with frontal positivity. Frontal positivity is characterised by positivity over the midline frontal regions. It has a similar onset as the N300 but it can extend over the duration of the N300. Experiments show that both modulations are greater for prospective memory cues that elicit a prospective memory response (West & Ross-Munroe, 2002), compared to prospective memory cues that are ignored or missed. These modulations have been observed in response to the perceptual attributes of the prospective memory cues (West, 2011); thus, the mechanisms underlying prospective memory in these cases are specific to event-based prospective memory, with cue detection driven by the physical attributes of the cue. More research is needed to investigate other types of cues, such as conceptually driven cue detection (see chapter 4 of this thesis).

Parietal positivity has been observed as a sustained positivity broadly distributed over the central, parietal and occipital regions of the scalp, between 400 and 1200ms. Two ERP components are part of this modulation (West, 2011): One is the P300, which is also related to the identification of low probability targets (observed in odd ball tasks). The second is the prospective positivity, associated with recognition of prospective memory cues (old-new effect) and context updating (configuration of the correct prospective memory response, different from the foreground ongoing task). West at al. (2011) have put great effort in differentiating these two modulations, P300 and prospective positivity, from modulations found in odd-ball and memory paradigms. In one experiment designed to differentiate prospective positivity from the P3, West (2005) observed that the latter is modulated by manipulations of the ongoing task, while prospective positivity is not, indicating that the positivity may reflect neural processes specific to prospective remembering. West (2005) also showed that the Old-New effect is elicited in both prospective and retrospective memory tasks. This result supports the idea that prospective and retrospective memory share common neural networks associated with retrieval of information. However, the positivity in prospective memory tasks emerged later than the positivity of the retrospective memory task and the amplitude of the prospective positivity is greater for correct prospective memory responses, at least when the target is not repeated during the experiment (West & Krompinger, 2005). These findings support the idea of a neural network particularly related to prospective memory. The topography of this activity goes from frontal-central regions to the parietal region. When the prospective cue has been detected but the intention has not yet been performed, prospective positivity is not elicited (West & Krompinger, 2005). West et al. (2005) proposed that prospective positivity probably reflects two different processes: one related to the retrieval of the intention from memory, which would be similar to episodic memory and another related to post-retrieval processes. These findings are consistent with the proposal of common neural networks associated with retrieval, and distinctive networks associated only with prospective memory, supported also by fMRI studies (Addis et al., 2007; Poppenk et al., 2010). However the question remains: are there distinctive networks and mechanisms associated only with prospective memory, are they different from attentional and executive function mechanisms described previously in the literature or are they are just different from retrospective memory?

2.4.2 Is it necessary to devote attentional resources to achieve a prospective memory response?

As noted, the other approach in ERP research studies the level of executive control of attention in response to different task manipulations (Cona et al., 2012; Knight et al., 2010; West, Bowry, & Krompinger, 2006; West, McNerney, & Travers, 2007). These studies explore how different manipulations affect the amplitude of the ERP components, under the assumption that greater amplitudes are a reflection of greater cognitive processes engaged.

Greater amplitude of early components as the N300 (related to detection prospective memory cues) has been shown as a neural correlate of strategic monitoring. Amplitude of the N300 declines as the demand of the ongoing task increases (West et al., 2006) or when the prospective memory cue has been ignored or missed (West, 2007). Similarly, amplitude of the prospective positivity (400-500ms) is reduced when the prospective memory cue has been ignored or missed (West, 2007), supporting the idea that strategic monitoring may support retrieval processes.

Attention also modulates the early processing of visual stimuli when participants wait for the prospective memory cue. This is reflected in higher amplitude of early visual components of the ongoing task compared to the baseline, observed in occipital electrodes (Knight et al., 2010). This effect was observed in event-based prospective memory tasks using a physical feature to detect the prospective memory cue. This finding is consistent with theories of selective attention that have shown that top-down control of attention can modulate perceptual processing of stimuli to supress or enhance certain sensory information (Hillyard, 1993; Hillyard & Anllo-Vento, 1998). In contrast, recent work using a time-based prospective memory task shows an increase of amplitude in frontal electrodes (Cona et al., 2012) as a neural correlate of time monitoring.

A brief discussion about the use of amplitude as a correlate of cognitive resource engagement will be presented in the following section.

2.5 Limitations of the event related potential technique

Although ERPs have been useful in understanding the temporal dynamics of neuronal activity related to prospective memory, this technique has important limitations that, if not considered, could lead to misinterpretation of data.

An important part of the interpretation of the literature of prospective memory and ERP is related to the amplitude of the ERP components. Otten (2005) points out important issues to keep in mind when interpreting ERPs: as the ERPs are usually analysed after the signal average, it can be the case that not all the trials included in the average showed the difference in amplitude. If that were the case, the results would be more related with a probability of engagement of the brain process being studied more than the degree to which that process is engaged. Also, a difference in amplitude can be produced by variability in the time dynamics of the ERPs rather than actual amplitude. It is hard to distinguish between these interpretations (Otten & Rugg, 2005). A potentially safe way to compare differences in amplitude is to consider the scalp distribution of the components – the same scalp distributions are associated with similar or the same intracerebral sources – as a way to see if a given manipulation affects the same cognitive processes but to different degrees (Otten & Rugg, 2005). However, scalp distributions also need to be interpreted with caution.

Scalp distributions represent differently weighted combinations of mean event-related activities, from several to many cortical sources having broad and strongly overlapping scalp projections. This makes interpretation of topographic projections difficult. Some researchers still interpret these projections as if the neurons under the area of the projection were producing the activity observed in the scalp. For instance, ERP modulations strongly observed over frontal electrodes do not necessarily involve activation of frontal areas of the brain. Topographic activity of the

ERP does not represent cortical activation.

One of the other disadvantages of the ERP approach is that it leaves out a large amount of information contained in the whole EEG – valuable data that can be used to better understand brain dynamics, is stored or wasted. On the other hand, research shows that the assumptions underlying ERP techniques are not strictly true (Makeig, 1993; Otten & Rugg, 2005). This would only be the case if, (1) evoked responses were stable across trials, (2) were completely independent of the ongoing EEG, and (3) if the ongoing EEG were not perturbed by experimental events. Several reports have shown that ERPs are neither stable nor completely independent of the EEG (Makeig, 1993). In addition, ERPs are the result of the mean of the signal, while many other statistical approaches can be made to study EEG signals. Although contrary to usual assumptions, and as mentioned previously, there is no certainty that the effects observed in the average are present in some (or all) of the single trials used to compute it (Makeig, Debener, et al., 2004). Therefore, new approaches become necessary to better understand the electrophysiological response of the brain (Rousselet & Pernet, 2011).

In general, the ERP approach assumes linearity in the brain processes, which makes the process of analysis and interpretation of results ‘easier’. Under this approach the brain is treated as a ‘linear system’ and the experimental paradigms are very simple; usually the stimuli are very well controlled in terms of luminosity, location on the screen, presented one at a time at specific time lapses, etc. (Rousselet & Pernet, 2011), far from situations that we face in real life. In real life situations there is overlap of multiple stimuli, we perform more than one task simultaneously and there are no obvious events with which to time lock.

2.6 New approaches: an Event Related Brain Dynamics view

The ERPs approach has contributed to understanding the temporal dynamic of certain cognitive functions. However, the approach has neglected important information given by the whole EEG. New approaches open the possibility of studying the complex spatiotemporal dynamics underlying ERPs, taking into account more information, such as trial-by-trial visualisation and time/frequency analysis. The approaches listed here will be found in the analysis of the EEG data of this thesis.

2.6.1 Trial-to-trial

Single trial analysis can add more information to the modulations observed in the ERPs. Rousselet (2011) proposes that crucial information is available in the variability across trials, so the ultimate goal should be to understand single-trial brain activity, not activity averaged within or across subjects. Single-trial analyses are used to map in detail the relationships between image properties, brain activity and behaviour (Rousselet, Gaspar, Wieczorek, & Pernet, 2011).

Jung and Makeig (2009) have developed a method for plotting single trials that make up an ERP. These trials can be organised and sorted using different criteria. As expected, the final ERP average does not change, but ERP images resulting from different trial sorting orders can differ dramatically from each other, bringing out different aspects of trial-to-trial variability in the data. Even though this is a very attractive approach, it is not easy to implement, mainly because of the low signal-to-noise ratio (Otten & Rugg, 2005). To use this method it is necessary to have a large signal of interest. See Figure 5-8.

2.6.2 Event related spectral perturbations (ERSP)

Event Related Spectral Perturbations (ERSP) reveal aspects of event-related brain dynamics not contained in the ERP average of the same response epochs. The ERSP measures the amplitude of spectral changes in different frequency bands in relation to the presentation of an experimental event (Makeig, 1993). Pfurtscheller (1999) was the first to introduce the idea of Event-related synchronisation and desynchronisation. The main difference between the approach introduced by Pfurtscheller and the ERSP approach is that the former measures spectral changes in particular frequency bands (Pfurtscheller & Lopes da Silva, 1999), whereas the ERSP is a wideband normalised measure of the changes in the event-related broad band frequency spectrum (Makeig, 1993). The power in the frequency band can be interpreted as the number of neural units synchronously active in a particular frequency (Klimesch, Freunberger, Sauseng, & Gruber, 2008). Different frequency bands, in turn, reflect different neural processing systems, based on the idea that different neural assemblies discharge at different frequencies (Sauseng & Klimesch, 2008). In this sense activity in particular frequency bands have been associated with different cognitive functions.

In general, oscillations relevant for the performance of a task are expected to increase in amplitude; for example, low frequency bands (delta and theta) tend to increase in amplitude during cognitive effort (Sauseng & Klimesch, 2008). However, Klimesch (2008) described the paradoxical alpha synchronisation, where the alpha band shows an amplitude reduction during active cognitive processing; this reduction is interpreted as an active cortical processing of information. In contrast, alpha synchronisation reflects inhibition of task-irrelevant cortical processes (Klimesch, 1999; Makeig, Delorme, et al., 2004). A similar phenomena is also observed for beta rhythm (Neuper, Wortz, & Pfurtscheller, 2006). See Figures 5-6.

Amplitude and frequency are only two of the parameters that describe oscillations. A third one is the phase of the oscillation, informative regarding the timing of neural activity (Sauseng & Klimesch, 2008).

Another method used to study brain dynamics is Inter Trial Coherence (ITC). ITC images decompose the ERP into its constituent phase-locked frequency bands, and provide additional information about the relationship between the ERP and the whole EEG data. ITC can be seen as a measure of the consistency across trials of EEG spectral phase at each frequency and latency window (Makeig et al., 2009).

2.6.3 Source level activity versus sensor level activity

Electrodes placed over the scalp measure a mixture of brain activity; a single electrode can detect activity coming from different brain sources and at the same time, a single brain source projects activity towards different electrodes on the scalp. This is better explained using the analogy of the cocktail party problem: microphones (sensors) located in a noisy room will detect all sorts of information coming from people talking, musicians playing, the sound of glasses, etc. The strength of recorded activity in microphone will depend on the distance and spatial arrangement of the sources (for example, how far people are from a microphone). The same applies for activity recorded by electrodes on the scalp (Onton et al., 2006).

Independent component analysis (ICA) separates the recorded signal into additive components, based on the assumption that the sources producing the brain activity are statistically independent in the time domain (Makeig & Onton, 2011; Onton et al., 2006). In the case of the noisy cocktail party room, ICA will extract the individual voices from the mixed signal; in the case of sensor EEG activity, ICA will result in a series of independent processing or information sources contributing to the scalp activity. ICA finds a 'weight matrix' that indicates the contribution of each of the independent components (ICs) or source level activity to the channels or scalp level activity. This process can also be understood as a spatial filtering, that indicates the contribution of the IC to the recorded signal in the sensor. It is also said that ICA performs a 'blind' source separation, meaning that it does not use a pre-defined model of the signal sources (Onton et al., 2006), only the time course information.

The advantages of using ICA methods are: (i) increased spatial resolution over traditional EEG analysis, allowing the study of EEG brain-imaging with high temporal resolution and improved accuracy for source localisation; (ii) increased signal-to-noise ratio, thereby obtaining more information from activities that are sensitive and specific to particular cognitive processes (Onton, Delorme, & Makeig, 2005), excluding other source activity (less sensitive to the cognitive process) and/or non-brain source activity that is usually contained in scalp sensors (Delorme, Sejnowski, & Makeig, 2007) such as, eye movements, scalp muscle activity, electrical line noise, etc.

As with all methods, ICA has limitations. Two assumptions underlying ICA are (Onton et al., 2006): (1) source areas must have nearly independent time courses and (2) the source domain remains spatially fixed. Regarding the independent time course, ICA methods, even the most sophisticated, are not perfect and mutual information can still be found between different independent component activities

(Delorme, Palmer, Onton, Oostenveld, & Makeig, 2012). On the other hand some EEG phenomena may violate the stationarity of brain sources and these may appear to travel across the cortex (Delorme et al., 2012). In addition, an independent component's activity can project to the scalp in a dipolar spatial pattern (Delorme et al., 2012) – which can be matched with the projection of field activity in a single cortical patch – but not all ICs have dipolar scalp maps (Onton et al., 2006).

On the other hand, the final number of ICs is related to the number of scalp sensors, meaning that high-density EEG (128 sensors or more) can detect more sources. Thus, the final number of sources obtained does not necessarily reflect all brain sources contributing. To obtain a reliable independent component decomposition, it is important to take into account the amount of information submitted to ICA; for a large number of channels, the amount of data required is greater, while for a small number of channels, a smaller amount of information is required. For example, with 256 channels, is necessary to have at least 85 minutes of data, in contrast with 6 minutes of data for 64 channels in order to obtain a similar quality decomposition, for more detail, see (Onton et al., 2006).

2.6.4 Single subject versus Group level analysis

One important issue with performing group level analysis is the between-subjects variability (Onton et al., 2005; Onton and Makeig, 2006; Rousselet & Pernet, 2011). When results of a group of subjects are pooled together it is possible to miss effects at single subject level, doubts arise regarding the reliability of grand-average approaches and to what extent this group analysis reflects what is going on at single subject level. There are several potential approaches to overcoming these difficulties including single subject level analysis or optimised group-averaging analysis based on source-resolved brain activity (the latter is described in the next section). When comparing two conditions using grand-average signals the result indicates a simple binary output reflecting whether an effect was or was not significant. A particular case when a single subject analysis may be necessary is when tasks show high variability in participants' performance (as was the case for the task in Chapter 6 of this thesis). It may also be relevant if the researcher has questions regarding individual strategies subjects may use to approach a task or if there is interest in exploring how the group-average result reflects the individual performance.

2.6.5 Group level analysis based on independent component clustering

One of the issues of averaging channels across participants is that it equates the location of channels, which may not receive the same combination of source activities, in each participant (Onton et al., 2006). Thus, it may pick up functionally different signals (Rousselet & Pernet, 2011) and neglect the between-subject variance. Group level analysis based on clustering independent components (ICs) tries to overcome these difficulties by finding similar patterns of activation across ICs of many subjects, with the aim of studying more homogeneous source activity across subjects rather than simply equating single-channel data by scalp location.

Two clustering methods were used in the present PhD work: one based on principal components analysis (PCA) and k-means methods (Onton & Makeig, 2006), and another using a recently published approach based on probabilistic methods (Bigdely-Shamlo, Mullen, Kreutz-Delgado, & Makeig, 2013).

PCA-based clustering consists of finding similar source-resolved EEG signals (ICs) based on the calculation of an abstract distance between every pair of ICs in the study. Different IC-derived measures (ERP, ERSP, dipole location, etc.) can be combined to produce the similarity value (distance) between each pair. Additionally, each measure can be weighted differently according to its relative relevance for the scientific questions being addressed. For example, if the analysis is focused on the frequencies (ERSPs) rather than on voltage changes (ERPs), the former will have a higher weight value, represented by a scalar. One of the most important elements in the clustering is the ICs equivalent dipole spatial location, which in this case are normalized to a standard spherical head model (individual structural MR brain image is ideal but not always available) (Akalin Acar & Makeig, 2013). As every other measure used in the clustering, the dipole locations can be modulated by a weighting factor depending on the considerations of the researcher. The final number of clusters is defined based on the total number of ICs and the number of participants, necessarily including in the cluster at least one IC per subject. This approach requires manually defining several parameters, such as the measures necessary for creating the abstract distances and the weights given to each of these measures, as well as the final number of clusters, which are both considered limitations of this method (Spadone, de Pasquale, Mantini, & Della Penna, 2012) . For more detail, see (Onton & Makeig, 2006). See Figure 6-8.

The other clustering method is Measure Projection Analysis (MPA), which offers a probabilistic approach to performing group level analysis by finding different domains, or brain areas, common across all the dipoles (projected from individual ICs) available for the study. MPA uses the dipole location of the ICs (or source-resolved EEG signals) as the main variable and then finds statistical similarity between the measures of interest produced by each IC dipole (ERP, ERSP or others). It then identifies, within each domain, IC dipoles whose measures exhibit sufficient difference compared to the other dipoles' measures. The final results are brain domains that contain dipoles with different probabilities of being part of that domain. As this is a probabilistic based approach, a single dipole has the probability of being part of two different (but close) domains. Unlike the PCA-based methods, MPA uses only one measure to find common domains, reducing the number of parameters assumed. This approach resolves some of the issues presented by the PCA-based methods, giving a more objective (low level of human influence) and data-driven way of finding similar brain activities among participants in a study. For more details, see Bigdely-Shamlo (Bigdely-Shamlo, Mullen, et al., 2013). See Figure 5-5

2.7 The trade-off between EEG and prospective memory

One variable that affects the quality of EEG research is the amount of information available for analysis, specifically, time points, or target trials. EEG studies tend to use experimental paradigms that provide a high number of repetitions of the event of interest. In the case of event based prospective memory this can be a problem, since one of the features that characterises prospective memory task is that the prospective memory event represents a minority of the experimental trials. It is important to find a good balance between low number of events and enough data for analysis. Another alternative is to focus the analysis, not in the prospective memory events themself, but on the ongoing trials.

2.8 The thesis at a glance

The first two chapters of this thesis present several ideas regarding current unresolved questions in prospective memory research, mainly associated with the involvement of attention and what monitoring means in the context of prospective memory tasks. It can be argued that monitoring involves different operations associated with the Supervisory Attentional System (Shallice & Burgess, 1996), which in turn interacts with memory and other attentional systems during intention maintenance and retrieval. The involvement of the SAS will depend on the prospective memory task condition. These ideas can be summarized in three questions: Is attention required to retrieve delayed intentions? What does monitoring mean in the context of prospective memory? Is prospective memory a particular memory system or it is based on already known attentional and memory mechanisms?

To answer these questions, we propose a set of prospective memory experiments involving different cognitive demands, ranging from event-based prospective memory tasks to time-based prospective memory tasks, including one experiment performed in free-movement conditions.

The pilot experiment (chapter 3) was designed to answer the following questions: (1) What aspects of prospective memory tasks can be manipulated in order to produce different monitoring demands during the retention interval? Previous research in prospective memory shows that cue *detection* and response *retrieval* (components associated with the intention retrieval phase) can be differentiated behaviourally; thus, the following questions arise: (2) Does difficult *detection* of prospective memory cues affect performance in the ongoing task during the retention interval phase? (3) Does difficult *retrieval* of the prospective memory intention affect performance in the ongoing task during the retention interval phase? (4) Is this paradigm suitable to be reproduced for EEG analysis?

The EEG event-based prospective memory experiment (chapter 4) was designed based on the results of the pilot experiment, aimed at answering the following questions: (1) Is attention required during low demanding prospective memory tasks? (2) Do two different prospective memory tasks share similar attentional mechanisms? (3) Do the ERPs described in the literature of prospective memory reflect general mechanisms or particular mechanisms associated with perceptual event-based prospective memory tasks?

For the case of time-based prospective memory tasks (chapter 5), there are no targets that will prompt the execution of the intention; thus, execution of the prospective memory task is self-initiated and executive control of attention is required to keep track of time across the experiment. The same ongoing task of the previous experiments was used in order to compare results associated with the ongoing task while holding a time-based intention. The questions underlying this experiment are: (1) What are the brain sources and dynamics involved in the absence of an external cue to trigger delayed intentions? (2) Are monitoring (attentional) mechanisms common to time-based and event-based prospective memory tasks? (3) How is the ongoing task affected when it has a time-based prospective memory task embedded?

The time-based prospective memory in free-movement conditions (chapter 6) is based on the same ideas tested in the non-movement time-based prospective memory experiment, with the following additional questions: (1) Can we obtain physiologically meaningful brain activities in free-movement time-based prospective memory tasks? (2) Are brain sources and dynamics obtained in free-movement prospective memory tasks similar to the dynamics obtained in a classical non-movement time-based prospective memory experiment?

The ERP technique is the most common approach used in EEG and prospective memory experiments, specifically the study of changes in the amplitude of ERP components associated with manipulations of ongoing and prospective memory tasks. In the present PhD work, we use other methods to overcome some of the ERP limitations, including source activity analysis, contribution of source activity to scalp ERPs and brain dynamics in the frequency domain.

Chapter 3
Pilot experiment: development of an experimental paradigm to study monitoring in prospective memory using electroencephalography

3.1 Abstract

Research on prospective memory has shown that the demands of cue *detection* and *response retrieval* – both associated with the intention retrieval phase of prospective memory – can be differentially manipulated in experimental paradigms. However, it is not clear how differential demands for cue detection and response retrieval affect the monitoring demands during the retention interval (while performing the foreground ongoing task). The aim of the study was to explore how manipulations of demands for cue detection and/or response retrieval affect the requirement of preparatory attention and executive functions at different stages of the prospective memory process: retention interval, cue detection and response retrieval. This experimental paradigm was developed to explore – in a subsequent phase – the neural correlates of attention and executive functions using electroencephalography. Participants were asked to perform an ongoing foreground task that required semantic categorisation of words. In addition, they were asked to perform a prospective memory task that varies in two dimensions. First, demands for cue detection: detect perceptual cues (low-demand) and detect conceptual cues (high-demand). Second, demand for response retrieval: give one possible response (low-demand) and select between two possible responses (high-demand). These manipulations were implemented simultaneously creating four demand conditions: Low-detection/low-retrieval; low-detection/high-retrieval; high-detection/low-retrieval and high-detection/high-retrieval. The results showed that demands on cue detection, but not on response retrieval, affected the requirement for monitoring during the retention interval. The next stage in the research was to study the neural correlates of monitoring during the retention interval under both low and high cue detection demands, using electroencephalography.

3.2 Introduction

The degree to which executive control of attention is involved in the different phases of prospective memory is a key unresolved question in understanding the process of realising delayed intentions. Studies have attempted to elucidate whether prospective memory can be performed spontaneously – without devoting attention to the prospective memory intention (Einstein et al., 2005) – or if active monitoring or executive control of attention is required (Smith & Bayen, 2004). Theoretical positions are still under debate (Gilbert et al., 2009; Scullin et al., 2010; Smith, 2010). On one side of the debate there is the idea that 'under certain circumstances' delayed intentions can be spontaneously retrieved, while on the other side there is the idea that 'preparatory attention' is always required to retrieve a delayed intention.

The first question to be answered is: Is preparatory attention required to perform a low-demand prospective memory task? One of the difficulties in answering this question is related to the great variety and different stages of prospective memory tasks. Thus, it is necessary to consider the cognitive processes underlying prospective memory beyond the retrieval of the intention itself, which is only one stage of the whole process of prospective remembering. Previous experiments have shown that cue identification (recognising the proper moment to act upon the intention) can be differentiated from intention retrieval (recall of what is the action to be executed) (Knight et al., 2010; Marsh et al., 2003; Simons et al., 2006) and both processes are recognised as part of the intention retrieval phase. The discussion has been mainly centred on this 'intention retrieval phase', rather than other stages of the prospective memory. We propose that, the requirement for preparatory attention can be examined considering the retention interval (while performing a different activity) as a different stage from cue detection (recognising the moment to perform the action) and intention retrieval (selecting the correct response).

Another question to be answered is: What does preparatory attention (or monitoring) mean in prospective memory? Preparatory attention has been defined as 'to be ready to give a prospective memory response when the context for retrieval is encountered' (Smith, 2008). However, it is not clear which attentional mechanisms are mediating this preparatory attention. Conversely, intention retrieval in the absence of preparatory attention is categorised as ‘spontaneous’ or ‘automatic’ (McDaniel & Einstein, 2000). We propose that these terms are misleading. It may be argued that some automatic processes underlie prospective memory in some of its stages or phases, as for example in the case of spontaneous memory retrieval (Hall et al., 2008) or reflexive-associative processes (McDaniel & Einstein, 2007), which may support response retrieval. However, the participation of these mechanisms does not exclude the involvement of attentional mechanisms during other stages or phases, such as during the retention interval or cue detection. On the other hand, research in neuroscience shows evidence of complex cognitive process without conscious attention (Koch & Tsuchiya, 2007; Okuda et al., 2011; Sklar et al., 2012), thus the absence of reported (conscious) attentional control or the absence of a behavioural correlate of attention cannot be understood as a lack of attention control (Smith, 2010). The question that arises then is what is the nature of the attentional processes involved in prospective memory? To continue with the discussion, we propose to use the terms ‘internally’ versus ‘externally’ driven attentional processes. The literature on attentional mechanisms describes two attentional networks: one driven by external events and the other by internal processes (Corbetta & Shulman, 2002). The same ideas are developed in prospective memory research, giving the role of attentional mediator to the frontopolar cortex, diverting attention towards the internal cognitive state or towards environmental events (Burgess et al., 2007; Burgess et al., 2008; Burgess et al., 2003; Gilbert et al., 2009). We propose that prospective memory will be mediated by externally or internally driven attentional control depending on the features of the prospective memory task. It may be argued that externally driven attentional mechanisms can be understood as ‘spontaneous’ for some researchers and as ‘preparatory attention’ for others. If that is the case, then the discussion is more related to terminology than cognitive mechanisms.

In this study, we manipulated demands for cue detection and response retrieval simultaneously, in order to explore how the demands on different components of prospective memory affect performance during the retention interval and how attention may be differentially involved depending on the demands of cue and/or response retrieval. Low-demand conditions for cue detection and response retrieval were thought to be more externally driven processes (for example, response to salient cues and a strong association between cue-response), whereas high-demand conditions required a higher degree of cue processing (for example, a response to the meaning of the cue and a weak association between the cue and the expected response).

3.3 Material and methods

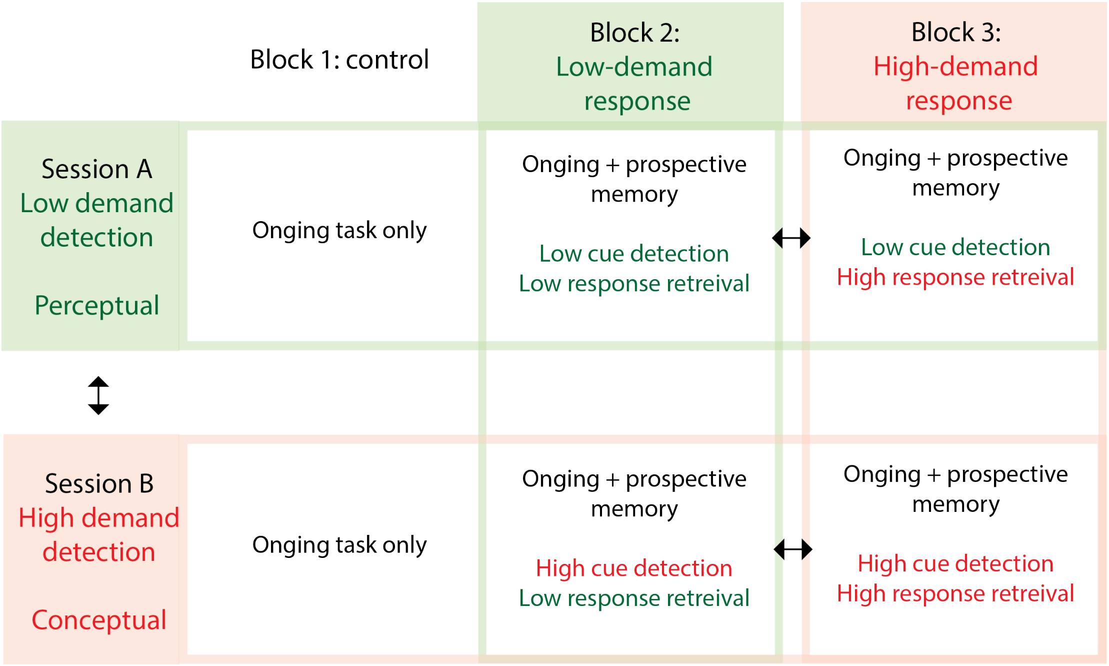
3.3.1 Participants

Fourteen students, native speakers of English from Glasgow University, took part in the experiment (two males, twelve females, mean age 22.4 years, range 19–31 years). Written informed consent was obtained before participating.

3.3.2 Procedure

Usually in prospective memory paradigms, the prospective memory task is embedded in an ongoing task and only corresponds to about 10% of the trials. This means that during the experiment, participants mainly perform an ongoing task and only a minority of the trials in the ongoing task correspond to the prospective memory task, with the aim of emulating real life prospective memory situations, where something non-routine has to be done after a delay.

The design of the experiment can be seen in figure 3-1. Manipulations of the cue detection demands were performed in two separate sessions with a week in between, counterbalanced across participants. Manipulations of the response retrieval demands were performed within each session, also counterbalanced.



	Block 1: control	Block 2: Low-demand response	Block 3: High-demand response
Session A Low demand detection Perceptual	Onging task only	Onging + prospective memory Low cue detection Low response retreival	Onging + prospective memory Low cue detection High response retreival
Session B High demand detection Conceptual	Onging task only	Onging + prospective memory High cue detection Low response retreival	Onging + prospective memory High cue detection High response retreival

Figure 3-1. Experimental design. Each session had three blocks: one control block, which consisted on the ongoing task only; a low-demand response block, consisting of giving a simple motor response with the left index finger in response to the prospective memory cue and; a high-demand response block, consisting of responding with either the left index or middle finger, depending on the prospective memory cue. Demands for cue detection were held constant within each session: low-demand cue detection (Perceptual condition) or high-demand perceptual condition (Conceptual condition), creating four different prospective memory demand conditions. The arrows represent counterbalancing condition across sessions and blocks. The control block was always performed at the beginning of each session, to avoid contamination of the ongoing control task by the prospective memory task (West et al., 2007). Stimuli used on both sessions were identical, only instructions regarding cue detection and intention retrieval were different. Regular breaks were offered to the participants during the whole experiment.

3.3.3 Prospective Memory task

The prospective memory task used for this experiment varied in the attentional demands required to detect the prospective memory cue and to retrieve the prospective memory response. Manipulation of demands for cue detection and response retrieval were performed simultaneously.

3.3.3.1 Manipulation of demands for cue detection

Common sense suggests that highly salient stimuli are more easily detected than cues that are not particularly physically different from their surroundings. Prospective memory studies have shown that manipulation in the amount of perceptual information contained in a cue influences probability of detection (Hicks, Cook, & Marsh, 2005; Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997). Perceptual cue detection will be less cognitively demanding during the retention interval, under the assumption that if the cue is easier to detect, less demand will be required to identify the right moment to act, since it relies on external stimulation, so the person can reduce the level of monitoring during the ongoing task. In addition, once the cue has been detected, fewer resources will be required to map on to the features of the cue to verify whether it actually matches with the prospective memory cue, since physical features of the targets are processed early in target visual processing and it involves sensorial, posterior cortex rather than more extended and complex networks, recruited later in the processing of visual targets (Makeig, Delorme, et al., 2004). Recognition would therefore be based on low-level feature extractions mechanisms.

The low-demand cue detection, in the present experiment, consisted of detection of words written with the first letter in upper case, for example ‘Toe’, with the rest of the words in the experiment written either in lower or UPPER case.

Distinctiveness of a cue is not just defined by its physical salience. Schmidt (1991) defines ‘Category distinctiveness’, as the case in which the distinctive item belongs to a different conceptual category, for example ‘animal names’ embedded in a list of ‘countries’. Previous reports show that perceptual distinctiveness leads to greater cue detection compared to conceptual distinctiveness (Brandimonte & Passolunghi, 1994; Cohen et al., 2003). Detection of prospective memory cue based on semantic categorisation supposes a more complex cognitive process relative to perceptual distinctiveness.

High-demand cue detection in this experiment consisted of detection of an animal word, in the context of a wide range of other semantic categories (see ongoing task section for more detail).

Words used for the prospective memory task were matched by frequency and length, using the MRC psycholinguistic database. Similar indices of concreteness and imagability were maintained in all cases when possible.

3.3.3.2 Manipulation of demands for response retrieval

The strength of the link between cue and intention has been associated with probability of intention retrieval, once the cue has been detected. In experimental paradigms, the strength of this association can be influenced by the way in which the instructions are given at encoding of the intention. Gilbert et al. (2009) created two conditions giving participants instructions with different emphasis: in the first condition specific cues were linked to specific actions using Implementation Intentions (Schweiger Gallo & Gollwitzer, 2007), whereas in the second condition the action was associated with a general goal and not with a specific cue. Implementation intentions encourage participants to focus their encoding on a particular cue for retrieval and to form a strong associative link between that cue and the intended intention.

The low-demand response retrieval in the present experiment consisted of responding with the left index finger when they saw either an animal word or capitalised word. The instructions were given in the following way: ‘Press the X key when you see an animal word’ or ‘Press the X key when you see a capitalised word’.

On the other hand, high-demand response retrieval requires executive control in order to establish the correct response. In this case the Supervisory Attentional System may be involved in selecting the proper response for the cue presented, thus more cognitive resources are required to retrieve the intention. Simons et al. (2006) manipulated the cue-intention association by varying the number of actions participants needed to perform in order to determine the appropriate response. The manipulation was made asking participants to make a decision based on perceptual information given by the cue (Simons et al., 2006).

The high-demand response retrieval, in the current paradigm, was made based on perceptual information for the perceptual cue detection (different responses for short and long words) and based on conceptual information for the conceptual cue detection (different responses if the animal had wings or four legs). Participants were asked to press a key on a response pad with their left middle finger if the capitalised word had 4 letters or more (‘L’ key) and with the left index finger if the word had 3 letters or less (‘S’ key). For the case of animal words, they were asked to press a key on a response pad with their left middle finger if the animal had wings (‘F’ key) and with the left index finger if the animal had four legs (‘W’ key). Keys for both sessions, perceptual and conceptual, had exactly the same position on the response pad. Only labels were changed. Each prospective memory block had 300 trials, 10% of the trials were prospective memory cues.

Participants gave responses for the prospective memory task with their left hand and responses for the ongoing task with their right hand.

3.3.4 The ongoing task

Prospective memory tasks are typically embedded in some attention-demanding ongoing cognitive activity. In the current study we used an ongoing task that required participants to make continuous semantic decisions, in order to maintain engagement in the ongoing task and avoid rehearsal of the prospective memory instructions. Participants were instructed to respond whether a stimulus displayed on the screen matched the semantic category of the stimulus presented one trial before. Participants responded with their right index finger when words were semantically ‘Related’ and with their right middle finger when the words were semantically ‘Unrelated’, the responses where given through a response pad for their right hand and the keys were labelled with the words ‘Related’ and ‘Unrelated’ respectively. Categories were made based on the updated version of Battig and Montague (1969) norms (Van Overschelde, Rawson, & Dunlosky, 2004).

In a first block participants were asked to perform only the ongoing task. Accuracy and reaction times were used as a control condition, against which to measure the interference produced by the prospective memory task under the different cue detection and response demand conditions. The control block was always performed at the beginning of each session to avoid contamination of the ongoing control task by the prospective memory task (West et al., 2007). The ongoing block consisted of 150 trials and the prospective memory blocks consisted of 300 trials each. Stimuli were presented during 500ms, and the total epoch length was 2000ms. Participants were able to respond at any time from the onset of the stimuli.

3.3.5 Delay task

This task was performed immediately after the instructions for the prospective memory task were given. It is called a delay task because it is used in prospective memory paradigms to distract participants from the prospective memory instruction, in order to initiate the ongoing task without a recent activation of the intended intention. In this case, the delay task consisted of pressing the same number on the response pad as they saw in the screen, as fast and accurately as they could.

3.3.6 Data analysis

Data was transferred from E-prime format to csv matrices. The analysis was performed using SPSS. We examined two aspects of the present experiment, firstly how different manipulations of the demand for cue detection and response retrieval affected the performance of the ongoing task, to inspect this issue we compared changes in the performance of the ongoing task – under the different prospective memory task conditions – relative to the performance of the ongoing task control (previous to the instruction for the prospective memory condition). Secondly, we examined how different manipulations of the demands for cue detection and response retrieval affected the performance of the prospective memory task itself.

Repeated measures ANOVAs were performed using the following factors: blocks (control, low-demand response and high-demand response) and sessions (Perceptual/low-demand detection and Conceptual/high-demand detection). A third factor, event type (‘Related’ and ‘Unrelated’), was included to examine changes in reaction times of the ongoing task.

3.3.6.1 Analysing how the performance of the ongoing task is affected by different manipulations in the demands of the prospective memory task.

Note that a ‘Blocks x Sessions’ interaction is informative of the differential effect we are examining in this experiment, meaning that differences between sessions (low versus high-demand for cue detection) were expected, only for blocks 2 and 3 (low and high-demand for response retrieval), since block 1 corresponds to the control task. The same control task is performed in both sessions, thus no difference between control tasks is expected. In addition, in case of significant main effect of blocks; if the post-hoc pairwise comparisons reveal differences between blocks 2 and 3, this is indicating that the low and high-demands for response retrieval affected the performance. If the differences are only found between blocks 1 (control) against block 2 and 3 together (low and high-demand response retrieval), this is indicative that the demands for response retrieval did not affect the performance differentially. A main effect of Blocks factor without interaction ‘Blocks x Sessions’ would indicate that only the manipulation of the demands for response retrieval affected the performance.

To examine changes in accuracy of the ongoing task, a Two-way repeated measures ANOVA was performed with factors Blocks and Sessions. Null hypothesis corresponded to non-significant interaction between Blocks and Sessions. For rejected null hypothesis, two separated one-way repeated ANOVAs were used to evaluate the interaction – using a 0.025 significance level, corrected by the number of main effect comparisons (0.05/2) (Kinner & Gray, 2008) – with post-hoc pairwise multiple comparisons with Bonferroni corrections.

To examine reaction times of the ongoing task, a Three-way repeated measures ANOVA was performed with factors Blocks, Sessions and Event Types. Null hypothesis corresponded to non-significant interaction ‘Blocks x Sessions x Event types’. For rejected null hypothesis, two separated Two-way repeated ANOVA were used to evaluate the interaction, using 0.0125 significance level, corrected by the number of main effect comparisons (0.05/4) (Kinner & Gray, 2008). Post-hoc analysis were the same as described above for examination of accuracy.

3.3.6.2 Analysing the effects of demand manipulations on the prospective memory task

For the prospective memory task the ANOVA factors were Sessions (high and low-demand cue detection) and Blocks (high and low-demand response retrieval), note that the Blocks factor in this case does not have the control level, since during control blocks participants performed the ongoing task only.

To evaluate the effect of the differential manipulation on the demands for cue detection and response retrieval, we expect a non-significant ‘Session x Blocks interaction’. Meaning that the main effects corresponded to either one or the other demand manipulations.

During the low-demand response retrieval block, participants were asked to give a simple response when they encountered a prospective memory cue (press a key with the left index finger), whereas during the high-demand response retrieval block participants had to select between two possible responses every time they encountered a prospective memory cue. It could be the case that a participant identified a prospective memory cue, i.e. ‘Sockets’ (capitalised word), but gave an incorrect response, i.e. ‘3 letters or less’. In this case the participant identified the prospective memory cue correctly because it gave a response different from the ongoing task response (note that responses for the ongoing task were given through a right response pad), however, failed in the response retrieval, pressing ‘3 letters or less’ instead of ‘4 letters or more’. To differentiate between correct cue detection and correct response retrieval two accuracy indexes were calculated.

The *Accuracy cue detection index* indicated when participants detected the prospective memory cue correctly. Whereas, the *Accuracy retrieval index* was calculated only for the high-demand response block (the only block with two possible responses) and indicated if response retrieval was correct. For example, a participant could have recognised 21 out of 30 cues, but just 18 of these 21 were correct, thus detection accuracy would be 70% and retrieval accuracy would be 86%.

3.4 Results

3.4.1 How is the performance of the ongoing task affected by different manipulations in the demands of the prospective memory task?

3.4.1.1 Effect on accuracy

The repeated measure ANOVA showed a significant interaction Blocks*Session, $F(2,26) = 5.297$, $p < 0.05$, partial eta squared = .290 (moderate effect size) and a significant main effect of Blocks factor, $F(2,26) = 12.617$, $p < 0.001$, partial eta squared = .493. Two one-way repeated measures ANOVA were performed in order to explore the main effects of the Blocks factor separately by sessions, using 0.025 as significance level (corrected by the number of main effect comparisons) (Kinner & Gray, 2008).

The perceptual condition (low-demand cue detection), showed a significant Block effect, $F(2,16.592) = 11.381$, $p < 0.025$, partial eta squared = .467 (large effect size) (with Greenhouse-Geisser correction). The post-hoc pairwise comparison with Bonferroni correction showed that the ongoing control task obtained higher accuracy ($p < 0.05$) relative to both low-demand and high-demand responses (blocks 2 and 3), no differences were observed between these last two blocks. Meaning that the performance of the ongoing task was affected by the low-demand prospective memory cue detection, independently of the demands for the response retrieval.

The conceptual condition (high-demand cue detection), also showed a significant Block effect, $F(2,26) = 7.624$, $p < 0.025$, partial eta squared = .370 (moderate/large effect size). The post-hoc pairwise comparison with Bonferroni correction showed that the ongoing control task obtained higher accuracy relative to the low-demand response retrieval block (block 2), however, the accuracy of the high-demand response retrieval (block 3) did not decrease significantly. Meaning that the performance of the ongoing task was affected by the high-demand prospective memory cue detection, particularly when the demands for the response retrieval were low.

Table 3-1. Accuracy (%) and Reaction Times (ms) of the ongoing task by sessions and blocks. Standard deviation in parentheses

	Control	Low-demand Response	High-demand Response
Low-demand Detection			
Related RT	702 (142)	784 (150)	767 (138)
Unrelated RT	764 (152)	829 (162)	850 (157)
Accuracy	96 (39)	94(30)	91 (60)
High-demand Detection			
Related RT	663 (121)	691 (106)	705 (131)
Unrelated RT	710 (114)	794 (158)	809 (142)
Accuracy	95 (36)	91 (40)	93 (50)

3.4.1.2 Effect on reaction times

The repeated measure ANOVA showed a significant interaction Blocks*Session*Event type, F(2,26) = 5.564, $p < 0.01$, partial eta squared = .3 (moderate effect size) and strong significant main effect for Event Type, F(1,13) = 29.825, $p < 0.001$, partial eta squared = .696. Showing that in general reaction times for related words were faster than reaction times for unrelated words.

Two post-hoc two-way repeated measures ANOVA were performed (at 0.0125 significance level), to explore Blocks and Session effects separately for the different event types, ‘related’ and ‘unrelated’.

For ‘related’ items, the two-way repeated ANOVA showed a main effect by Blocks, F(2,26) = 13.514, $p < 0.001$, partial eta squared = .51 (large effect size). The post-hoc pairwise comparison with Bonferroni correction showed that the ongoing control task obtained faster reaction times ($p < 0.001$) relative to both low-demand

and high-demand response (blocks 2 and 3), no differences were observed between these last two blocks. Meaning that reaction times of 'related' items of the ongoing task slowed down during the prospective memory task, independently of the low or high-demand for response retrieval. (Block 1 < Block2 = Block 3). The main effect Session was also significant, F(1,13) = 12.392, $p < 0.01$, partial eta squared = .488 (large effect size), showing that participants were faster during the perceptual session (low-demand cue detection). However, the interaction Session*Blocks was not significant, F(2,26) = 2.331, $p > 0.05$, indicating the participants were slower during this session even during the control task, independently of the prospective memory instructions.

For 'unrelated' items, the two-way repeated measures ANOVA showed a main effect by Blocks, F(2,26) = 13.719, $p < 0.001$, partial eta squared = .513 (large effect size). The post-hoc pairwise comparison with Bonferroni correction showed that the ongoing control task obtained faster reaction times ($p < 0.005$) relative to both low-demand and high-demand response (blocks 2 and 3), no differences were observed between these last two blocks. Meaning that reaction times of 'unrelated' items increased during the prospective memory task, independently of the low or high-demand for response retrieval. (Block 1 < Block 2 = Block 3). No significant effects were found for the session factor, F(1,13) = 4.745, $p > 0.05$. The interaction Session*Blocks was not significant either, F(2,26) = 0.259, $p > 0.05$. Indicating that reaction times for unrelated items were similar in both sessions (low and high-demand for cue detection) and slowed down during the prospective memory blocks (2 and 3), independently of the demands for response retrieval.

The reaction times for 'related' items of the perceptual session were slower than 'related' items of the conceptual session, including the responses given during the control task, which was performed before the instructions for the prospective memory task, note that the control task was identical in both sessions session. Reaction times for 'unrelated' items were also slower during the perceptual session, but did not reach statistical significance. In order to explore changes in the reaction time during both sessions, that were not explained by the changes observed between control tasks, we decided to explore the relationship between related and unrelated items across the three different blocks for the two sessions, see table 3-2.

Table 3-2. Difference in reaction times (Δ RT) in milliseconds between related and unrelated items by sessions and blocks. Standard deviations in parenthesis.

	Control	**Low-demand Response**	**High-demand Response**
Low-demand Cue			
Δ RT: Unrelated - related	61 (54)	45 (54)	83 (71)
High-demand Cue			
Δ RT: Unrelated - related	46 (53)	103 (77)	103 (54)

The repeated measures ANOVA performed on ΔRT between related and unrelated items reveals a significant interaction effect 'Blocks x Sessions', F(2,26) = 5.564, $p < 0.01$, partial eta squared = .3 (moderate effect size). We explored the main effects for each session separately using two one-way repeated measures with corrected significance level at 0.025.

The repeated measures ANOVA in the perceptual condition (low-demand cue detection), showed no significant main effect, F(2,26) = 2.987, $p > 0.05$, whereas the conceptual condition (high-demand cue detection), showed a significant block effect, F(2,26) = 8.763, $p < 0.01$, partial eta squared = .403 (large effect size). The post-hoc pairwise comparison with Bonferroni correction showed that the ongoing control task obtained smaller difference between related and unrelated items (Block1 vs Block 2: $p < 0.05$, Block 1 vs Block 3: $p < 0.001$) relative to both low-demand and high-demand responses (blocks 2 and 3), no differences were observed between these last two blocks.

3.4.2 How is the performance of the prospective memory task affected by manipulations in the demands of cue detection and response retrieval?

Table 3-3. Accuracy (%) and Reaction Times (ms) of the prospective memory task by sessions and blocks. Standard deviation in parentheses.

	Low-demand Response	**High-demand Response**
Low-demand Detection		
PM RT	830 (199)	1095 (170)
Acc. detection	91 (6)	87 (11)
Acc. Retrieval	--	86 (13)
High-demand Detection		
PM RT	789 (125)	1047 (124.10)
Acc. detection	76 (17)	83 (13)
Acc. Retrieval	--	96 (7)

3.4.2.1 Cue detection accuracy

The two-way repeated measures ANOVA with factors Blocks (low and high-demand response retrieval) and Sessions (low and high-demand cue detection) showed a significant interaction effect, F(1,13) = 7.822, $p < 0.05$, partial eta squared = .376 (large effect), and a main Sessions effect, F(1,13) = 7.822, $p < 0.05$, partial eta squared = .376 (large effect). Blocks effects were not significant, F(1,13) = 4.07, $p > 0.05$. Meaning that the difference between sessions (Perceptual versus conceptual) depended on the response retrieval demand manipulations.

Two post-hoc t-tests were performed with significance level at 0.025, corrected by the number of main comparisons. The results showed that conceptual cues (high-demand cue detection) were more difficult to detect only during low-demand response retrieval block (M=76, SD=17), whereas perceptual cues (low-demand cue detection) had higher accuracy (M=91, SD=6), t(13)= -3.347, $p < 0.01$. Cue detection had similar accuracy for low-demand cue detection (M=87, SD=11) and high-demand cue detection (M=83, SD=13), when the demand for response retrieval was high, t(13)=-1.237, p>0.05. These results indicate that manipulation for cue detection was effective only in the low-demand response retrieval condition; the high-demand response retrieval condition interfered with cue detection.

3.4.2.2 Response retrieval accuracy

Accuracy for response retrieval was calculated counting the number of correct answers out of the total number of cues detected (see methods). The paired t-test revealed that response retrieval was more accurate for conceptual session (M=96, SD=7), when participants had to indicate whether the prospective memory cue ‘animal word’ had wings or four legs, relative to perceptual session (M=86, SD=13), when participants had to say if the prospective memory cue ‘capitalised words’ was short (3 letters or less) or long (4 letters or more); t(13)=3,1, p < 0.01.

3.4.2.3 Reaction times

The two-way ANOVA yielded a main Blocks effect, F(1,13) = 81.409, p < 0.001, partial eta squared = .862 (large effect), the post hoc analysis showed that high-demand response retrieval was much slower than low-demand response retrieval for both cue detection demand conditions, the interaction effect was not significant, F(1,13) = 0.20, p > 0.05 (see table 1). Manipulation of demands for cue detection did not affect reaction times, F(1,13) = 2.059, p > 0.05.

3.5 Discussion

The aim of the present study was to explore how manipulations of demands for cue detection and response retrieval affect the requirement of preparatory attention and executive functions at different stages of the prospective memory process: retention interval, cue detection and response retrieval. The goal was to prepare a paradigm for studying, in the next experiment, the neural correlates of attention and executive functions using electroencephalography (chapter 4).

The most relevant result of the present study is that, varying demands for cue detection, but not for response retrieval, affected the requirement for monitoring during the performance of the ongoing task (retention interval). Thus, in the following experiment (chapter 4) we explore the neural correlates of the ongoing task and prospective memory tasks in relation to low- and high-demand for cue detection.

We observed that high-demand cue detection affected performance of the ongoing task during the retention interval to a greater extent than low-demand cue detection. In addition, demands for response retrieval did not affect the performance during the retention interval (performance of the ongoing task), but they increased the executive demands - during the intention retrieval phase of the prospective memory process.

These results show that the monitoring demands during the retention interval are related to demands for cue detection, rather than to demands associated with response retrieval; in other words, the monitoring required during the retention interval is not related with the complexity of the intention to be executed, but with the difficulty of finding the moment to perform the intention.

Is preparatory attention required to perform a low-demand prospective memory task? The present experiment presented some confounding results. We did not expect any type of behavioural impairment of the ongoing task during the low-demand cue detection. However, results showed decreased in accuracy; it may be that participants engaged some attentional resources to respond to the task, even though it was thought to be low demanding. The next experiment (chapter 4) contributes to clarifying this issue.

What does preparatory attention or monitoring mean in prospective memory tasks? We observed that the manipulations performed in this experiment affected the performance of the ongoing task and the prospective memory task differentially across the different stages of the prospective memory process. Manipulations of attentional demands for cue detection affected; (i) the performance of the ongoing task during the retention interval phase, and (ii) also affected the accuracy for cue detection of the prospective memory task. Whereas manipulation of demands for response retrieval particularly affected (iii) the response retrieval phase and did not affect the performance during the retention interval (the ongoing task).

These results suggest that: high-demand response retrieval manipulation was effective in requiring more executive control, particularly during the retrieval phase of the prospective memory process. Whereas, high-demand cue detection increased requirement for monitoring during retention interval and cue detection.

This contributes to the idea that mechanisms for monitoring during the prospective memory process will be strictly associated with features and demands of the prospective memory task. One mechanism can be associated with attentional control (Corbetta et al., 2008) during the retention interval and another with response monitoring (van den Berg, Aarts, Midden, & Verplanken, 2004).

The results of the pilot experiment are discussed in detail in the following paragraphs.

3.5.1 High-demand cue detection has greater impact on the retention interval relative to low-demand cue detection, measured in terms of reaction times of the ongoing task

An initial prediction was that high-demand cue detection would have greater impact on the performance of the ongoing task, relative to low-demand cue detection. This prediction was based on the hypothesis that the main mechanism of monitoring during the retention interval is associated with the executive control of attention required to detect the prospective memory cues or events. Thus, for the case of a perceptually salient prospective memory target, the detection of the cue can be more externally driven so the person can reduce the level of monitoring during the ongoing task. Furthermore, we predicted that the demand for response retrieval would have less (or insignificant) impact on the performance of the ongoing task during the retention interval based on the hypothesis that the mechanisms engaged by response retrieval difficulty are associated with response monitoring, a later level of stimulus processing (van den Berg et al., 2004) which is not required until the prospective memory cue has been already detected.

Reaction times of the perceptual condition showed a general increase across the three blocks (including control block), showing that reaction times were affected by some variable external to the manipulation of demands for cue detection. For that reason, we decided to explore the difference between ‘related’ and ‘unrelated’ words (RT unrelated minus RT related), under the assumption that if there were an external variable affecting the performance, this would affect the reaction times independently of the item. Note in the table 3-1 a general increase of reaction times during the perceptual session.

Table 3-2 showed the response time difference between ‘related’ and ‘unrelated’ words. For the low-demand cue detection session (perceptual), this difference remained constant across the different blocks – control, low-demand response and high-demand response block. In contrast, for the high-demand cue detection session (conceptual), the time difference increases in a similar faction during second and third blocks (low and high-demand response retrieval blocks) compared to control block. This result indicates that the high-demand cue detection, affected the reaction times of the ongoing task during the retention interval, independently of the type of manipulation for response retrieval. Meaning that only the manipulation of demand for cue detection differentially affected the performance of the ongoing task during the retention interval. However, this ‘cost’ was observed in terms of the relationship between the related and unrelated items, probably explained by an increase of reaction time for unrelated items (Table 3-1).

We did not expect any type of behavioural impairment of the ongoing task during the low-demand cue detection, however, results showed decreases in accuracy of the ongoing task during the retention interval (blocks 2 and 3) of both sessions (low and high-demand cue detection). It may be that participants engaged some attentional resources to respond to the task, even though it was thought to be low demanding. However, it is important to note that this paradigm used multiple retrieval cue items, which were not individually specified at the beginning of the experiment.

In the conceptual condition only a category name is given to denote a set of cues, the instruction given indicates a category (animal words), instead of naming each of the cues (cat, dog, etc.). In the same way, the perceptual condition does indicate a general feature to identify a prospective memory cue, 'upper case letter', resulting in an unspecific cue-action link, even when the instruction is very specific: 'press a given key when you see a capitalised word'. This situation may also have influenced performance (Ellis & Milne, 1996).

Perhaps, for the perceptual condition, the fact of not learning the exact prospective memory cue impacted the requirement of monitoring to detect the cue. But, to give such a specific instruction in this paradigm was not possible, because we used a list of prospective memory cues, consisting on different words with first letter in upper case. One alternative for improving the encoding of the cue would have been to use the same cue repeated ~60 times during the experiment. However, then the doubt arises of whether ERP modulations in response to a particular cue repeated many times over an experiment may then be associated to that particular event rather than to a prospective memory cue. In addition, habituation or familiarity may influence modulations observed in the Event-related potentials (Curran, 2000). However, using a large list of cues would increase the difficulty in the verification process (verify that the cue detected actually corresponds to a prospective memory cue), which is a variable that was maintained minimal in the present design. This point is very relevant to EEG experiments, because one of the methodological conditions required for a good quality EEG analysis is to have enough information (data points). For that reason the minimum number of prospective memory cues usually used in prospective memory EEG paradigms is between 30 and 60 events.

In summary, it was the manipulation of demands for cue detection, and not for response retrieval, that affected reaction times during the ongoing task. In addition, high-demand (conceptual) cue detection affected reaction times to a greater extent. The demands for response retrieval did not affect the reaction times of the ongoing task. This confirms the idea that monitoring during the retention interval is related to the control of attention required for cue detection, rather than holding the actual content of the intention or the demands required for response retrieval. Response retrieval may require other monitoring mechanisms, for example, the ones involved in the implementation of the right set of actions in response to an environmental demand.

3.5.2 Cue detection of prospective memory is facilitated by low-demand cue detection. However, high-demand response retrieval also increased cue detection accuracy. Why?

Perceptual distinctiveness or low-demand cue detection increased accuracy of the prospective memory task, even when the manipulation for the cue detection was subtle. Conceptual cues and the ongoing task stimuli were presented in upper and lower case, while perceptual cues were presented using upper case just in the first letter with the rest of the word in lower case. So perceptual cues are not markedly different from conceptual cues and from ongoing task stimuli in terms of physical features. This can be an advantage when replicating this study with electroencephalographic recording, to control for perceptual information given by the task, but it can also be a disadvantage if we consider that the Event Related Modulations explored in EEG studies are more evident when there is higher perceptual distinctiveness (West, Wymbs, Jakubek, & Herndon, 2003).

Predictions made relating to how the retrieval phase would be affected by the manipulations were partially met. Cue detection accuracy was higher for perceptually distinctive cues as predicted. However, we observed that the high-demand response retrieval based on conceptual information of the cue also had an effect on cue detection (according to the prediction, the accuracy for cue detection should not be affected by demands of the response retrieval). This increase of accuracy raised the issue of how semantic distinctiveness can be increased through the instructions given in the task (Ellis & Milne, 1996). An explanation for this result may be that the use of conceptual information, for the high-demand response condition of the conceptual condition, may have increased the categorical 'distinctiveness of the cues' by narrowing the set of possible cues, the instruction was to identify 'animal words' and to indicate if the animal had wings our four legs, thus the 'animal' category implicitly narrowed to birds and four footed animals. It is important to remember at this point that the response retrieval manipulation used for the perceptual condition was based on the perceptual information contained by the cue (length of the word), this manipulation seemed not to affect the accuracy of cue detection.

Manipulation of demands for cue detection did not affect the reaction times obtained during the prospective memory task, meaning that perceptual or conceptual distinctiveness was not associated to the timing of the responses. Manipulation of the executive control required for response retrieval affected the retrieval phase and not the retention interval (performance of the ongoing task). The results also showed that high-demand response retrieval were much slower than low-demand responses. As expected, this difference was independent of the manipulation for the cue detection. These results are consistent with previous studies, where manipulation of perceptual distinctiveness of the cue (cue detection) and association cue-intention (response retrieval) were done in separate experiments (Cohen et al., 2003; Cohen, West, & Craik, 2001).

3.5.3 Accuracy for response retrieval is greater for responses based on conceptual information rather than perceptual information. Why?

Accuracy for response retrieval was calculated only for the high-demand response block (the only block with two possible responses) and indicated if, after identifying the cue, the response retrieval was correct. Accuracy for response retrieval was calculated counting the number of correct answers out of the total number of cues detected. The results showed that accuracy for retrieval was higher when the response was related with the conceptual information of the cue. These findings support the idea that perceptual distinctiveness supports cue detection, while semantic distinctiveness supports the recall of the content of the intention. Cohen et al. (2001) explored this idea, proposing that data-driven (i.e. perceptual) processes primarily support the prospective component of prospective memory (cue detection), whereas conceptually driven processes primarily support the retrospective component of prospective memory.

The manipulation of the demand for response retrieval made for perceptual cues was based on perceptual information; the accuracy was lower when the retrieval was associated to perceptual information.

These findings support the idea that perceptual distinctiveness supports cue detection, while semantic distinctiveness supports the recall of the content of the intention.

In summary, the results are consistent with our proposal: the cost of maintenance of the intention during the retention interval is associated with cue detection difficulty, rather than with the content of the intention. This is based on the idea that the main element of monitoring during the ongoing task is associated to the executive control of attention in order to detect the right moment for the retrieval (cue detection). In contrast, executive resources during retrieval may be associated with the access (direct or indirect) to the response schemata.

3.5.4 Limitations

One aspect that requires further exploration is related to manipulations for intention retrieval. In the current design the intention retrieval manipulation was focused on different processes, based either on perceptual or conceptual information. Although, we were not looking for differences using different types of intention retrieval, we realised that using conceptual distinctiveness favours the retrieval. In other words, people did worse detecting conceptual distinctive cues, but when they found them, there was higher probability of retrieving the correct intention. In addition, we realised that giving the instruction of responding to the animal word by indicating if the animal had wings or four legs, also increases the conceptual distinctiveness of the cue, reflected in higher cue detection accuracy.

A clearer design could explore this issue further by creating similar demands in terms of the number of possible responses, still having different demands in terms of association cue-response but without using information that can be associated with the distinctiveness of the cue, for example indicating the length of the word for both the perceptual and conceptual conditions. Alternatively, another manipulation could be to vary the degree of semantic relatedness between the prospective cue and the intention (Cohen 2001), based on the idea that conceptually driven processes primarily support retrieval from memory. Despite this being a very interesting issue, the following experimental designs in this thesis are aimed at exploring the requirement of executive control of attention during the retention interval under different prospective memory situations, and the results showed that demands for cue detection, rather than demands for response retrieval, are associated with the requirement of attention during the retention interval.

3.5.5 Future work

The most consistent effect produced by the manipulations of the prospective memory was associated with varying demands for cue detection. We showed that there was a cost of holding the intention during the ongoing task, measured in terms of accuracy and similar for both, perceptual and conceptual cue detection conditions. We only observed a difference between conceptual and perceptual conditions (at the ongoing task level) in terms of reaction times, when we compared the difference between related and unrelated items, this difference was led by an increase of reaction time of ‘unrelated’ items. In addition, the detection of prospective memory cues was more accurate when based on perceptual information rather than conceptual information.

It may be argued that different types of event-based prospective memory tasks (conceptual and perceptual cue detection) use similar mechanisms to maintain the prospective memory intention during the ongoing task, but different mechanisms are used at the time of cue detection, when the detection is driven by either perceptual or conceptual information. If this is the case, we can think that similar monitoring processes are required to maintain different types of event-based prospective memory intentions during the ongoing task and maybe different mechanism of monitoring are devoted to checking or evaluating the stimuli once they are encountered. Chapter 2 of this thesis explained in detail how executive control of attention might be associated with monitoring mechanisms during the retention interval. Maybe other monitoring mechanisms are associated with verification of prospective memory cues and retrieval of responses during the intention retrieval phase. To explore these ideas further we propose an EEG experiment that will give us the possibility of studying the neural correlates of the different components of monitoring during ongoing and prospective memory tasks. We will modify the current paradigm to focus only on perceptual versus conceptual detection, since we proved that manipulations of demands for response retrieval are not (or less) related to the demands of monitoring during the ongoing task. This modification will also allow us to have a higher number of prospective memory cues for EEG analysis, considering that the amount of time points is a critical aspect to get good quality results.

Chapter 4
Differential contribution of brain sources depending on the attentional demands of the event-based prospective memory task: an ERP and ICA approach.

4.1 Abstract

Previous studies have shown that perceptual salience of prospective memory cues facilitates cue detection compared to conceptual distinctiveness. However, it is not clear how features of the prospective memory cues affect the requirement for monitoring during the intention maintenance period. In addition, it is not clear whether the EEG dynamics previously described in the literature correspond to general mechanisms associated with prospective memory or whether they correspond to mechanisms associated with detetion of perceptual features of the cue. In order to clarify these questions we studied the contribution of source brain activity to scalp electroencephalographic recordings in two prospective memory tasks, which varied in the attentional demands required to detect the prospective memory cue. The results showed enhanced early occipital negativity associated with maintenance of the prospective memory intention supporting the idea that, in experimental conditions, our brain deals with delayed intentions by constantly monitoring the environment for the occurrence of a target event, even in the absence of behavioural signs of task interference. This result contributes to the question of what monitoring means in prospective memory tasks. In addition, detection of prospective memory cues is supported by different mechanisms depending on the features of the cue; the N300 described in literature of prospective memory is associated with perceptual prospective memory cues, whereas the N400 is associated with conceptual ones. Finally, occipital and parietal areas are mainly involved in the response retrieval of perceptual prospective memory task, whereas midline (probably cingulate cortex) and frontal areas seem to support conceptual prospective memory task. The different brain sources participating in both conditions contribute to similar slow frontal and parietal positivities observed at the scalp level. These results support the idea that prospective

memory is not a discrete memory system, but rather an orchestration of attentional and executive systems.

4.2 Introduction

Prospective Memory is the ability to perform previously planned actions at the right time and place. This ability underlies many simple tasks in our daily life (Boelen et al., 2011; Kliegel, Mackinlay, et al., 2008) and failures are quite frequent. When prospective remembering is triggered by an external event it is called event-based prospective memory task. There at least two phases associated with event-based prospective memory tasks: cue detection (to identify the right moment to perform the action) and response retrieval (remember what the intention to be performed is).

Previous studies have shown that perceptual salience (e.g. colour of the target event) of prospective memory cues facilitates cue detection compared to conceptual salience (e.g. category of the target event) (Brandimonte & Passolunghi, 1994; Cohen et al., 2003), however, it is not clear how focusing on different features of the prospective memory cue affects the requirement for monitoring during the intention maintenance period. In addition, previous studies of prospective memory using EEG have used perceptual features to characterise prospective memory cues (West, 2011). Thus it is not clear whether the EEG dynamics previously described correspond to general mechanisms associated with prospective memory or whether they correspond to particular features of the task.

In order to clarify these questions we used electroencephalography and explored contribution of brain sources to scalp activity using Independent Component Analysis (ICA) to examine whether: (1) the requirement of monitoring during the intention maintenance interval is related with particular features of the prospective memory cue and (2) different brain mechanisms are required depending on the type of prospective memory task, thus prospective memory reflects a particular orchestration of attentional and executive mechanisms rather than a discrete memory system.

We used two types of prospective memory tasks, which varied in the cognitive demands required for cue detection, but maintained the same demand for intention retrieval. People were asked to respond to a continuous semantic categorisation task as a foreground ongoing task while holding a prospective memory intention that could be either: detect a prospective memory cue driven by perceptual information of the cue (Upper case letter) or by conceptual information of the cue (animal word). Each participant performed both prospective memory tasks in two counterbalanced sessions; prospective memory cues only corresponded to 10% of the total trials. The first block of each session corresponded to the performance of the ongoing foreground task only, which was subsequently compared to the performance of the ongoing foreground task plus the prospective memory intention.

Despite the detailed information obtained through the ERP technique associated with prospective memory tasks, there are methodological and technical issues that are not addressed in the prospective memory and ERP research. One example is that the electrical activity recorded by the scalp sensors, corresponds to a mixture of signals produced by many cortical patches perpendicular to the sensors and located at different parts of the cortex. Meaning that the activity recorded at each of the electrodes does not represent single cortical activation but rather a mixture of activity coming from different brain areas. Thus, from examination of the electrode alone is impossible to determine which brain sources are participating in the task, and also how they contribute to the processing of the stimuli in the different task conditions. An alternative to resolve this problem is the use of Independent Component Analysis (ICA), which is an algorithm able to identify source areas in the brain with nearly independent temporal activity (Makeig & Onton, 2011; Onton et al., 2006). Source localisation algorithms applied to the independent component activities increase the accuracy for brain source (dipoles) localisation. In the present experiment we used ICA to find brain sources contributing to scalp activity averaged and looked at: (1) ongoing task events only, called the ongoing task control, (2) ongoing task events during maintenance of the prospective memory (PM) intention, called ongoing task PM and (3) prospective memory task events, called PM task.

4.3 Materials and Methods

4.3.1 Participants

Twenty-five university students (age=23 years, SD=5.19, 16 females and 9 males) recruited from Glasgow University, all native English speakers, participated in the study. They received monetary compensation for their participation (£18). Ethical approval was obtained, and all participants provided informed consent prior to participation.

4.3.2 Procedure

Participants were required to perform the experiment in two sessions with one week in between. They performed two types of prospective memory tasks, which varied in the cognitive demands required for cue detection, but maintained the same demand for intention retrieval and the same foreground ongoing task. The stimuli used in both sessions were the same, the different cognitive demands required for cue detection were produced by giving different instructions for the prospective memory tasks.

The first part of each session consisted of performing the ongoing control task. During the second part of the experiment participants were given instructions for the prospective memory task and performed the ongoing task and the prospective memory task simultaneously. They were also asked to perform a ‘delay task’, immediately after the prospective memory instructions, with the aim of distracting participants from the delayed intention prior to the initiation of the ongoing prospective memory (PM) task (Figure 4-1). The delay task consisted of responding to numbers presented on the screen by pressing the same number on a response pad, as accurately and fast as they could.

Only 10% of the ongoing PM trials corresponded to prospective memory events, with the aim of emulating real life prospective memory tasks, where something non-routine has to be done after a delay.

4.3.3 Ongoing task

Participants undertook an ongoing task that prevented the continuous rehearsal of the intended intention. It consisted of a 1-back categorisation task, in which participants had to decide if the current word on the screen belonged to the same category as the previous word on the screen. Participants were instructed to press a key with their right index for ‘related words’ (when the word belonged to the same category) and to press a key with their middle finger for ‘unrelated words’ (word did not belong to the same category). The ongoing task was performed under two different conditions. An ‘ongoing control condition’, in which participants were naïve about the prospective memory instructions, and an ‘ongoing prospective memory (PM) condition’, in which participants had to perform the ongoing and the prospective memory task simultaneously. The ongoing control block consisted of 300 trials of 2 seconds. The ongoing PM blocks consisted of 600 trials. Participants had regular breaks every 20 trials. 10% of the 600 PM trials corresponded to prospective memory events, which were presented pseudo-randomly, to assure two prospective memory cues between breaks. The prospective memory cues were presented in four possible locations, trial 5, 9, 17 or 18.

4.3.4 Prospective memory task

Participants performed two types of prospective memory tasks. In one session participants were asked to press a response pad key with their left index finger in response to perceptual cues. In the other session they were asked to respond to conceptual cues. Note that the responses for the ongoing task were given with the right index and middle finger.

Perceptual cues were defined by the first letter of the word written in uppercase, for example ‘Toe’. Conceptual cues corresponded to animal words, which could be written either in upper or lower case, for example ‘pig’. The words of the ongoing task were also written in upper or lower case (Figure 4-1). The instructions included examples and a short practice trial.

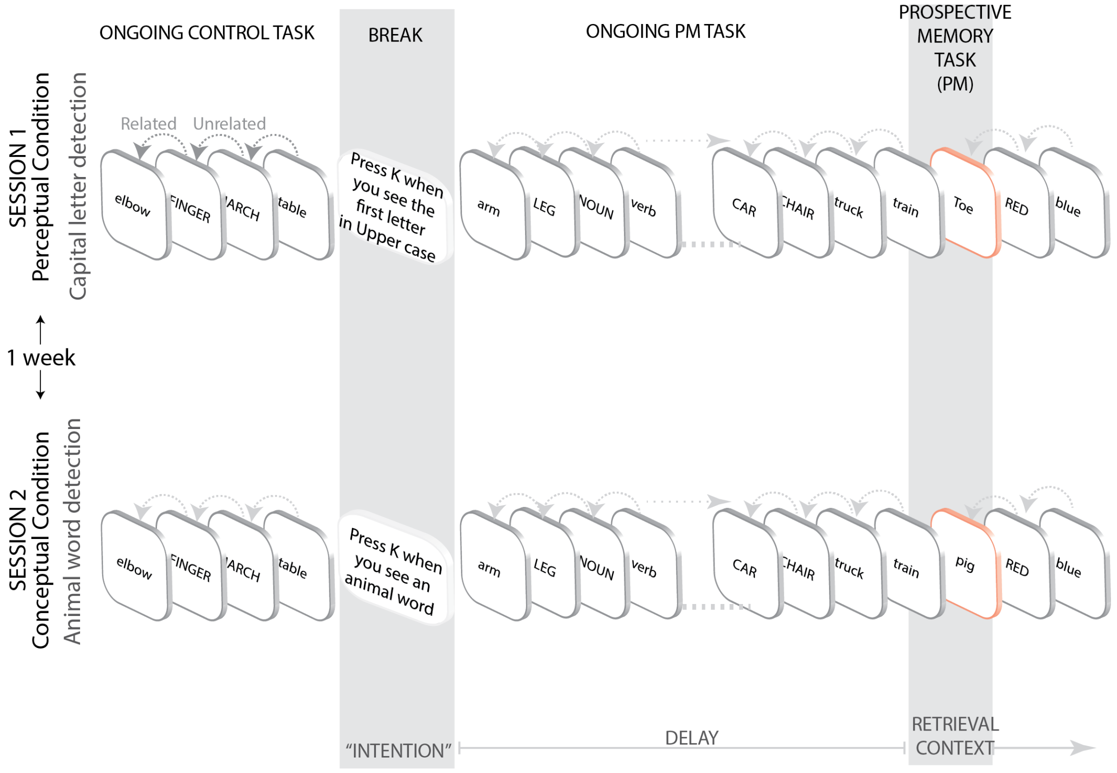


Figure 4-1. Experimental paradigm. Intention creation and retrieval context are shaded in grey. The retention interval (delay) was filled with the ongoing task. The top of the figure indicates labels for all the tasks: ongoing control, ongoing PM and prospective memory task. The delay task was performed immediately after giving the instruction (not shown in the figure). Related: Previous words belong to the same category. Unrelated: previous words do not belong to the same category. Words for the ongoing task and conceptual PM task were written in upper or lower case. Words for the perceptual PM task were written with only the first letter in upper case, for example 'Toe'. The instructions included examples and a short practice trial.

4.3.5 EEG recording

EEG data were recorded vertex-referenced using a 128-sensor Geodesic Sensor Net (Electrical Geodesics Inc.). The sensor net was soaked in a saline electrolyte solution and adjusted until all pedestals were properly seated on the scalp. Individual sensor impedances were adjusted until they were below 50 kΩ, (in some participants electrodes with impedances between 50 and 100 kΩ were kept). Data were sampled at 250 Hz with an analog filter bandpass of 0.1–200 Hz. A Macintosh computer running EGI's Netstation software was used for data collection. E-Prime running on a PC was used for stimulus presentation. Two four-button response pads (one for each hand) were used to collect finger press responses to stimulus events.

4.3.6 Behavioural data analysis

Behavioural performance in the experiment was examined using repeated measures ANOVA. To evaluate monitoring cost, or the cost of maintaining the prospective memory intention, accuracy and reaction times of the ongoing PM task were examined relative to the performance during the ongoing control task. Note that ongoing control and ongoing PM corresponded to the same task, with the only difference being that during the ongoing PM, people were instructed to also respond to prospective memory events. To examine the effect of the perceptual versus conceptual cue detection, accuracy and reaction times of the prospective memory tasks were compared using the performance of the ongoing task as a baseline, considering that the two conditions were performed on two different days.

The factors used for the repeated measures were: Block (control and PM) and Session (conceptual, perceptual). An additional factor was added to compare performance between ongoing tasks: Ongoing trial type (Related, Unrelated). Bonferroni correction was used for all post-hoc comparisons. SPSS software was used for behavioural statistical analysis.

4.3.7 EEG data analysis

The EEG data preprocessing and analysis were performed using EEGLAB (Delorme & Makeig, 2004) and code written in matlab. Data were visually inspected for bad channel removal. A high-pass filter at 1Hz (cut-off frequency of 0.5Hz) and a low-pass filter at 40Hz (cut-off 45 Hz) were applied to continuous EEG. The continuous data were cleaned as follows: Short-time high-amplitude artifacts were removed by statistically interpolating – in a sliding 1-second window – any principal components of the short-time EEG window. Criteria for removal was variance above a threshold of 15 or more standard deviations from the variance of uncontaminated EEG (taken from the cleanest part of the data). Each affected time point of EEG was interpolated by multiplying it by the interpolation matrix $I = M(V'\circ T)^{+}V'$ where M is a mixing matrix calculated from clean EEG, V are the principal components in the 1-

second window, and T is a matrix of 0's for every principal component above the variance threshold and 1's for every component below the threshold, respectively.

Adaptive model ICA (AMICA) was performed to decompose the continuous data into source-resolved activities. The data were segmented into epochs of two seconds with one second of baseline. Bad epochs were rejected using improbability method for channel measures (SD = 10) and IC activities (SD = 5). Equivalent current dipole estimation was performed using a Boundary Element Model of the MNI head model (DIPFIT). A plugin for EEGLAB used to fit dipoles to the topographical potential distribution of independent components (http://sccn.ucsd.edu/eeglab/dipfittut/dipfit.htmlold). Independent components from all participants were clustered using k-means with spectral power, ERPs and dipole location as clustering criteria.

4.3.7.1 EEG statistical analysis

The goal of the statistical analysis was to investigate if scalp ERPs show monitoring (ongoing PM task minus ongoing control task) and prospective memory effects (PM task minus ongoing PM task) in both session (Perceptual and Conceptual) and also which brain sources (or clusters) explain those effects.

Although our focus of interest was on the differences between the experimental tasks, before doing any task comparisons, we investigated if we would find any difference between 'related' and 'unrelated' words of the ongoing task. We carried out firstly a descriptive analysis comparing the envelope of the signal locked to 'related' and 'unrelated' words. We found that the temporal processing of these events differ between 300 and 600ms (see Figure 4-2), with 'unrelated' items depicting a negative deviation relative to 'related' items. Thus, the following inferential statistical analysis was performed on each event type separately. In addition, our focus of interest is not on the processing of semantically related or unrelated words, but on the effect that the intention maintenance has on the processing of those events and on how the temporal processing of the prospective memory events differ from the related and unrelated events. For these reasons we decided to perform simple effect t-tests using planned comparisons (Ruxton, 2008) between events occurring during the ongoing control, ongoing PM and prospective memory tasks, correcting for multiple comparisons using False Discovery Rate (FDR).

The EEG analysis followed two steps; the first step involved descriptive statistics and consisted of calculating the envelope of the difference between tasks and finding the main brain sources explaining the variance of the difference. We used the function *envtopo* (http://sccn.ucsd.edu/eeglab/allfunctions/envtopo.html) freely available in the EEGLAB website, which calculates the most positive and negative channel values at each time point of the difference. The envelope descriptive approach locates the time windows where there may be statistical differences. Then, we looked for the clusters that explained most of the variance accounted for (PVAF) in the time window where the differences were identified from the envelope results: PVAF=100x(1-var(Data-comp)/var(Data)). The second step in the analysis used inferential statistics performed on scalp average ERPs, obtained from back-projecting the activity of the brain sources toward the scalp, including and excluding the main contributing clusters found in the descriptive statistical step, the statistical test was applied to each of these projections. We used electrode sites that have previously shown prospective memory effects (West, 2011): electrode E59 (close to PO7), electrode E85 (close to PO8), electrode E62 (close to Pz) and electrode E6 (close to Fz). The statistical test performed corresponded to nonparametric permutation t-test, corrected for multiple comparisons using False Discovery Rate (FDR) at 0.01 significance level. In order to find the anatomical dipole location of the main contributing clusters, we obtained the coordinates of the centroids using the EEGLAB function std_dipplot (http://sccn.ucsd.edu/eeglab/allfunctions/std_dipplot.html) and used the Talairach Client software (http://www.talairach.org/client.html) to find the closest Brodmann area. The first (descriptive statistic) and second (inferential statistic) steps are explained in more detail below separately for the two effects of interest: Monitoring and Prospective Memory effect.

The Monitoring effect – or the temporal processing of ongoing task events during intention maintenance – was investigated by contrasting the signal locked to the ongoing task events while maintaining the PM task in a pending state (ongoing PM) minus the ongoing task only (ongoing control) (see Figure 4-3). The envelope of the difference between the ongoing PM and the ongoing control, showed that the greatest difference between the channel values are around the 200 milliseconds, thus we investigated which brain sources contributed to the difference in the time window 100 – 250 ms. The clusters that explained most of the variance accounted for (PVAF) in the indicated time window, were back-projected to the scalp along with the other brain clusters, excluding eye-movements. In order to confirm the contribution of the clusters to the monitoring effect, we performed a second back-projection, this time excluding the main contributing clusters (Figure 4-3). Scalp average ERPs for each session (Perceptual and Conceptual) were subjected to a nonparametric permutation t-test, to explore the difference between the ongoing PM and the ongoing control tasks separately for event types (related and unrelated), results were corrected for multiple comparison using False Discovery Rate (FDR). The statistical comparison was performed point-by-point in the time window -200 to 800ms (200 data points at 250 Hz sampling rate). The statistical differences between related and unrelated items were not within the scope of the present work.

Prospective Memory effect – or the temporal processing for detection and retrieval of delayed intentions – was investigated by subtracting the envelope of the signal locked to the PM events minus the envelope of the signal locked to ongoing events during the PM block. The envelope of the difference showed that the main differences may be found in two time windows 200-400ms and 400-800ms for the Perceptual condition and, in the time window 400-800ms for the Conceptual condition. Thus we investigated which brain sources explained most of the difference in those two time windows (Figure 4-4). The clusters that explained most of the variance accounted for (PVAF) in the indicated time windows were back-projected to the scalp along with the other brain clusters excluding eye-movements. In order to confirm the contribution of the clusters to the Prospective Memory effect we performed a second back-projection, this time excluding the main contributing cluster, see Figure 4-5 for the Perceptual condition and Figure 4-6 for the Conceptual condition. Scalp average ERP for each session (Perceptual and Conceptual) was subjected to a nonparametric permutation t-test to contrast activity between Related words versus Prospective memory events and Unrelated words versus Prospective memory events (the related and unrelated events included in this comparison were taken from the ongoing PM block, in order to exclude differences that may be explained by the monitoring effect). The results were corrected for multiple comparisons using False Discovery Rate (FDR). The statistical comparison was performed point-by-point in the time window -200 to 800ms (200 data points at 250 Hz sampling rate).

4.4 Behavioural results

4.4.1 Monitoring cost

The repeated measures ANOVA for the reaction times of the ongoing task revealed a main effect for event type, F(1,24) = 57.1, $p < 0.001$, partial eta squared = .7 (large effect), such that responses to 'related' events were faster than responses to 'unrelated' events. However, we also found an interaction effect between the three factors: event types (Related; Unrelated), session (Conceptual; Perceptual) and blocks (Ongoing Control; Ongoing PM), F(1,24) = 5.37, $p < 0.05$, partial eta squared = .183 (large effect). In the following post-hoc analysis, a new ANOVA was run separately for each session, using the factors block and event type, with significance level corrected at .05 divided by 2 (the number of tests for simple main effects), with the aim of exploring the interaction block x event type individually for each session.

Results of the Perceptual session again showed a main effect of event type, F(1,24) = 52.6, $p < 0.001$, partial eta squared = .678 (large effect), such that responses for 'unrelated' events were considerably slower than 'related' events, independently of the block (no main or interaction effect). This result suggests that the intention associated with detection of perceptually distinctive cues did not interfere with the performance of the ongoing task.

The conceptual condition, by contrast, showed a main effect for the event type, F(1,24) = 47.1, $p <0.001$, partial eta square = .663, plus a significant 'block x event type' interaction effect, F(1,24) = 23.8, $p < 0.001$, partial eta square = .498 (large effect size). The difference between 'related' and 'unrelated' events was associated with the block where the ongoing task was performed, 'control' or 'PM'. The post-hoc analysis showed that reaction times for 'related' events were similar in both control and PM block. However, reaction times for 'unrelated' events during the ongoing PM block were significantly slower compared to ‘unrelated’ events in the ongoing control block, F(1,24) = 8.7, $p < 0.01$, partial eta square = .266. This result suggests that the intention associated with detection of conceptually distinctive cues particularly affected reaction time of ‘unrelated’ events.

The accuracy of the ongoing PM task was not affected, relative to the accuracy obtained during the ongoing control task, meaning that no monitoring cost was observed in terms of accuracy for any of both conditions (Table 1).

In summary, the behavioural results showed that reaction times for ‘unrelated’ events (words that do not belong to the same category) were slower when people had to identify an animal word as the prospective memory cue (conceptual condition). In contrast, ‘related’ events had similar reaction times in both control and PM block. Meaning that only ‘unrelated’ items of the conceptual conditions showed monitoring cost. No behavioural signs of monitoring cost were observed for the perceptual condition. No monitoring cost in terms of accuracy was observed for either of the prospective memory tasks.

Table 4-1. Accuracy (%) and Reaction Times (ms) per session (standard deviation in parenthesis)

	Perceptual	Conceptual
Ongoing Control		
RT Related	712 (129)	687 (116)
RT Unrelated	788 (160)	752 (112)
Accuracy	95 (3)	95 (3)
Ongoing PM		
RT Related	716 (105)	687 (99)
RT Unrelated	801 (137)	791 (108)
Accuracy	94 (2)	95 (2)
Prospective Memory		
RT	697(88)	752 (87)
Accuracy	88(8)	78(14)

4.4.2 Cue detection

A repeated measure ANOVA for reaction times, with factors session (Conceptual, Perceptual) and event type (related, unrelated, and PM event), revealed a significant session x event type interaction, F(2,48) = 21.8, $p < 0.001$. Post-hoc results showed that perceptual cue detection was faster than conceptual detection ($p < 0.01$) and close to reaction times of ‘related’ events of the ongoing PM task in both conditions. In contrast, reaction time for detection of conceptual cues was similar to reaction time of ‘unrelated’ events of the ongoing PM task in both conditions.

Accuracy for the prospective memory task was lower than accuracy for the ongoing PM task, F(1,24) = 40, $p < 0.001$, partial eta squared = .629 (large effects). We also observed an interaction between tasks (Ongoing and PM) and sessions (Perceptual, Conceptual), F(2,48) = 15.9, $p < 0.001$, partial eta squared = .399. The post-hoc comparisons showed that accuracy for detection of conceptual cues was lower than all the other accuracy measures; all post-hoc comparisons resulted below 0.001 significance level.

In summary, the results showed that perceptual distinctiveness favours cue detection over conceptual distinctiveness. In addition, the average reaction time for perceptual cues was similar to the reaction times for ‘related’ events, whereas reaction time for conceptual cues was closer to ‘unrelated’ events (see table 1).

4.5 EEG results

We first describe the ICs clusters associated with the difference between ‘related’ and ‘unrelated’ items of the ongoing task (semantic effect). The subsequent sections show the ICs clusters accounting for the prospective memory effect at two stages of the prospective memory process: First, during the maintenance of the intention and second, when a prospective memory cue was encountered (cue detection and response retrieval).

4.5.1 Difference between ‘unrelated’ and ‘related’ events

The background ongoing task of the present experiment involved two types of event responses: ‘related’ and ‘unrelated’. The processing of both types of stimuli was similar until about 300 milliseconds (Figure 4-2A). The main differences between these events are observed between 300 and 600 ms. ‘Unrelated’ events have a stronger negativity in both conditions, Perceptual and Conceptual, with a main contribution from the central midline cluster. This negative modulation resembles the N400, which is associated with semantic processing (Figure 4-2B), and is consistent with a large body of research showing that ‘related’ items have reduced N400 amplitudes relative to ‘unrelated’ items in different experimental paradigms and across different modalities. For more detail see (Kutas & Federmeier, 2000).

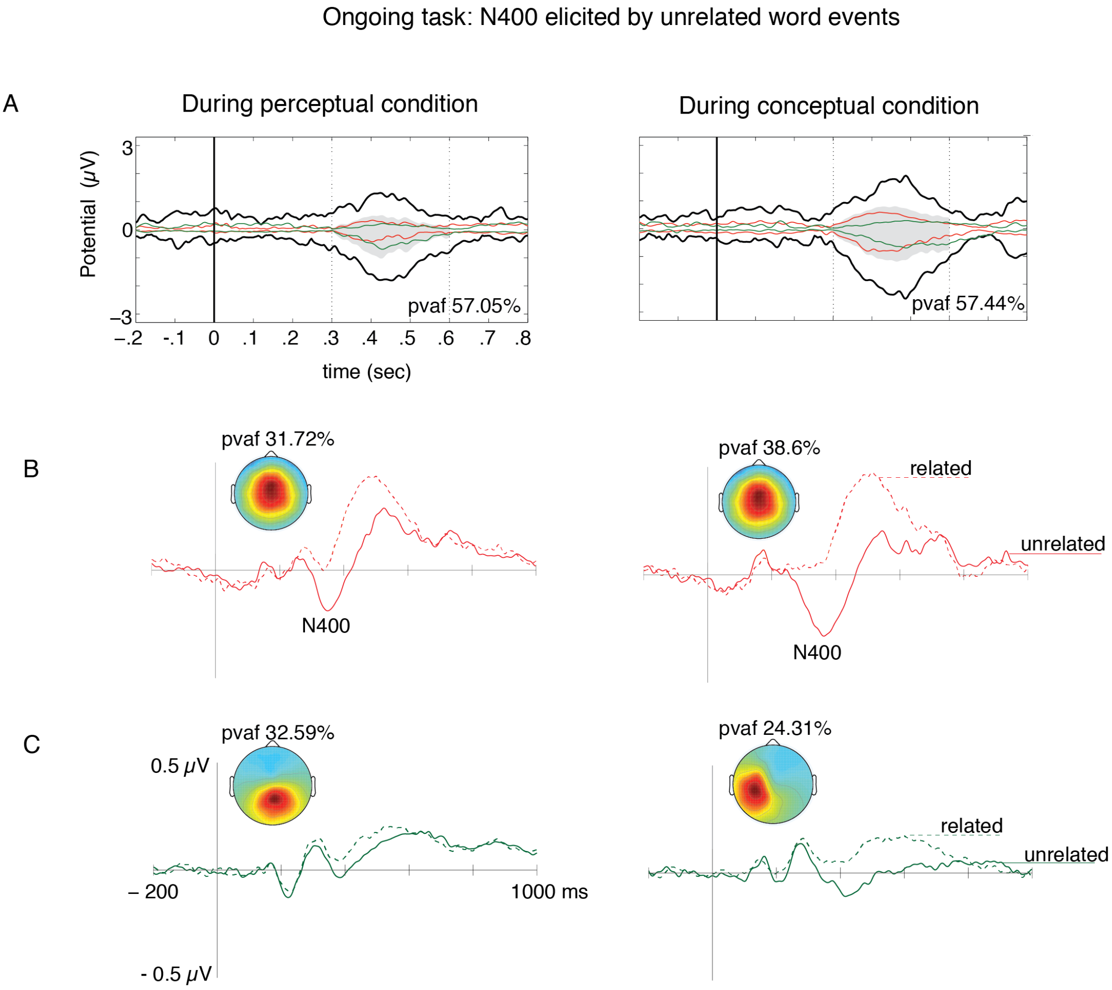


Figure 4-2. N400 elicited by unrelated words. (A) Envelope of the difference ERP between related and unrelated items of the ongoing PM block. Black traces of the envelope correspond to most positive and negative channel values at each time point of the difference between related and unrelated grand-meand ERP envelopes. Red traces indicate the contribution of the midline cluster to the difference (B). Green traces indicate the contribution of parietal clusters (C). The area shaded in grey is the envelope of the ERP data accounted for by the components of the two clusters together. (B) Scalp map and ERP of the frontal-midline cluster depicting the N400 for unrelated items. (C) Scalp map and ERP of the centro and left parietal clusters for the perceptual and conceptual condition respectively. PVAF: percentage of variance acounted for the cluster in the ERP data.

4.5.2 Maintenance of the intention during the ongoing task

To study maintenance of the intention during the ongoing task when different types of intentions were embedded, we explored the differences between the ongoing control and the ongoing PM task. Note that prospective memory trials were excluded from the ongoing PM task. Only correct responses were considered (as the error rate is low).

Figure 4-3 shows the increase of amplitude around the 200 ms for ongoing PM trials (related and unrelated collapsed) relative to the ongoing control task for both conditions, perceptual and conceptual cue detection. In both cases, the main source contributing to the modulation was the left-occipital cluster.

Note that the ongoing task is the same for both control and PM blocks, the only difference being that during the performance of the ongoing PM block participants monitored for the appearance of either animal words (conceptual condition) or capitalised words (perceptual condition). When the left-occipital cluster is excluded from the projection, the difference disappears completely for both conditions (Figure 4-3C), confirming that the difference observed at the posterior channel is mainly due to the activity detected at left occipital areas of the brain.

Differences between ongoing control and ongoing PM blocks were observed only before 300 ms. Thus, ‘related’ and ‘unrelated’ events were collapsed.

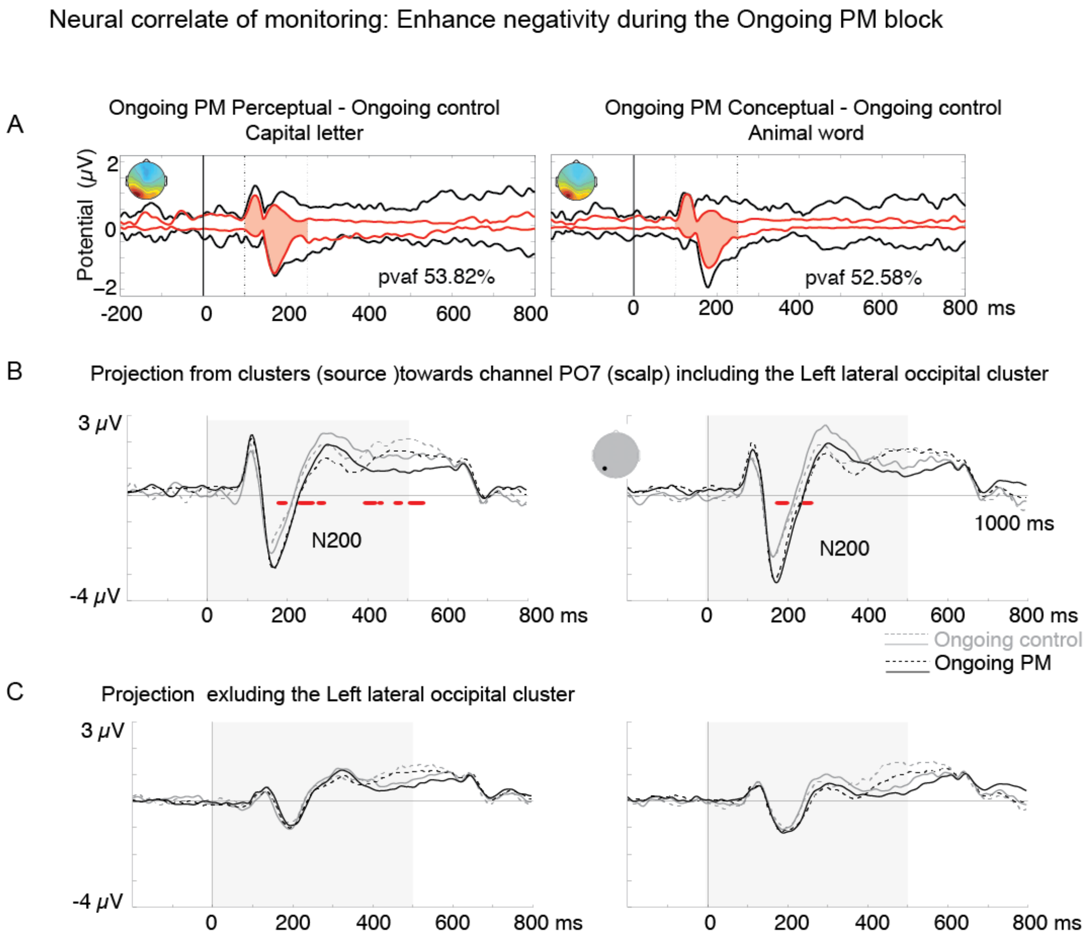


Figure 4-3. Negativity over occipital regions during performance of the Ongoing task. (A) Envelope of the difference ERP between baseline and ongoing tasks reveals a strong contribution of the left-occipital cluster in both conditions, perceptual and conceptual, between 100 and 250 ms. Black traces of the envelope correspond to most positive and negative channel values at each time point of the difference between ongoing control and ongoing PM grand-meand ERP envelopes. Red traces indicate the contribution of left-occipital cluster. (B) Scalp ERPs (PO7) resulted from the back-projection of all brain clusters (excluding eye-ICs and muscle-ICs) for both conditions, perceptual and conceptual. (C) After exclusion of the left-occipital cluster, the remaining negativity is much smaller. The grey area shows the onset of the words. Permutation t-test was applied to each data point on the complete time window (-200 to 800ms) corrected using FDR (p<0.01), red marks show differences between ongoing control and ongoing PM. PVAF: percentage of variance accounted for the cluster in the ERP data.

4.5.3 ERP modulations associated with prospective memory cues

We studied EEG modulations associated with prospective memory cues by examining the envelope of the difference ERP between the ongoing PM block and the prospective memory task in the two conditions, perceptual and conceptual (Figure 4-4). In addition, we back-projected brain activity to the scalp excluding eye-ICs and muscle-ICs (Figure 4-5 and 4-6) using as reference points scalp locations that have shown prospective memory effects (West, 2011): Fz, Pz, and PO8. We excluded the main contributing clusters from the back-projection to the scalp with the aim of confirming the contribution of the brain sources to the effects described, the result of the back-projections without the main contributing sources resulted in much smaller remaining effects.

4.5.3.1 N300 and N400

We observed a strong contribution of the right-occipital cluster between 200 and 400 ms in the perceptual condition (Figure 4-4,A-C). In contrast, the conceptual condition did not show differences for the same time window.

For the perceptual prospective memory task, back-projection of the whole brain activity to location PO8 showed an enhanced negativity for the detection of capital letters (Figure 4-5, left bottom ERP). This negativity resembles the N300, previously associated with detection of prospective memory cues based on perceptual attributes. This negativity disappears when the left-occipital cluster is excluded from the projection (Figure 4-5, right bottom ERP).

For the conceptual prospective memory task (animal word detection), differences between the ongoing PM and the prospective memory events only appear after 400 ms (Figure 4-4, E-G). Back projection to occipital scalp location (PO8) did not show the negativity observed in the perceptual prospective memory task (Figure 4-6, left bottom). However, projection to centro parietal area (Pz) and frontal area (Fz) showed a negativity around 400ms associated with detection of animal words and similar to ‘unrelated’ trials of the ongoing task. Note that both tasks, conceptual prospective memory and the ongoing task, require semantic categorisation for giving the response.

4.5.3.2 Parietal and frontal slow-wave scalp positivities

Conceptual and perceptual PM tasks each showed a positive slow-wave over parietal and frontal regions of the scalp (Figure 4-5 and 4-6). However, different brain sources contributed to the slow-wave positivity in each condition (Figure 4-4). For the conceptual condition the positivity was mainly produced by the frontal-midline cluster (Figure 4-4E) and spread over parietal and frontal regions. This cluster contributed to a lesser extent to the positivity observed in the perceptual condition, where the main contribution came from parietal clusters (figure 4-4), which produced the positivity observed at parietal and frontal sites. The onset of the perceptual positivity effect was also about 100ms earlier than the conceptual effect onset. When the main contributing sources are excluded from the back-projection, the frontal and parietal positivities are considerably reduced (Figure 4-5 and 4-6 right column). Thus, positivities observed at frontal and parietal sites result from a mixture of brain sources. In addition, similar-appearing scalp-channel positivities have different contributing brain sources.

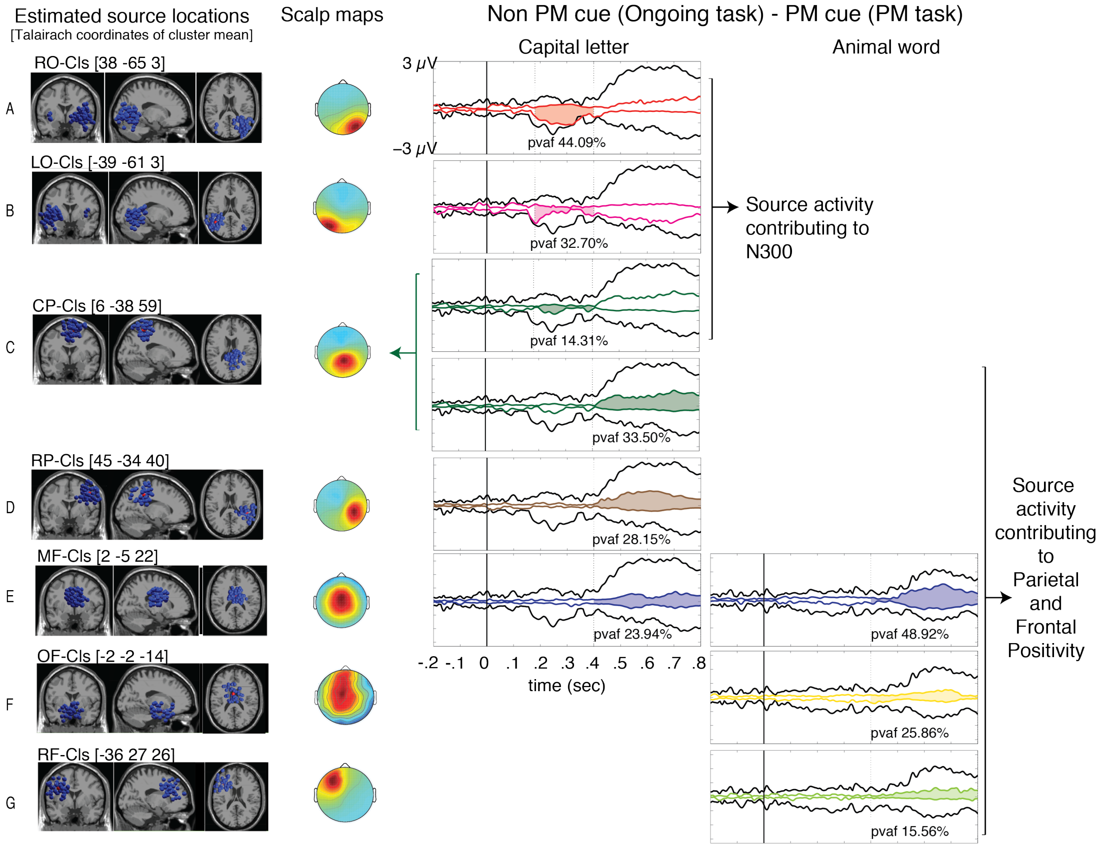


Figure 4-4. Differential contribution of source activity for capital letter and animal word conditions. Clusters accounting for most of the variance (higher pvaf) when comparing grand-mean ERP of the ongoing PM task relative to grand-mean ERP of the PM task (Ongoing PM minus PM task). Different colours are used to show the contribution of each cluster. (A-C) Envelope of the difference ERP reveals a strong contribution from occipital and centro-parietal regions between 200 and 400 ms in the perceptual condition. These clusters explain the enhanced negativity observed in the perceptual condition over occipital areas, labelled as N300 (cf. Figure 4-5). (C-D) For the perceptual condition, ERP differences observed after 400ms are mainly due to parietal clusters with smaller contribution from the frontal-midline cluster. In contrast (E), the frontal-midline cluster contributes most of the slow positivity beginning at 500ms in the conceptual condition, in addition to left-frontal (F) and orbitofrontal region (G). Black traces of the envelope correspond to most positive and negative channel values at each time point of the difference between ongoing control and ongoing PM grand-meand ERP envelops. Colour traces indicate the contribution of each individual cluster to the scalp ERP data. PVAF: percentage of variance accounted for in the ERP data.

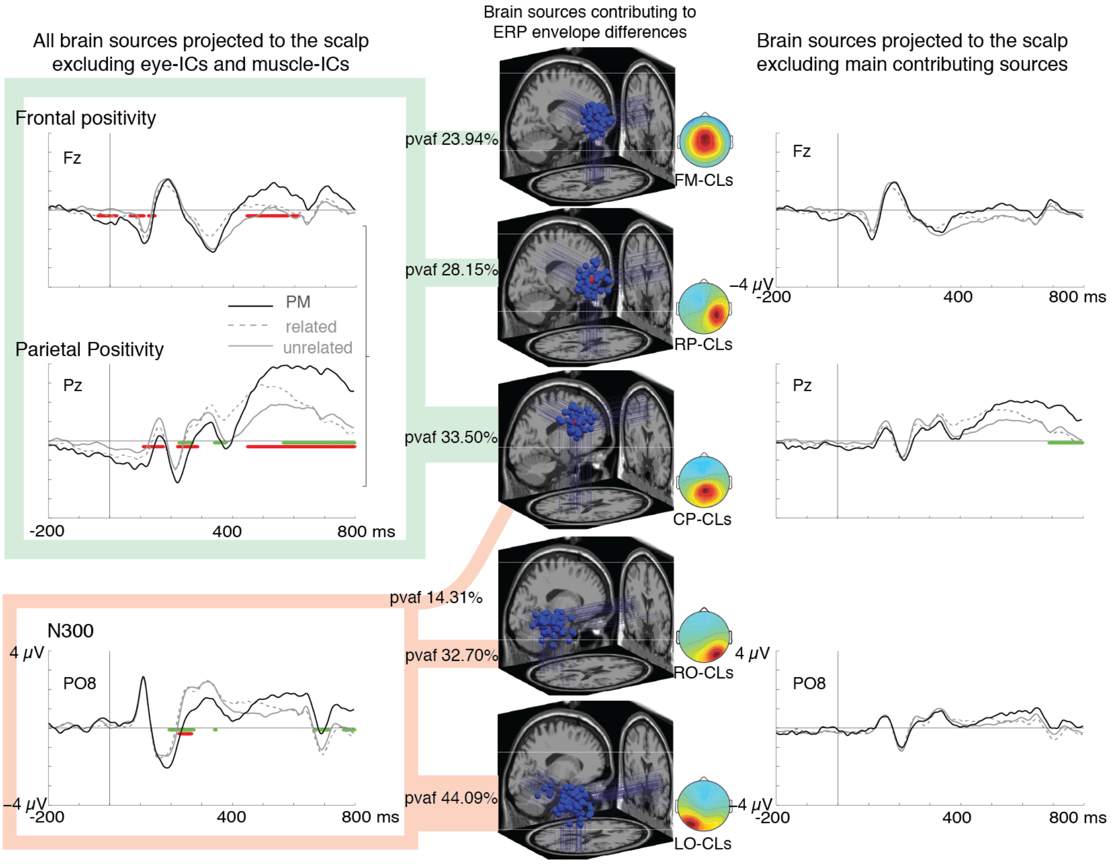


Figure 4-5. Perceptual (Capitalised word) ERPs and contributing brain sources. Left column shows source brain activity back-projected to scalp locations where prospective memory effects have been previously found (West, 2011). N300, Parietal and Frontal positivity are clearly depicted. The thickness of the lines indicates the contribution of each cluster to the scalp ERP, pvaf (percentage of variance accounted for) is also indicated. Note that Parietal and Frontal positivities result from a mixture of mainly parietal sources (fronto-medial cluster contributes in a lesser extent). The middle column shows estimated location for all the components of each cluster. Right columns show the resulting ERPs after excluding the main contributing clusters, occipito-parietal for the N300 and parieto-frontal for the positivities. Permutation t-test was applied to each data point on the complete time window (-200 to 800ms) corrected using FDR ($p<0.01$), red marks show differences between Unrelated items and prospective memory events, green marks show differences between Related items and prospective memory events. PVAF: percentage of variance accounted for the cluster in the ERP data.

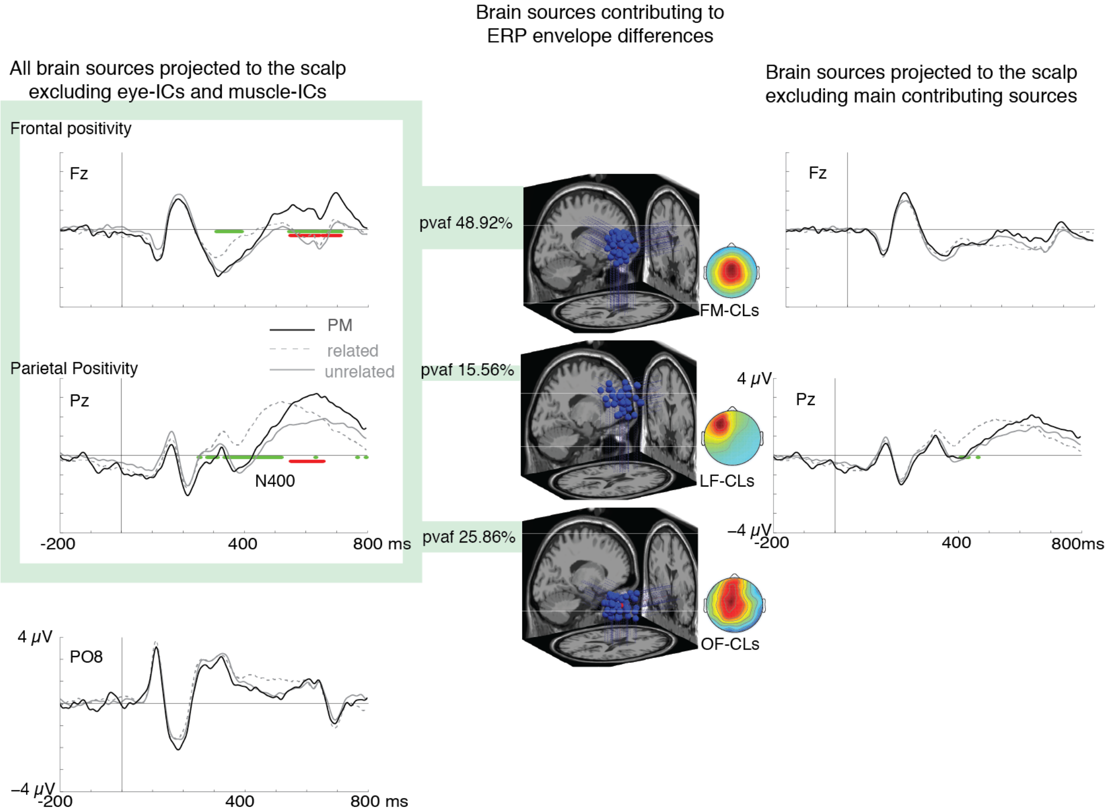


Figure 4-6. Conceptual (Animal word) ERPs and contributing brain sources. Left column shows source brain activity back-projected to scalp locations were prospective memory effects have been previously found (West, 2011). Only Parietal and Frontal positivity are depicted, the N300 is not observed for conceptual cue detection. The ERPs for cue detection closely follows the one of ‘unrelated’ items, showing the N400 as a probable indicator of conceptual cue detection. The thickness of the arrows indicates contribution of each cluster to the scalp ERP, pvaf is also indicated (percentage of variance accounted for). Note that the Fronto-medial cluster is the main contributing source, its probable location corresponds to the anterior cingulate cortex. The middle column shows estimated location for all the components of each cluster. Right columns show the resulting ERPs after excluding the main contributing clusters. Permutation t-test was applied to each data point on the complete time window (-200 to 800ms) corrected using FDR (p<0.01), red marks show differences between Unrelated items and prospective memory events, green marks show differences between Related items and prospective memory events. PVAF: percentage of variance accounted for the cluster in the ERP data.

4.6 Discussion

In the present experiment we addressed the following questions: (1) is attention required during a low demand prospective memory task? (2) Do two different prospective memory tasks share similar attentional mechanisms? (3) Does the ERP described in the literature on prospective memory reflect general mechanisms of prospective memory or particular mechanisms associated with perceptual event-based prospective memory tasks?

Our results showed that: (1) attentional monitoring is required even in the absence of behavioural signs of monitoring cost; (2) The requirement of monitoring during the intention maintenance interval is related to particular features of the prospective memory cue; (3) Different brain mechanisms are required depending on the type of prospective memory task, thus prospective memory reflects an orchestration of attentional and executive mechanisms rather than a discrete memory system. In addition, we showed that slow-wave prospective memory modulations observed at parietal and frontal sites of the scalp are produced by the same brain sources within either perceptual or conceptual session, but by different brain sources between sessions. These results are discussed in the following section.

4.6.1 Maintenance of the intention during the ongoing task

Based on the idea that we have a limited attentional capacity, we can suppose that if a prospective memory task is demanding there will be a certain level of impairment of the background ongoing task, because the maintenance of the intention and/or the monitoring for the prospective memory cue, would divert attentional resources from the ongoing task. This is the logic traditionally used to evaluate how effortful a prospective memory task is (Smith, 2010; Smith et al., 2007). In the present experiment we manipulated the difficulty of the prospective memory task by using two different prospective memory cues: one characterised by physical features (letter case) and the other characterised by semantic features (animal category). Two of the questions that motivated this design were: Is attention required during low demanding prospective memory task? Do different types of event-based prospective memory tasks share similar attentional mechanisms?

The behavioural results showed no evidence of monitoring or interference of the intention maintenance for the perceptual condition (letter case detection). In contrast, we observed reduced speed of responding to the ‘unrelated’ items during the conceptual condition. It seems that only the conceptual condition created interference. In addition, detecting capitalised words produced greater accuracy and faster reaction times compared to detecting animal words.

Slower responses can be a sign of fatigue. However, this possibility is unlikely if we consider that only ‘unrelated’ items of the conceptual condition showed this effect. Perhaps the increase in the reaction times reflected a monitoring process, considering that animal words were also ‘unrelated’ items for the ongoing task, thus to give a correct conceptual prospective memory response required inhibition of the ongoing task response. In contrast, the prospective memory response for the perceptual prospective memory cue did not require word categorisation; this is consistent with the reaction times (see Table 4-1)

If we interpret the behavioural results alone we would say that the conceptual condition was more effortful than the perceptual condition. The perceptual condition did not require continuous assessment of the ongoing events and the identification of the prospective memory cue (letter case) would be stimulus driven, thus requiring less monitoring. This would support the Multiprocess theory (Einstein et al., 2005), which states that depending on the nature of the prospective memory task, monitoring may or may not be required to detect a prospective memory cue. However, the use of ‘behavioural cost’ as a sign of monitoring is controversial (Einstein & McDaniel, 2010; Smith, 2010; Smith et al., 2007). In fact this interpretation is incomplete (and somewhat incorrect) without considering the EEG results.

For both conceptual and perceptual conditions, we found an enhanced negativity around 200ms with the highest contribution from the left-occipital cluster (Figure 4-4). Higher amplitude of ERPs over occipital areas has been previously interpreted as a sign of top-down attentional modulation (Knight et al., 2010); in other words, the activity in the occipital region would be modulated in order to enhance certain attributes of the expected visual stimulus. This enhanced negativity relative to the ongoing control block indicates that more cognitive resources are required to process the events in the ongoing prospective memory block, even in the absence of a behavioural indication of monitoring (as is the case in the perceptual condition). This interpretation supports the Preparatory Attention and Memory processes (PAM) theory (in contrast with the previous interpretation based only on behavioural data). The PAM theory states that preparatory attention is always required to detect a prospective memory cue (Smith & Bayen, 2004; Smith et al., 2007).

In the case of the perceptual condition, brain activity is modulated in order to facilitate detection of capitalised words, which relies on physical features of the task stimuli. The demands of the perceptual conditions were not enough to produce impairment of the ongoing task. However, the enhanced negativity can be a sign of monitoring or preparatory attention. If we explain the enhanced negativity as a result of modulation of brain activity to facilitate processing of certain physical features, we would expect to find this negativity associated only with the perceptual condition. However the same phenomenon is present in the conceptual condition. Interestingly, the mean of the left occipital cluster is located close to the caudal portion of the left fusiform gyrus (left occipitotemporal area, Talairach coordinates: -39 -61 3). Activity in this area has been associated with memory (Leube, Erb, Grodd, Bartels, & Kircher, 2001), language and visual processing of stimuli (Blonder et al., 2004). Previous work showed that this area is activated during semantic categorisation (Thioux, Pesenti, Costes, De Volder, & Seron, 2005), which is the nature of the ongoing task performed in this experiment. The use of prospective memory cue detection based on the meaning of the word may elicit stronger activity in areas related to categorisation of words.

In summary, both cues (perceptual and conceptual) are visually processed and we interpret the enhanced negativity with a source in the left occipital lobe as a neural correlate of monitoring that is caused by defining a prospective memory cue in terms of the features of the visual stimuli used in the ongoing task. In a different experiment performed in our laboratory, we used the same ongoing task in addition to a time-based prospective memory task, and observed activation in the same area (caudal portion of the left fusiform gyrus) but enhanced activity was not observed during the ongoing prospective memory block. In that case the prospective memory task was associated with time estimation instead of assessment of the ongoing stimuli (chapter 5).

One aspect that requires further analysis is the fact that only ‘unrelated’ items of the ongoing task under the conceptual condition showed increased reaction times. In the EEG analysis performed we did not observe any feature of the ERPs associated with this delay. Please note that we focused the analysis of the ERP on amplitude of the signal and source of the modulations. A detailed analysis based on the latencies of the ERPs may shed more light on this aspect.

4.6.2 Differential mechanisms facilitate cue detection depending on the nature of the event-based prospective memory cue: the N300 and N400

We observed an enhanced negativity around 200ms only in the perceptual condition, which lasted until 400ms. This negativity resembles the N300, which has been previously described as a neural correlate of cue detection. The right-occipital cluster explains most of the effect, with contribution from left-occipital and centro-parietal clusters (Figure 4-4). Note that the mean location of both occipital clusters is located close to the Brodmman area 37 (caudal portion of the fusiform gyrus) and the centro-parietal cluster shows its mean in the Brodmman area 5 (superior parietal lobe), which is part of the dorsal attentional network (Corbetta & Shulman, 2002). This region is associated with top-down attentional modulations and it is probably responsible for attentional modulation observed over sensory areas (Shomstein, 2012).

For the conceptual condition the target was an animal word and we did not observe the enhanced negativity elicited in the perceptual condition. However, we observed an N400 similar to the one shown by ‘unrelated’ items of the ongoing PM events (Figure 4-6). The ERP modulation of the conceptual prospective memory cues closely follows modulation of the unrelated items, at least between 200 and 400ms. Plus, the main cluster contributing to the positivity over parietal and frontal regions is the frontal-midline cluster, which also contributes most to the differentiation between ‘related’ and ‘unrelated’ items (Figure 4-2). The detection of the conceptual cue occurred later in the temporal processing of the events and was not associated with early features of the word, but to more complex cognitive processes, such as the extraction of the meaning of the word. It is possible that the same semantic processes used to identify ‘unrelated’ items in the ongoing task mediate detection of conceptual prospective memory cues, thus the differences reflect response retrieval and response implementation.

To summarise, we think that the early modulations observed in perceptual event-based prospective memory designs are associated with detection of perceptual cues rather than general mechanisms of prospective memory processes. In other words, the N300 is a modulation particular to the use of perceptually distinctive cues; when the prospective memory task does not use perceptual cues, the N300 is no longer observed. Detection of conceptual prospective memory cues is mediated by the N400.

4.6.3 Scalp parietal and frontal positivities share the same brain sources

The slow-wave positivity observed at different scalp sites (Figure 4-5 and 4-6) were found to have the same brain sources (Figure 4-4), which is confirmed by subtracting the main contributing clusters to the back projections. The scalp positivities observed at frontal and parietal sites have been associated with detection of prospective memory cues and response retrieval respectively. We will discuss these positivities in terms of the clusters contributing to them, rather than the locations on the scalp, because the results showed that slow-wave positivities at frontal and parietal scalp locations are a mixture of the different brain source activity relevant for the performance of the prospective memory task, thus they do not represent different cognitive processes. We propose that these brain sources are the responsible for verification of the prospective memory cue and response retrieval, probably mediating processes associated with shifting attention from the ongoing to the prospective memory task, inhibition of the response for the ongoing task or activation of motor schema associated with the response required by the prospective memory task, resulting in pressing a button different from the one used in the ongoing task.

Previous ERP and prospective memory research has associated the slow-wave positivity at frontal scalp sites with cue detection (West et al., 2001; West & Krompinger, 2005) and it seems to be tightly coupled with the N300. In the present experiment, only the perceptual condition showed the N300 and the frontal positivity started around 300ms relative to the 'unrelated' items (fig 4-5). We think that the scalp frontal positivity is a result of activity originated in sites far from the frontal regions itself, but probably its association with perceptual cue detection is not completely inaccurate, considering that it shares with the N300 the centro-parietal brain source (Figure 4-4). The relevance of this cluster to detect perceptual prospective memory cue is discussed in the following section.

4.6.4 Cue verification and response retrieval: slow-wave positivities of the perceptual and conceptual condition are similar on the scalp but have different sources

For the perceptual condition, the main contributing clusters that explained most of the effect observed after 400ms corresponded to the centro-parietal cluster (with cluster mean estimated in the superior parietal cortex, BA5) and the right-parietal cluster (with cluster mean estimated in the right parietal cortex, BA40), which corresponds to a portion of the Temporo-Parietal Junction (TPJ), this area has been indicated as one of the possible neural sources of the P300 (Geng & Vossel, 2013).

The superior parietal cortex and the TPJ have been shown to be part of the dorsal and ventral attentional system respectively, the first associated with goal-directed attention and the second to stimulus-driven attention. Activation of these areas seems to modulate the activity observed over sensory regions (Shomstein, 2012), as is the case of enhanced negativity (N300) associated with the detection of perceptual prospective memory cues (Figure 4-5).

Shomstein et al. (2012) reviewed the function of the parietal cortex on attentional modulation and stated that the superior parietal cortex is involved in enhancing processing of stimulus features that are relevant for the performance of the task (top-down attentional modulations) (Corbetta & Shulman, 2002). In the present experiment the relevant feature of the cues was a capitalised letter. In turn, activity in the TPJ would be triggered (modulated by the superior parietal cortex) when the relevant feature is encountered in a cue. As a result, the presence of capitalised letter would capture attention (stimulus-driven attention), with the subsequent shift of task setting from the ongoing task to the prospective memory task.

Activity in the TPJ has been associated with shifts in attention produced by external stimuli that contain features relevant for task decisions (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta & Shulman, 2002). Activity in this area has been found in experiments that use highly salient and unexpected external cues that drag attention towards the stimulus, though this is not the case in the present experiment. However, activity in this area may be an indication of a shift of attention (Posner & Dehaene, 1994) from the ongoing task towards the prospective memory task.

Another finding that supports this interpretation is that the positivity projected towards the parietal site Pz (Figure 4-5) resembles the P3b, which originates from activity in temporal–parietal areas (Geng & Vossel, 2013). One interpretation of the P3b is that it reflects contextual updating based on external stimuli. In other words, a stimulus prompts the modification of the task settings (for instance, the capitalized word requires a prospective memory response, instead of category classification). In this case, the prospective memory cue does not clearly require a reorientation of attention but indicates that an update of context is required to set following actions.

In summary, the contribution from the parietal cluster to the slow-wave positivity may reflect detection of the perceptual prospective memory cues and updating of the task setting. These results are in line with the finding described by West and collaborators (2011).

The parietal clusters are not the only contributors to the positivity in the perceptual condition; the frontal-midline cluster also participates, though to a lesser extent compared to conceptual condition. In the following paragraphs we explain why we think that the participation of this cluster probably reflects processes associated with response retrieval.

At first sight, the slow-wave positivity of the conceptual condition may seem similar to the one observed in the perceptual condition. Note that in the conceptual condition the main cluster contributing to the positivity is the frontal-midline cluster, with its estimated mean location close to the anterior cingulate cortex (Brodmman area 24) (Figure 4-4 and 4-6). In addition, the positivity observed in Pz for the conceptual condition is smaller compared to the perceptual condition. Parietal sources (associated with origin of the P300) are absent from the positivity in the conceptual condition, thus cognitive processes such as detection of cue and updating of task context (associated with the P3b in the perceptual condition) may not be present. In the conceptual condition the ‘contextual update’ of the task is not necessary, since both ongoing and prospective memory tasks require categorisation of words (this may explain the small contribution from parietal clusters that caused the parietal positivity in the perceptual condition).

The N400 of the conceptual prospective memory cues is similar to the N400 of the ‘unrelated’ items, implying that the cue has been recognised as an ‘unrelated’ item, thus the subsequent process is to inhibit the response given for the ongoing task and to give a prospective memory response (press the ‘animal word’ key instead of the ‘unrelated’ item key). Thus, the positivity originated in the Frontal midline cluster may be indicating the retrieval of the correct response.

The slow-wave positivity in the perceptual condition receives contribution from the frontal midline cluster as well, suggesting that this region may mediate the retrieval of the prospective memory response, independently of cue detection. The frontal-midline cluster (with estimated location in the anterior cingulate cortex) has been associated with executive-control (Carter et al., 1999; MacDonald et al., 2000), working memory (Onton et al., 2005), attentional shift (Kondo, Osaka, & Osaka, 2004) and mediating responses to visual targets (Makeig, Delorme, et al., 2004).

The other frontal clusters that contributed (to a lesser extent) to the slow-wave positivity are the left-frontal (with estimated mean source in the Brodmman area 9) and a deep frontal cluster. Their main dipole location is difficult to estimate, but it is probably part of the medial temporal lobe (BA 34) or the ventral anterior cingulate cortex (BA 24), note that in equivalent dipole fitting, depth is the dimension of least certainty (Akalin Acar & Makeig, 2013). Brodmman area 9 has been shown to participate in prospective memory tasks and also in planning (Fincham, Carter, van Veen, Stenger, & Anderson, 2002), however this area contributes in a small portion to the positivity (Figure 4-4).

A final point that we will make in relation to the response retrieval is that response in the conceptual condition necessarily occurs after the categorisation of the word (N400). By contrast, the perceptual cue is identified earlier than the conceptual cue (N300), and in this case the categorisation of the word is not required (if the word is capitalised, it is a prospective memory cue, independent of the category the word). So the response retrieval occurs early in the perceptual condition. Reaction time and onset of the slow-wave positivity are concordant with this description.

In summary, the frontal-midline region (probable anterior cingulate cortex) is related to response retrieval in event-based prospective memory tasks (using perceptual and conceptual cues), the recruitment of parietal areas is only observed in the case of perceptual event-based prospective memory tasks, and are probably associated to contextual update and detection of relevant features of the prospective memory cue.

4.6.5 Contribution of the current work to the debate on prospective memory theories

As mentioned earlier, one of the topics still under debate relates to the requirement for preparatory attention to recognise prospective memory cues and retrieve the delayed intention. The results of this experiment show that top-down attentional modulations are observed during the performance of an ongoing task (reflecting, we hypothesise, maintenance of the intention), even in absence of behavioural interference, supporting the idea that some kind of preparatory attention mediates cue detection in low-demand prospective memory tasks. We believe that one is more likely to encounter monitoring or preparatory attention in experimental conditions rather than in real life situations, first because of the relatively short period between the instruction and the execution of the prospective memory task and second, because of the repetition of the prospective memory trials in order to obtain sufficient data points for posterior analysis.

It is unlikely that in the short time period used in experimental prospective memory tasks participants forget about the prospective memory instruction to the same extent as occurs in everyday activities with very long delays between intention formation and action. Indeed, most of the time participants reported that they maintained the instructions in the 'back of the mind'. To explore if prospective memory cues are detected without preparatory attention, detection should be measured in conditions where participants are not expecting the prospective memory cue.

We show evidence that the preparatory attention is not necessarily observed in behavioural terms and participants can use strategic monitoring as a strategy without being aware of it. The modulations observed in the present experiment are very early in the timeline of the stimulus processing, in a time window where processes are traditionally associated with sensory processing more than cognitive processes. Thus, we believe that the concept of preparatory attention and automatic processes in prospective memory deserve a detailed definition, since there is extensive evidence from neuroscience that shows that complex features of stimuli are processed at very early stages and far from awareness (Koch & Tsuchiya, 2007; Okuda et al., 2011; Sklar et al., 2012; VanRullen & Thorpe, 2001a, 2001b; Vuilleumier & Driver, 2007).

4.6.6 Limitations of the study

The use of an ongoing task with two types of events, 'related' and 'unrelated', made it more difficult to identify the modulations associated with the prospective memory cue and the 'unrelated' event was similar to the conceptual prospective memory cue. Thus, a simpler paradigm requiring completely different cognitive processes for the ongoing and the prospective memory cue would contribute to support the finding presented in this chapter. In addition, a new task using the same rationale of prospective memory detection (based on perceptual and conceptual attributes) but using images or pictures may complement the present experiment by extending the finding to non-English speakers.

In terms of the methodology used for this experiment, the grand-mean ERP does not mean that all the trials in the experiment and all the cluster activities showed the same modulations. A more detailed trial-to-trial analysis and a single subject approach is required to approach this issue. In addition, the use of clustering to group independent components of all participants resulted in some clusters not containing all participants, the reason why some participants do not contribute in a cluster is not clear, it may be that the participant did not show the involvement of that brain region or because of quality issues of the brain signal.

4.6.7 Conclusion

Top-down attentional modulation is required during performance of experimental ongoing tasks to detect event-based prospective memory cues (evidence of monitoring).

The scalp negativities and positivities observed in the two types of prospective memory tasks reflected different cognitive processes, depending on the form of prospective memory cue. Perceptual cues led to greater cue detection, associated with the N300, and parietal areas were involved in contextual update and detection of relevant features of the prospective memory cue. For conceptual cue detection, the N400 reflected cue detection, and no contextual update was required since both ongoing and PM tasks were mediated by semantic processes. The frontal-midline cluster was the only cluster common for both types of event-based prospective memory tasks, suggesting that this region is probably related to response retrieval.

4.6.8 Future work

A relevant finding of this work is related to the strategic monitoring during the ongoing task. The two types of prospective memory tasks produced similar effects on the ongoing task, leading us to think that there are general mechanisms for monitoring associated with event-based prospective memory tasks. But, what happens if the prospective memory task does not use specific events to indicate the right moment for the intention retrieval and instead uses time? In this case we should observe other mechanisms of monitoring to maintain the prospective memory task ‘in mind’, and those mechanisms may be more demanding or require more executive control than the case of monitoring for a specific cue to occur. The following questions will lead the following experimental chapter: (1) what are the brain sources and dynamics involved in absence of external cue to trigger delayed intentions? (2) Are monitoring (attentional) mechanisms common to time-based and event-based prospective memory tasks? (3) How is the ongoing task affected when it has a time-based prospective memory task embedded?

Chapter 5
Time estimation and executive control of attention as the main components of monitoring during time-based prospective memory tasks: an EEG and ICA approach.

5.1 Abstract

The execution of time-based delayed intentions is initiated in the absence of an external event. Theories in prospective memory propose that time-based intentions are self-initiated based on strategic monitoring, which may require active maintenance of the intention plus external time checking. However, what the nature of strategic monitoring is and how it operates has not been clearly defined. The present experiment was designed to answer the following questions: What does monitoring mean, and what are the mechanisms underlying intention maintenance, in time-based prospective memory task? Participants were asked to reset a clock every 4 minutes, while performing a foreground ongoing word categorisation task. They were also allowed to check the time as much as they needed with the only constrain of maintaining a good performance in the word categorisation task. EEG activity was recorded during the performance of the task. Behavioural results suggested that participants used internal time estimation during the first minutes and switched to external time estimation (clock checks) towards the 4-minute target time. EEG analysis showed that brain activity with a source in the anterior cingulate cortex was the main candidate for maintaining this strategic performance in the time-based prospective memory task. We propose that time estimation and executive control of attention are the mechanisms underlying strategic monitoring in time-based prospective memory tasks, by means of activity in the anterior cingulate cortex.

5.2 Introduction

Many of our daily life activities involve execution of non-routine intentions, such us: attending a meeting, taking a child to the doctor or calling a friend on her birthday. Successful performance of these activities is relevant to fulfilling our life roles. Failures in prospective memory are common in neurological conditions and therefore, a key issue in cognitive rehabilitation (Boelen et al., 2011; Fish et al., 2010) and an increasing area of research (Ellis & Freeman, 2008; Ellis & Kvavilashvili, 2000; Fish et al., 2007).

Research in prospective memory has been centred on event-based prospective memory tasks (e.g. remember to give a message to a colleague when you see her in the corridor), meaning that an environmental event signals the moment to retrieve the intention. Less attention has been placed on time-based prospective memory tasks (remember to call someone in 10 minutes), when the retrieval of the intention is signalled by the passage of time.

It has been proposed that time-based prospective memory tasks are more demanding and require higher levels of monitoring compared to event-based prospective memory tasks (Henry, MacLeod, Phillips, & Crawford, 2004). The word 'monitoring' is commonly used in prospective memory tasks that rely on internal strategies for successful performance. Guynn's Monitoring Theory (2008) defines two components of monitoring: (1) the retrieval mode, which is a sustained process that reflects an active maintenance of the intention and (2) target checking, an intermittent process associated with the evaluation of environmental cues that could match with a prospective memory cue (Guynn, 2003; Guynn, 2008). As stated by the Monitoring Theory, the retrieval mode, in time-based paradigms, can be measured in terms of an impaired performance on the ongoing task when compared to a control condition, and target checking would be reflected by clock checks performed during the task. To the best of our knowledge, Guynn has not tested her theory on time-based paradigms. In addition, although the theory describes how prospective memory may operate, it lacks a detailed description of the neural correlates or brain mechanisms associated with these components of monitoring. For more detail on theories of prospective memory see section 1.4 and 1.6 in Chapter 1 of this thesis.

In general, intention maintenance is associated with activity in frontal brain regions (Cona et al., 2012; Okuda et al., 2007), particularly Brodmann area 10 (BA10). Medial BA10 and anterior cingulate cortex seem to be more activated in time-based tasks relative to event-based paradigms (Okuda et al., 2007). Anterior cingulate cortex also participates in other tasks with time estimation demands (Rubia, 2006; Rubia & Smith, 2004). In summary, the evidence shows that differential regions of the prefrontal cortex are involved in time-based prospective memory tasks relative to event-based paradigms. However, these studies have focused on cumulative changes during the maintenance phase (imaging functional magnetic resonance and positron emission tomography), rather than trial-locked activity. Only one study has used electroencephalography in a time-based paradigm. Based on ERP analysis Cona et al., (2012) showed greater voltage in activity over frontal electrodes during the maintenance phase, though they did not explain how this frontal positivity may be associated with monitoring, specially considering that processing of ongoing task events is irrelevant in time-based prospective memory tasks (unlike event-based prospective memory tasks where processing of the ongoing events is fundamental to identifying the prospective memory cue). From this perspective, it is difficult to know what is the exact contribution of frontal areas for the performance of time-based prospective memory tasks. The use of high-temporal resolution methods such as EEG is a good alternative to overcome these difficulties. The present experiment was designed to answer the following questions:

i. How is the ongoing task affected when it has a time-based prospective memory task embedded? This is related to the broader question of, what are the attentional mechanisms required for maintenance of time-based prospective memory intentions?
ii. What EEG measures are associated with the passage of time in a time-based PM task, if any? This is related to the broader question of whether monitoring is associated with time perception.
iii. Are attentional mechanisms common to time-based and event-based prospective memory tasks?

To answer these questions we ran an ongoing task under two different conditions, in the absence of the prospective memory intention (ongoing control) and with the addition of a time-based prospective memory intention embedded (ongoing PM). The prospective memory task consisted of resetting a clock every 4 minutes. The ongoing task used for this experiment was the same as the one used in the previous experiment in this thesis (Chapter 4), with the aim of comparing involvement of brain sources and dynamics of the ongoing task with different prospective memory tasks embedded. Independent Component Analysis (ICA) was used to identify the source of brain activity associated with the time-based prospective memory task.

5.3 Materials and methods

5.3.1 Participants

Twenty-four university students participated in the study, (mean age=21 years, SD=5, 13 females and 11 males) recruited from Glasgow University, all native English speakers and right handed. They received monetary compensation for their participation. Ethical approval was obtained (CSE01307), and all participants provided informed consent prior to participation.

5.3.2 Ongoing task

Participants undertook an ongoing task that, as in daily life PM tasks, prevented the continuous rehearsal of the intended intention. It consisted of a continuous 1-back categorisation task, in which participants had to decide if the previous word on the screen belonged to the same semantic category as the current word on the screen. Participants were instructed to press a key with their right index finger for ‘related words’ (when the word belonged to the same category) and to press a different key with their middle finger for ‘unrelated words’ (when the word did not belong to the same category). For more details see Chapter 4.

5.3.3 Prospective memory task

Participants were instructed to reset a clock every four minutes by pressing a key with their left index finger. A timer showed up in the centre of the screen every time participants reset the clock, showing the exact time in minutes and seconds counted from the previous clock reset (MM:SS). In addition to the clock-reset instruction, participants were also told that they could check the passage of time. To do time-checks participants were instructed to press another key on the response pad (with their left middle finger). Time-checks displayed the same timer on the screen (MM:SS), with the only difference that the clock was not reset. In summary, the prospective memory task had two event types: Clock-reset events and time-check events.

A clock-reset-trial corresponded to the period of time between two clock-reset events (Figure 5-1). A single clock-reset-trial contained a variable number of ongoing task events and time-check events, depending on the performance of the participant.

Participants were instructed to be as accurate as they could in the 4-minute clock-reset, while maintaining a good performance in the ongoing task. The timer popped up in the centre of the screen masking the ongoing task stimuli, thus every time the clock was displayed they missed a trial of the ongoing task. The idea of masking ongoing trial events with the clock was to encourage participants to check the clock strategically, in order to maintain a good performance in the ongoing task. Participants had regular breaks during the experiment and they were informed that time continued running during the breaks.

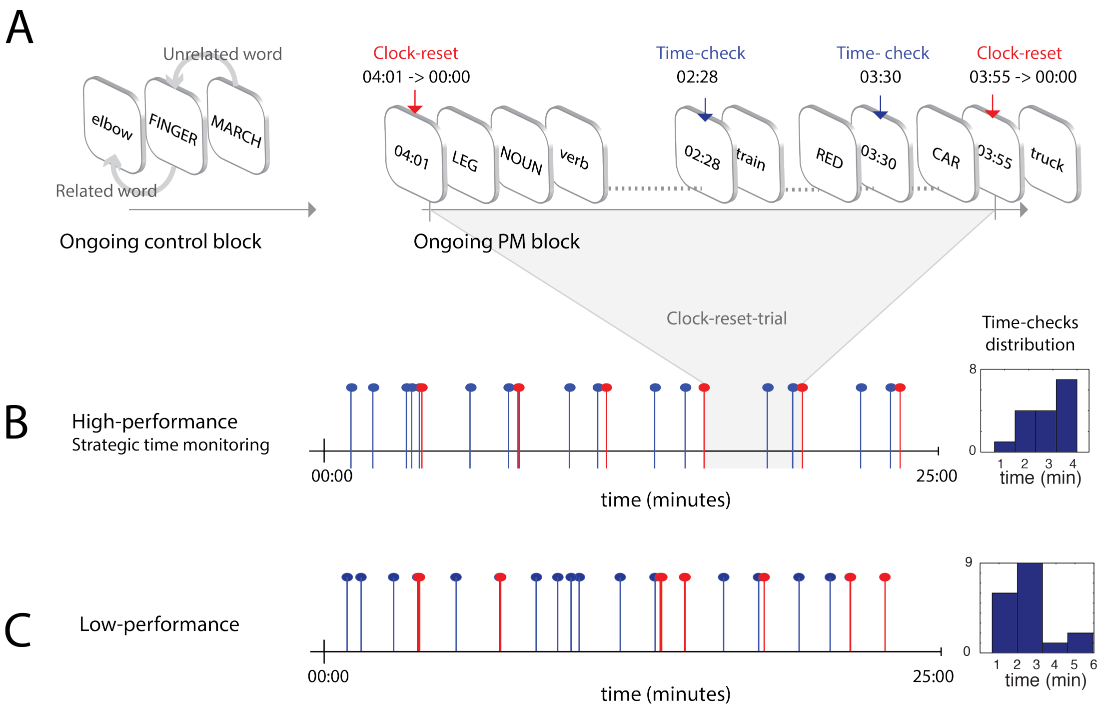


Figure 5-1. Experimental paradigm and example of performance from two participants. (A) The ongoing task consisted of a continuous 1-back categorisation task. Participants had to decide if previous words on the screen belonged or not to the same category as the current word on the screen. Participants first performed the ongoing task alone and in a second block they performed the ongoing task in addition with the prospective memory task. The prospective memory task consisted of resetting a clock every four minutes (red arrows) by pressing a 'clock-reset key'. Participants could also check the time as much as they needed (blue arrows) pressing a 'time-check key'. As the figure shows, the clock popped up in the centre of the screen (instead of a word) every time participants pressed 'clock-reset' or 'time-check' keys, the rest of the time the clock was hidden to avoid continuous time checking and encourage 'time estimation'. The area shaded in grey indicates a single clock-reset-trial, which contains a variable number of ongoing task events and time-check events. (B) Example of a high-performance showing strategic time monitoring, the distribution of time-checks shows greater time-checks towards the 4 minutes (target time). (D) Example of low-performance. In both examples, blue bars represent time-checks and red bars represent clock-resets, distributed along the ongoing PM block.

5.3.4 Procedure

The experiment took approximately one hour to complete: around 20 minutes to set up the electrode net and adjust impedances, plus 40 minutes approximately to complete the actual task. The first part of the task was a control block, where participants completed only the ongoing task: ongoing task control. The second block of the experiment consisted on the same ongoing task plus the time-based prospective memory task: ongoing task PM (Figure 5-1A). Participants had frequent breaks after a randomised number of ongoing task events, so they could not use breaks as an indicator of the passage of time.

5.3.5 Data acquisition

EEG data were recorded vertex-referenced using a 128-sensor Geodesic Sensor Net (Electrical Geodesics Inc.). The sensor net was soaked in a saline electrolyte solution and adjusted until all pedestals were properly seated on the scalp. Individual sensor impedances were adjusted until they were below 50 kΩ, (in some participants electrodes with impedances between 50 and 100 kΩ were kept). Data were sampled at 250 Hz with an analog filter bandpass of 0.1–200 Hz. A Macintosh computer running EGI’s Netstation software was used for data collection. E-Prime running on a PC was used for stimulus presentation. Two four-button response pads (one for each hand) were used to collect finger press responses to stimulus events.

5.3.6 Behavioural analysis

In line with previous studies of time-based prospective memory tasks (Mantyla, Carelli, & Forman, 2007), efficient monitoring behaviour was defined as a combination of the following three factors: Clock reset accuracy, frequency of time checks and performance in the ongoing task while performing the time-based prospective memory task simultaneously.

5.3.6.1 Clock reset accuracy

Participants were instructed to reset a clock every 4 minutes while performing an ongoing foreground task that lasted around 20 – 25 minutes. Participants were expected to do 5 accurate clock resets.

Non-parametric descriptive statistics were used to explore performance at single subject level. The advantage of this approach was that, the assumption of the distribution of time-checks and clock-resets performed by each participant was not previously assumed. In addition, we obtained detailed information on the distribution of these two variables using boxplots, which graphically depicts the variation in the times for clock-reset and time-checks. Previous studies in time-based prospective memory tasks used an arbitrary limit to define what is an accurate clock reset, for example giving a range of 20 or 30 seconds around the target time (Cona et al., 2012; Harris & Wilkins, 1982; Hicks, Marsh, & Cook, 2005). The use of the median offers a more accurate idea of the general performance of each participant across the clock-reset trials, because it is less influenced by extreme time-reset values, for example, in the case that one participant reset the clock very early in the 4-minute period, but performed almost perfectly in the rest of the trials.

Good single subject performance is defined as: median close to 4 minutes with small interquartile range (measure of statistic dispersion that corresponded to the difference between the upper and lower quartiles, IQR = Q3 – Q1), meaning that participants were consistent in resetting the clock close to the four minutes across all clock-reset-trials. Greater IQR would mean that participants were not accurate for all trials.

Group level performance: The clock-reset median of each participant was subtracted from 4 minutes to explore how far or close participants were from resetting the clock every 4 minutes (absolute values were used in this comparison). The distribution of the deviation from 4 minutes was inspected using a boxplot. The median of the group was used to form two different performance groups: low and high-performance groups. Finally, all participants were sorted using two criteria: (1) Performance above or below the group median and (2) Interquartile range, the range of the IQR can be considered as an index of consistence in the performance.

5.3.6.2 Time-checks frequency

Higher frequency of time-checks towards the end of the 4-minute period is considered to reflect strategic monitoring of time (Mantyla et al., 2007; Mioni & Stablum, 2014). All time-checks were tagged with the exact clock-reset-trial time, indicating the exact time when the event occurred. This information was used to plot the distribution of the time-checks for each participant within each clock-reset-trial and to plot the distribution of time-checks at group level. Segments of 1 minute were used to plot the distribution of time-checks, resulting in a different number of bins for the histogram of low and high-performers. To explore if time-checks were more regular towards the end of the clock-reset-trial, we performed a repeated measures ANOVA with within factor ‘time segments’ (number of bins used in the histogram) and between factor ‘groups’ (low-performance, high-performance).

5.3.6.3 Performance in the ongoing task

To explore how the ongoing task was affected by the time-based prospective memory task, we compared reaction time and accuracy during the ongoing task PM relative to performance in the ongoing control block. The repeated measures ANOVA considered the factors: blocks (control, prospective memory) and event type (related, unrelated words). A between group factor (low-performance, high-performance) was also included. Note that errors committed during the time-checks were not considered to calculate final performance, since the appearance of the clock in the screen masked the ongoing task event.

The ongoing task events were tagged with the exact clock-reset-trial time, indicating when the event occurred. This information was used to examine whether the timing of the errors was related to the passage of time within each clock-reset-trial. The timing of the incorrect ongoing task responses was subjected to repeated measures ANOVA with the within factor ‘time segments’ (number of bins used in the histogram) and between factor ‘groups’ (low-performance, high-performance).

Significant interaction effects were examined with one-way ANOVAs and significance level corrected by number of main factor comparisons (Kinner & Gray, 2008). Bonferroni correction was used for all post-hoc comparisons. SPSS software was used for behavioural statistical analysis.

An ideal performance consists of someone (i) resetting the clock consistently close to the 4 minutes (at least 4 accurate clock-resets during the whole experiment), (ii) with higher time-check frequency towards the end of the four-minute period and maintaining a (iii) good performance on the background ongoing task (Figure 5-1B).

5.3.7 EEG data analysis

The aim of the analysis was to identify features of the EEG that were associated with the maintenance of the time-based intention during the ongoing task and with the time-check events. In order to answer the research questions, the data were analysed using two approaches (Figure 5-2):

1. Approach 1: To answer the question of how the ongoing task is affected when it has a time-based prospective memory task embedded, we examined the interference in the processing of ongoing task stimuli during time estimation. This approach is informative of neural correlates of intention maintenance during the performance of the ongoing task. Event-related potentials (ERP) and event-related spectral perturbations (ERSP) locked to the ongoing task events, were examined in different contexts:
    a. Context 1: ongoing task performance during control block
    b. Context 2: ongoing task performance during prospective memory block.
2. Approach 2: To examine the mechanisms associated with time checking and whether brain dynamics of these events are associated with the passage of time, we explored brain dynamics locked to the time-check events across different time points within each clock-reset-trial.

The EEG data pre-processing and analysis were performed using EEGLAB (Delorme & Makeig, 2004) and code written in MATLAB. The first step, before any data manipulation, was to tag every event of the whole experiment with information relevant for the time-based prospective memory performance. The format of this new information was done using hierarchical event descriptor (HED) tags for analysis of EEG data (Bigdely-Shamlo, Kreutz-Delgado, et al., 2013). This information was useful for post-hoc classification of events according to when exactly the event occurred.

5.3.7.1 Single subject level EEG data processing

Data were visually inspected for bad channel removal. A high-pass filter at 1Hz (cut-off frequency of 0.5Hz) and a low-pass filter at 40Hz (cut-off 45 Hz) were applied to continuous EEG. The continuous data were cleaned as follows: Short-time high-amplitude artifacts were removed by statistically interpolating – in a sliding 1-second window – any principal components of the short-time EEG window. A criterion for removal was variance above a threshold of 15 or more standard deviations from the variance of uncontaminated EEG (taken from the cleanest part of the data). Each affected time point of EEG was interpolated by multiplying it by the interpolation matrix $I = M(V'\circ T)^{+}V'$ where M is a mixing matrix calculated from clean EEG, V are the principal components in the 1-second window, and T is a matrix of 0's for every principal component above the variance threshold and 1's for every component below the threshold, respectively. The Infomax independent component analysis (ICA) algorithm was performed on the continuous data to decompose into source-resolved activities or independent components (ICs). The scalp distribution produced by each ICs was used to find the most probably source location, whose projection offers the best fit to the topographical potential distribution of independent components (ICs scalp map distribution). The equivalent current dipole estimation was performed using a Boundary Element Model of MNI head model (DIPFIT). (http://sccn.ucsd.edu/eeglab/dipfittut/dipfit.htmlold).

Two different data segmentations were performed for the two approaches used for analysis. For the first approach, the data were segmented into epochs of two seconds with one second of baseline, locked to the ongoing task events. For the second analysis approach, data were segmented into two-second epochs, locked to the time-check events. The whole epoch was used as a baseline for frequency analysis of the time-checks. Data segmentation resulted in two epoched datasets produced from the same pre-processed continuous data. Epochs containing an overlap of task events, ongoing task and time-based PM events, were not considered in the analysis.

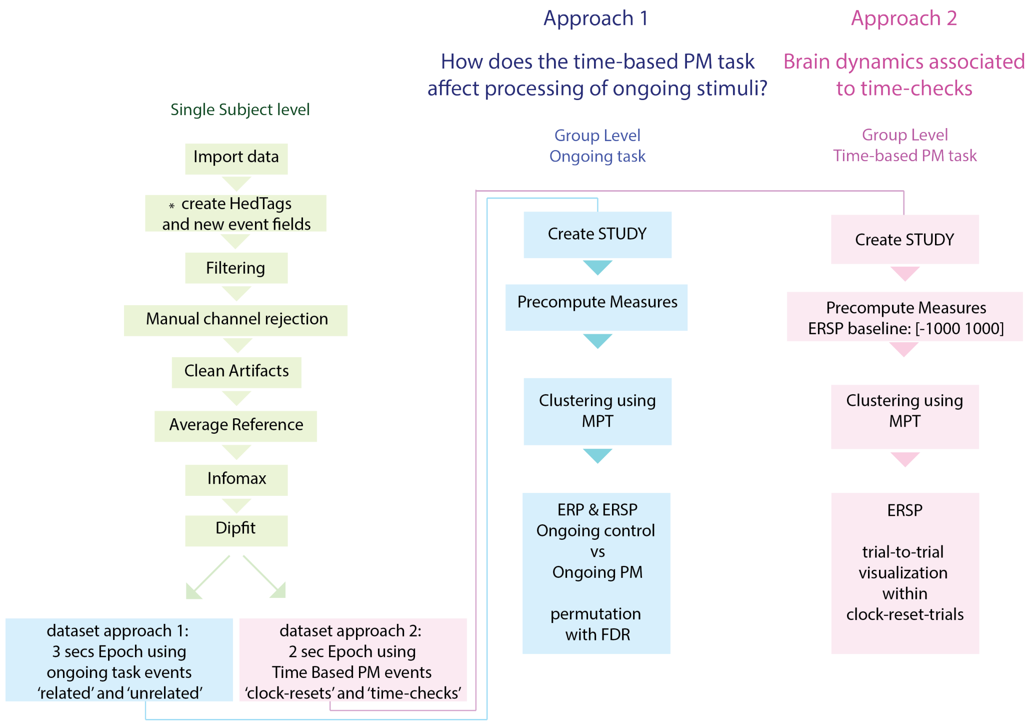
5.3.7.2 Group level statistical analysis

Datasets for each analysis approach were grouped using the STUDY function written for EEGLAB (Delorme & Makeig, 2011). The clustering method used to group Independent Components (ICs) from all participants was the Measure Projection Tool (MPT) (Bigdely-Shamlo, Mullen, et al., 2013). MPT offers a probabilistic approach to performing group level analysis using source-resolved EEG signals or ICs. Each source-resolved activity resulted from ICA contributes to Measure Projection Analysis (MPA) with an associated dipole location (DIPFIT) and a particular brain measure. In the present work, these measures correspond to changes in brain activity in terms of voltage (ERP) and changes in frequency power (ERSP), locked to the presentation of task events. MPA resolves the issue of equating scalp channel location across subjects and sessions and also proposes a more objective (low level of human influence) and data driven way of finding similar brain activities among participants in a study. We explain the steps followed in MPA in general terms, based on the parameters that can be manually adjusted, which are: (1) a *width parameter* representing each source location within a brain model, (2) a (p-value) *significance convergence threshold* indicating brain locations exhibiting similar brain measures associated to it and (3) a maximum *domain exemplar measure similarity threshold* which indicates how similar are the different resulting brain domains or clusters among them. (1) MPA computes for each dipole a *measure vector,* which is obtained from a combination of the measure (ERP or ERSP) associated with the dipole location. This measure vector is assigned to possible brain locations within a common brain model considering a standard error of 12mm and allowing a maximum of three standard errors (these width parameters can be manually adjusted). An important point is that this measure vector is computed considering either ERP or ERSP, it does not combine these values, as it is done in other clustering approaches (for example, k-means). Thus, MPA clustering is based on finding similar dipole location as the main factor and uses only one type of measure to find similarity between dipoles. As a result, the final number of clusters and their probable location may vary depending on the measure that was used. In the present study, we show clustering results for each analysis approach using ERP and ERSP (2 analysis approach by 2 EEG measures resulted in 4 different clustering results, see Figures 5-5 and Figure 5-7). (2) The *measure vectors* obtained from step 1 are evaluated to find whether they are similar among them and if their spatial distribution is not random (but corresponds to a particular brain region within the brain model). Each measure vector is assigned to possible brain locations, which have a local convergence value. This value is subjected to statistical analysis in order to find significantly similar vector measures that can be considered to reflect similar physiological processes. These brain locations form a subspace of significant convergence. The significance threshold (p-value) to find areas of convergence can be manually adjusted ($p < 0.01$ in the present study). As a result, all significant local convergence values showed that there is a set of measure vectors associated with particular brain regions (not randomly distributed) and they are similar to other measure vectors associated to the same locations. It is also important to note that one measure vector can be significantly associated to different brain locations. (3) The last step is to form clusters or brain domains, within the subspace of significant convergence, that exhibit sufficiently different measures from each other so they can be considered as different clusters. This process is done using *affinity clustering* - it starts with a minimum number of clusters (1 or 2) and then, in an iterative process, creates clusters until their *measure exemplars* reach certain similarity (correlation). The measure exemplar is a demonstrative sample of the measure associated with the cluster; it is assumed that all dipoles within a brain domain exhibit measures similar to the cluster exemplar. The parameter that defines the threshold to consider measure exemplars as to be sufficiently similar is called the *maximum domain exemplar correlation* (set to a correlation value of 0.7 in the present study). When affinity clustering finds the Maximum Domain Exemplar Correlation, the iterative process stops and gives a final number of clusters. For example, if the correlation is set to a low value (0.2), the cluster exemplars are the most different they can be (the longest distance between the exemplars), and as the threshold is set to a low value the process stops there and the final number of clusters is small. In contrast, if the correlation is high (0.7), affinity clustering will run until obtaining cluster centroids that are very similar to each other (shorter distance between exemplars), resulting in a higher number of clusters. As a result of this last step, each dipole has a probability of membership to a domain, and it can be the case that the same dipole may be part of more than one domain.

For approach 1, aimed at answering the question of how the ongoing task is affected when it has a time-based prospective memory task embedded, we tested ERP and ERSP from each brain domain for significant differences between the ongoing control and ongoing PM blocks. We used permutation two-way ANOVAs corrected for multiple comparisons using False Discovery Rate (FDR) at 0.01 significance level. Factors for the ANOVA were: Blocks (control, PM) and Ongoing Task Events (Related, Unrelated). We used the function std_stat freely available in the EEGLAB website (http://sccn.ucsd.edu/eeglab/allfunctions/std_stat.html). This function gives results by simple effects of each factor, blocks and event type, plus the main factor effects (pooling the data by blocks or event types). Only the Blocks factor p-values were reported, as our focus of interest is on the difference between ongoing task control and ongoing task PM and not on the semantic effect (related versus unrelated words). For the ERP comparison we obtained a set of vectors of 300 p-values corresponding to the voltage value at each time point between -200 and 1000 milliseconds. The significant p-values for the block factor effect were depicted in the Figure 5-5, C (grey areas). For the ERSP analyses we obtained a set of matrices of 200 X 20 p-values, corresponding to the time points and log frequencies (3-40Hz), respectively. For ERSP differences we reported related and unrelated words separately, due to the complexity of plotting both events in the same plot (in contrast with ERP that are two dimensional and several waveforms can be plotted together). Thus, we reported the simple block effect (control, PM) separately for each event type. To depict the results we masked the difference between control and PM blocks by 0.05 significance level (Figure 5-5, D).

The ERP and ERSP cluster results showed a common brain domain with significant differences for the block factor, probably located in the anterior cingulate cortex. In order to investigate if this brain area was associated with the time monitoring strategy of the participants, we performed a post-hoc comparison separately for low- and high-performance group (see Behavioural analysis section for definition of low- and high-performers). Two separate two-way ANOVA with FDR correction were performed for low- and high-performers, with factors blocks (control, PM) and event type (related, unrelated). We used the time window between 300 and 800ms, where the main differences were observed for the ERP and ERSP in the previous comparison. Results were masked at a p-value of 0.05.

For approach 2, aimed at exploring brain dynamics associated with time checks, we plotted ERP and ERSP activity from each resulting brain domain involved in time-checks (external time monitoring) (Figure 5-7). Both brain measures showed a brain domain probably located in the Anterior Cingulate Cortex. Then, we explored if the spectral changes observed around the time checks were significant and if they were correlated with the progression of time within the Clock-reset-trial. We decided to use a trial-to-trial analysis of power in different frequency bands (Figure 5-8). The ERP and ERSP measures generated by the Measure Projection Tool (MPT) were not suitable for this analysis, given that the single trial information is not available from the final measure output (the output corresponds to a weighed average of the signal, which does not contain single trial information). An alternative way to access the single trial information is to find out which dipoles have highest probability of being located inside the brain domain, thus we selected one IC per participant, with the highest probability of being part of the selected domain. Trial-to-trial visualisation was built calculating the spectral power on the peak frequency within the frequency band windows: upper alpha (9-15 Hz) and beta (15-24 Hz) for each trial. These frequency bands were selected based on the power changes shown by the ERSP plot of the anterior cingulate domain. The information of each trial is represented by colour-sequence lines and is stocked above each other, resulting in an image with the trial number in the y-axis, time in the x-axis and power in colour code. Events were sorted according the time within the clock-reset-trial, indicating changes in the frequency power for each trial in relation to the passage of time; first trials (or small numbers in the y-axis) occurred early within the clock-reset-trial whereas last trials occurred later within the clock-reset-trial. To statistically assess whether activity in alpha and beta bands are resynchronized, the mean changes in power (dB) are plotted indicating 1% confidence limits according to surrogate data from random windows in the baseline. The time courses of the frequency power that fall within the confidence intervals were not significant. No consistent changes were observed in relation with time, thus no statistical test was performed to evaluate changes across trials (y-axis).



*hedTags and new event fields, tag each event with infromation about the time-based PM task, e.g. indicating the time when the event occurred.
Example of hedTag: 'Custom/Accuracy/OnTime, Custom/TimeinClock/3.42, Custom/TimeAfterLastCheck/1.02'

Figure 5-2. Pipeline for pre-processing and data analysis.

5.4 Behavioural results

5.4.1 Clock-reset accuracy

We calculated the difference between the median clock-reset time of each participant and 4 minutes (target time). The group showed a median deviation of 12 seconds (Figure 5-3). Participants that reset the clock with a median of 12 seconds around the 4 minutes were grouped as 'high-performers' (above median performers) and participants that had a median deviation greater than 12 seconds were considered as 'low-performers' (below the median). Table 5-1 shows general performance for clock-reset accuracy for both groups.

Table 5-1. Clock-reset accuracy (min) per group. Interquartile Range (IQR) = Q3-Q1.

	Q3	Median	Q1	IQR
High Performers (n=12)	3.95	3.90	3.85	0.10
Low Performers (n=12)	3.67	3.64	2.82	0.85

Participants in the high-performance group reset the clock four times on average, between 3.64 and 4.28 minutes (lower and upper whiskers of the group distribution). Whereas participants in the low-performance group, reset the clock only twice on average within the same time window.

Single subjects were sorted according two criteria: performance above or below the group median and, according the Interquartile range (IQR), a small IQR meant a small dispersion around the 4 minute target, this IQR was considered as an index of consistency for clock-reset times (Figure 5-3).

5.4.2 Time-check frequency

We examined the distribution of time-checks within the clock-reset-trial using a repeated measures ANOVA with 'time segments' as a within factor and 'groups' as a between factor. The factor group was significant, meaning that participants from the high-performance group checked the time more frequently relative to low-performers, $F(1,22) = 11.205$, $p < 0.01$, partial eta squared = 0.337 (Figure 5-3C).

The time-check events showed a different distribution between the groups. The results showed a significant interaction 'time segments x group', $F(5,110) = 6.932$, $p < 0.001$, partial eta squared = 0.240. The high-performance group checked the time more frequently as the time progressed, $F(5,55) = 22.009$, $p < 0.001$, partial eta squared = 0.667. Time segment 4 (between 3 and 4 minutes) was significantly different from time segments 1 and 5, ($p < 0.01$) (Figure 5-3B). The low-performance group showed a homogeneous distribution for time-checks before the 4 minutes, the only significant difference was between time segment 2 and 6, meaning that the low-performance group did not show strategic monitoring of time.

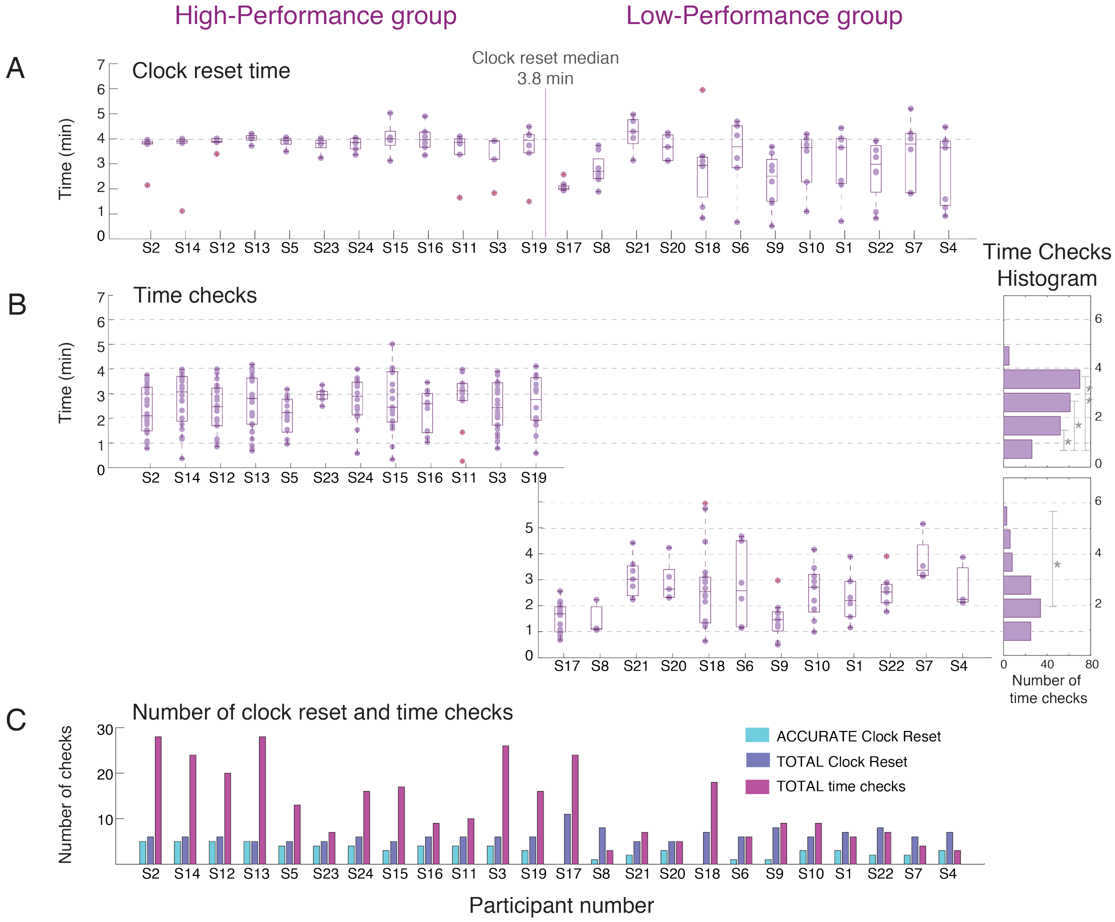


Figure 5-3. Single subject performance in the time-based prospective memory task. (A) Boxplots for each participant in the study show the median and dispersion of clock-reset times. Purple circles show individual clock-resets. The vertical line indicates the median of the group and separates the subject in two groups. Participants within each group are sorted from smaller to greater interquartile range (IQR). (B) Shows single time-checks for each participant. Histograms to the left of the figure show the distribution of the time-checks for each group. Note that high-performers increased time-checks towards the 4 minutes. Grey lines in the histogram indicates significant differences, * $p < 0.01$, ** $p < 0.001$. (C) The bar plot shows total number of time-checks per participant (dark pink), total number of clock-reset (purple) and number of clock-resets performed above the group clock-reset median (3.8 min). Note outstanding performance of subject 23: clock reset median close to 4 minutes, small IQR and all time-checks performed between 3 and 4 minutes.

5.4.3 Effects of the time-based PM task on the performance of the 1-back categorisation task (ongoing task)

To explore how the time-based prospective memory task affected the performance in the ongoing task, accuracy and reaction time were submitted to a two-way repeated measure ANOVA, with within factors blocks (control and prospective memory) and between factor group (high-, low-performance). Participants decreased their accuracy in the performance of the ongoing task when they also had to undertake the prospective memory task, $F(1,22) = 26.224$, $p < 0.001$, partial eta squared = .544. There was no interaction effect 'Blocks x groups', $F(1,22) = 0.743$, $p > 0.05$, meaning that the high and low-performance groups decreased accuracy during the ongoing prospective memory task in a similar way.

To explore reaction times, an additional factor level was added to the ANOVA: event type (related, unrelated). The results showed a significant interaction effect between event type (related and unrelated words) and blocks (control and PM), $F(1,22) = 11.566$ $p < 0.01$, partial eta squared = .345. The post-hoc test showed that only reaction times of unrelated items decreased during the PM block, $t(23) = 1.98$, $p < 0.05$, though this difference is marginal and over the corrected significance level 0.025. Reaction times of related items remained the same. Faster response for unrelated events might reflect a practice effect.

The results also showed a main effect of group - the high-performance group was faster than the low-performance group, $F(1,22) = 4.368$, $p < 0.05$, partial eta squared = .166 (small effect size), independently of their performance in the control or the prospective memory block. Non-significant interaction group x event type x block, $F(1,22) = 1.490$, $p > 0.05$.

Table 5-2. Interference effect of time-base prospective memory task. Accuracy (%), Reaction time (ms), standard deviation in parenthesis

Performance Group	Ongoing Control			Ongoing PM		
	Accuracy	Reaction Time		Accuracy	Reaction Time	
		Related	Unrelated		Related	Unrelated
High (n = 12)	94 (3)	677 (75)	785 (117)	92 (3)	685 (87)	714 (78)
Low (n = 12)	93 (3)	771 (102)	867 (128)	90 (4)	762 (130)	836 (142)
Total (n=24)	94 (3)	724 (99)	826 (127)	91 (4)	723 (115)	791 (135)

As noted earlier, participants decreased accuracy during the ongoing PM block relative to the ongoing control block, meaning that a behavioural cost was observed for the maintenance of the prospective memory task. An assumption may be that the distribution of the errors during the ongoing PM block would be associated with the progression of time within the clock-reset-trials, meaning that participants would increase error rate with increase of time-checks. However, neither of the two groups showed this error distribution.

The two-way repeated measures ANOVA showed an interaction effect between factors ‘time segments’ and ‘groups’, F(5,110) = 3.831, $p < 0.01$, partial eta squared = .148. We inspected the distribution of the errors along the time segments separately for each performance group, with significance level corrected at 0.025.

The high-performance group showed a significant time segments effect, F(5,55) = 28.836, $p < 0.001$, partial eta squared = .724 (large effect size), the error rate remained similar during the first 3 minutes of the clock-reset-trial and decreased during the time segment 5, this decreased was significant only in relation to the first time segment ($p < 0.001$) (Figure 5-4B).

The low-performance group also showed a main time segment effect, F(5,55) = 17.072, $p < 0.001$, partial eta squared = .608. However, the distribution of errors was different from the high-performance group. Participants showed a higher number of errors during the first time segment relative to the time segments 3 to 6. The number of errors during time segments 2, 3 and 4 remained similar (Figure 5-4B).

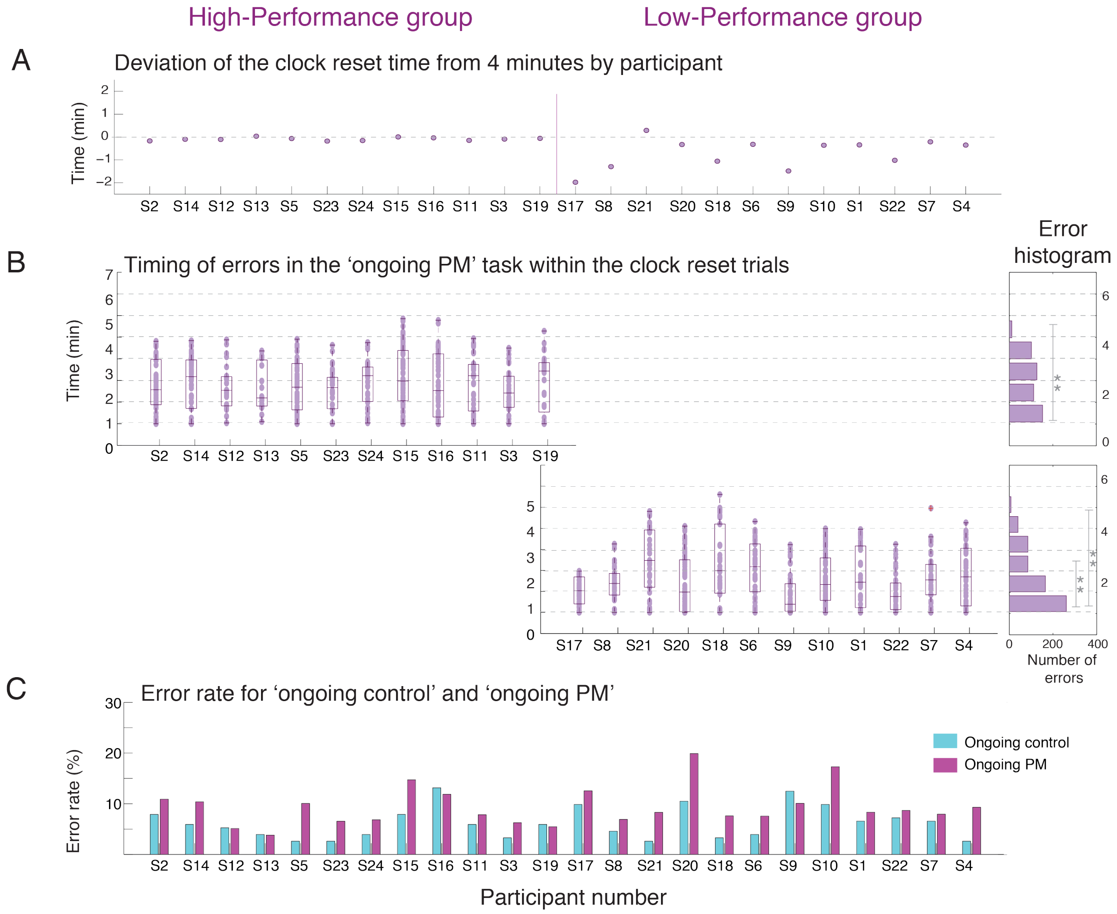


Figure 5-4. Single subject performance in the ongoing task. Results are showed for both groups high and low performers. (A) Depicts the median deviation of clock-reset times from 4 minutes for each participant. (B) Boxplots for each participant in the study show the median and dispersion of the time when errors occurred within each clock-reset-trial. Histograms to the left of the figure show the distribution of the errors for each group. Note that the high-performance group showed a homogenous distribution of the errors, whereas the low-performance group shows greater number of errors for the first minute of the clock-reset-trials. Grey lines in the histogram indicates significant differences, ** $p < 0.001$. (C) The bar plot shows the error rate of the ongoing control and ongoing PM blocks. Note that in general, participants committed more errors when performing the ongoing task simultaneously. Note that some participants maintained a good performance during the ongoing PM block with high accuracy in for the clock reset (see A and C for subjects 12 and 13). In contrast, some participants showed a high 'monitoring' cost (see A and C for subject 16).

In summary, the time-based prospective memory task affected the performance of the ongoing task only in terms of accuracy. Reaction times were not affected. Unrelated items of the ongoing PM task showed a marginal practice effect. The main behavioural differences between high- and low-performance groups were: (1) the high-performance group showed greater number of time-checks and strategically distributed within the clock-reset-trial period. This may explain the better results in resetting the clock close to the 4 minutes. In contrast, the low-performance group showed a smaller number of time checks, homogeneously distributed across the first 4 minutes of the clock-reset-trial.

5.5 EEG results

Pre-processed continuous data from each participant was subjected to two different data segmentations in order to study EEG brain dynamics locked to the ongoing task events and to time-check events. Different data segmentation was necessary, because the epochs locked to time-checks had 2-second length and the whole time window was used to remove the baseline. The two types of data segmentation resulted in two groups for post-hoc analysis: one focused on how the processing of ongoing task stimuli is affected by maintaining the time-based delayed intention (section 5.5.1) and the other focused on what brain regions and dynamics are associated with time-checks (section 5.5.2).

The measure projection analysis performed on the two ‘group analysis approaches’ showed different brain domains, depending on the measure used (ERP or ERSP) and on the task events (ongoing task events or time-checks events). Interestingly, the anterior cingulate gyrus (BA24) was the area with highest significant convergence for ERP and ERSP measures for both types of events: ongoing task events (Figure 5-5) and time-check events (Figure 5-7), meaning that a high number of independent components (ICs) from each participant, showed similar dipole location and brain activity (measure similarity) in that area, consistently across blocks and measures.

5.5.1 Source-resolved EEG measures for ongoing task events.

The measure projection analysis revealed 5 brain areas with highest convergence for ERP measures: (1) Anterior cingulate gyrus, (2) Left superior parietal gyrus, (3) Superior parietal lobe/precuneus, (4) Right inferior parietal lobe/angular gyrus and (5) Left temporal lobe/fusiform gyrus. A sixth brain domain was localised in Brodmann area 23 (part of the cingulate cortex). This domain was not considered for post-hoc analysis since inspection of the main contributing ICs revealed a high overlap with the anterior cingulate domain, the latter showing highest level of significant convergence.

Four brain domains were revealed for the ERSP measure projection analysis: (1) Anterior cingulate gyrus, (2) Posterior cingulate gyrus, (3) Left precentral gyrus and (4) Right precentral gyrus. Anatomical information about of these areas is displayed in the figure 5-5.

ERP and ERSP measures from ongoing task events were submitted to a permutation two-way ANOVA with FDR correction, using the factors event type (related and unrelated) and blocks (control, PM). The test was run on every single data point of the whole epoch window for each brain domain activity (Figure 5-5), in order to explore how the temporal processing of the ongoing task events were affected by holding the time-based delayed intention.

ERP activity with source in the anterior cingulate cortex depicted the N400-like pattern (Figure 5-5C), consistent with the semantic decision participants were required to make in the ongoing task: the unrelated words showed an enhanced negativity (N400) relative to the related words in both control and PM blocks. This difference was observed between the 300 and the 600 milliseconds (event type main factor effect). However, our main interest was in the comparison between control and PM blocks, rather than related versus unrelated words. The comparison between control and PM blocks showed significant differences starting at 400 ms in the anterior cingulate cortex, with amplitude modulations smaller for the ongoing PM block relative to the ongoing control block. Left superior parietal, right inferior parietal and left temporal lobe/fusiform gyrus, showed differences around the 600ms between the ERP modulation of control and PM blocks. Note that both posterior domains showed earlier negative deflection for ongoing PM events (Figure 5-5C, bottom ERPs).

ERSP analysis showed stronger alpha/beta (7-15 Hz) suppression in the anterior and posterior cingulate gyrus during the ongoing PM block relative to control (Figure 5-5D top). Changes were observed in a similar time window with changes observed for the ERPs of the anterior cingulate and superior parietal cortex. Domains in the precentral gyrus (motor areas) showed an opposite behaviour, with stronger alpha/beta suppression during the control block compared to PM blocks (Figure 5-5D bottom).

The anterior cingulate cortex was the area with the highest convergence for both measures ERP and ERSP in the ongoing task. In addition, both measures revealed changes in the ongoing task while maintaining the time-based instruction. We focused the post-hoc analysis on the activity of this brain domain comparing the activity between control and PM blocks separately for both groups, high- and low-performance. The rationale for this was that if this area was affected by the time-based prospective memory task, the differences may be relative to the performance participants obtained in the time-based task. Activity between going control and ongoing PM was compared using a permutation ANOVA with FDR correction for the time window between 300 and 800ms, where the main differences were observed for the ERP and ERSP in the previous comparison.

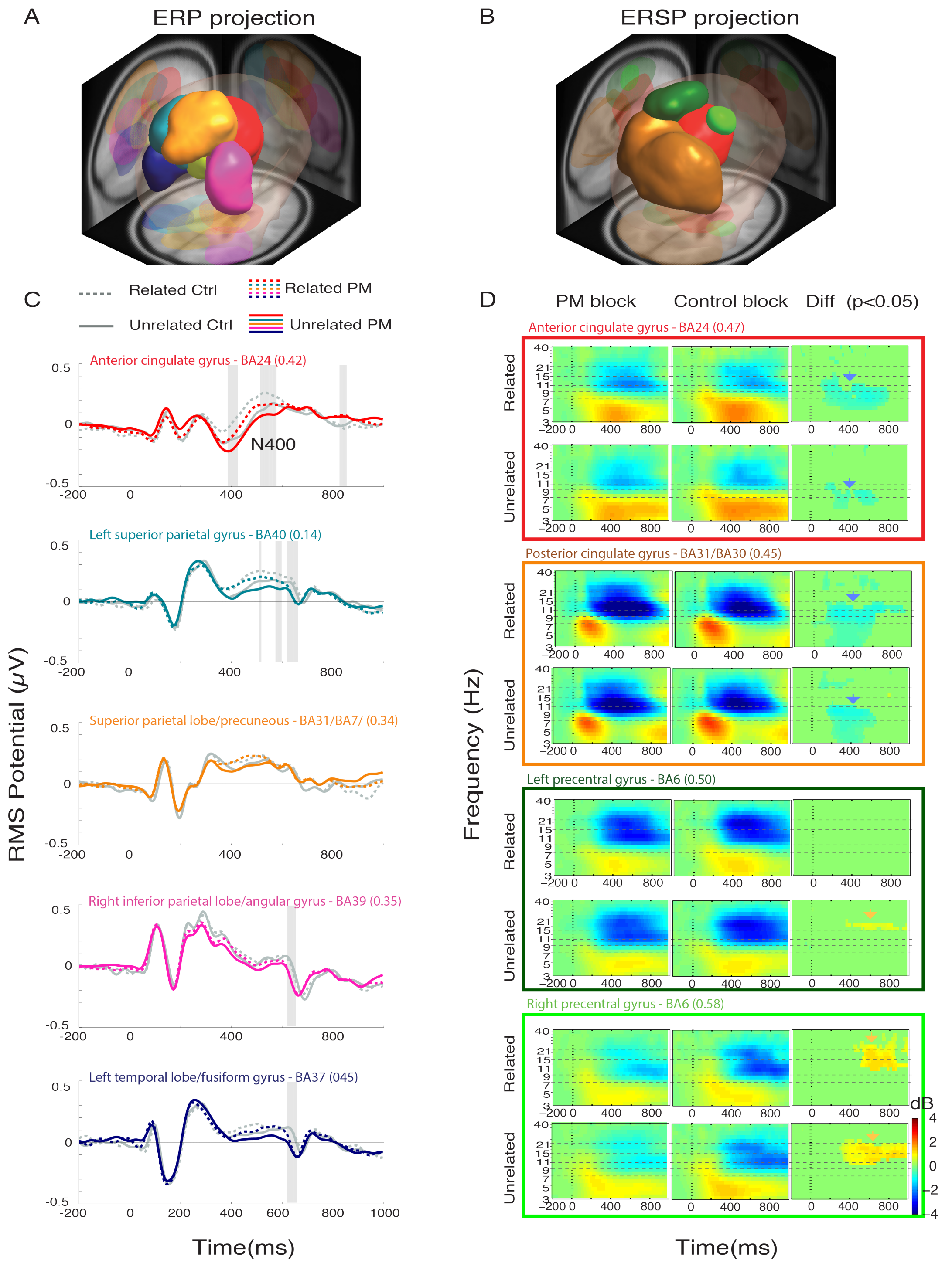


Figure 5-5. Measure projection analysis for ongoing task events. Domains obtained from measure projection analysis of ERP (A) and ERSP (B), the coloured brain regions represent locations with significant convergence ($p<0.01$), revealing 5 probable domains for ERP and 4 domains for ERSP. (C) ERPs are coloured following the colour of its corresponding brain domain. (D) ERSP figures are framed by colour lines according the ERSP brain domains. Anatomical information of each brain domain is indicated above each ERP/ERSP with its probability in parenthesis. All statistical test performed corresponded to permutation ANOVA with FDR correction. Significant time points are shaded in grey for the ERP and masked at 0.05 significance level to depict differences in the ERSPs. Main Block factor effect (control, PM) is reported for ERPs (pooled by event type) and simple Blocks effects (control, PM) are reported separately for related and unrelated ERSPs.

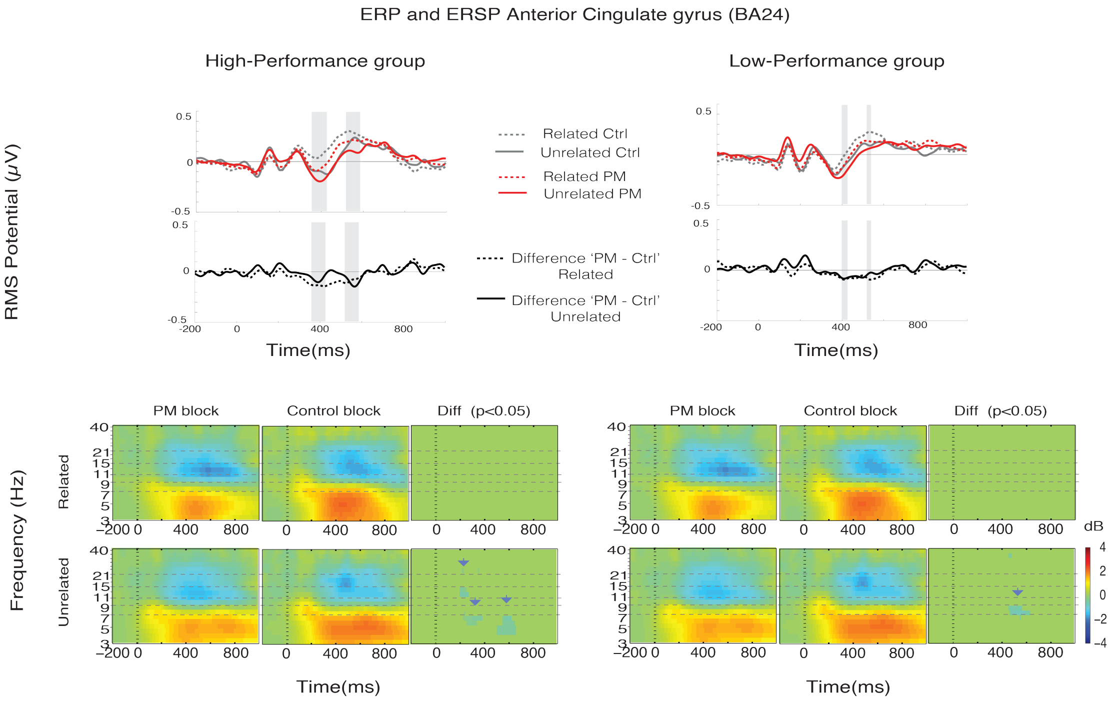


Figure 5-6. ERP and ERSP activity of the anterior cingulate cortex for high- and low-performance groups. All statistical tests performed corresponded to permutation ANOVA with FDR correction for the time window between 300 and 800ms (where previous significant changes were observed). Significant time points are shaded in grey for the ERP and masked at 0.05 significance level to depict differences in the ERSPs. Main Block factor effect (control, PM) is reported for ERPs (pooled by event type) and simple Blocks effects (control, PM) are reported separately for related and unrelated ERSPs.

The results showed that the high-performance group showed greater difference in the amplitude of the ERP modulations between control and PM relative to the low-performance group. This difference was significant around 400ms and 600ms (Figure 5-6). Results showed that related items had similar ERSP for control and PM tasks. The significant differences observed for the initial group level analysis did not appear in the comparison by groups. However, the difference between unrelated items of the control versus the PM blocks, showed greater differences for the high-level performance group, starting at 300ms post-stimulus presentation. The differences showed a decrease in the theta band for the PM block.

5.5.2 Brain dynamics associated with time checks

The measure projection analysis for the ERP measure of the time-based prospective memory task, revealed 4 brain areas: (1) Anterior cingulate gyrus, (2) Right inferior Parietal lobe/angular gyrus , (3) Left temporal lobe/fusiform gyrus and (4) the Brodmann area 23 (part of the cingulate cortex). The latter domain was not considered for post-hoc analysis. The main contributing ICs showed a high overlap with the anterior cingulate domain, the latter showing highest level of significant convergence (Figure 5-7A).

The ERSP measure projection analysis revealed 2 main brain domains: (1) Anterior cingulate gyrus and (2) Middle Temporal gyrus. Two other areas were also identified, with high overlap of ICs and smaller level of significance convergence, thus, they were not considered for post-hoc analysis (Figure 5-7B).

The anterior cingulate cortex was the domain with the highest convergence level for both measures ERP and ERSP. The ERSP showed increase in the spectral power of upper alpha (9-12 Hz) and beta (12-25 Hz) before the time-check and strong alpha/beta suppression after the time-check event (Figure 5-7D, top).

In order to explore if changes in alpha/beta bands were associated with time estimation, the spectral response of the anterior cingulate domain was examined locked to time-check events and sorted by time on the clock-reset-trial (as explained in methods). Both performance groups showed strong alpha/beta suppression after the time check, but the correlation with the passage of time was unclear (see black diagonal line and the increase in alpha suppression in the figure 5-8). However, for the high-performance group, it seems that the first 100 trials, in the alpha band, showed a tendency to increase alpha suppression after time-checks associated with time in the clock-reset-trial.

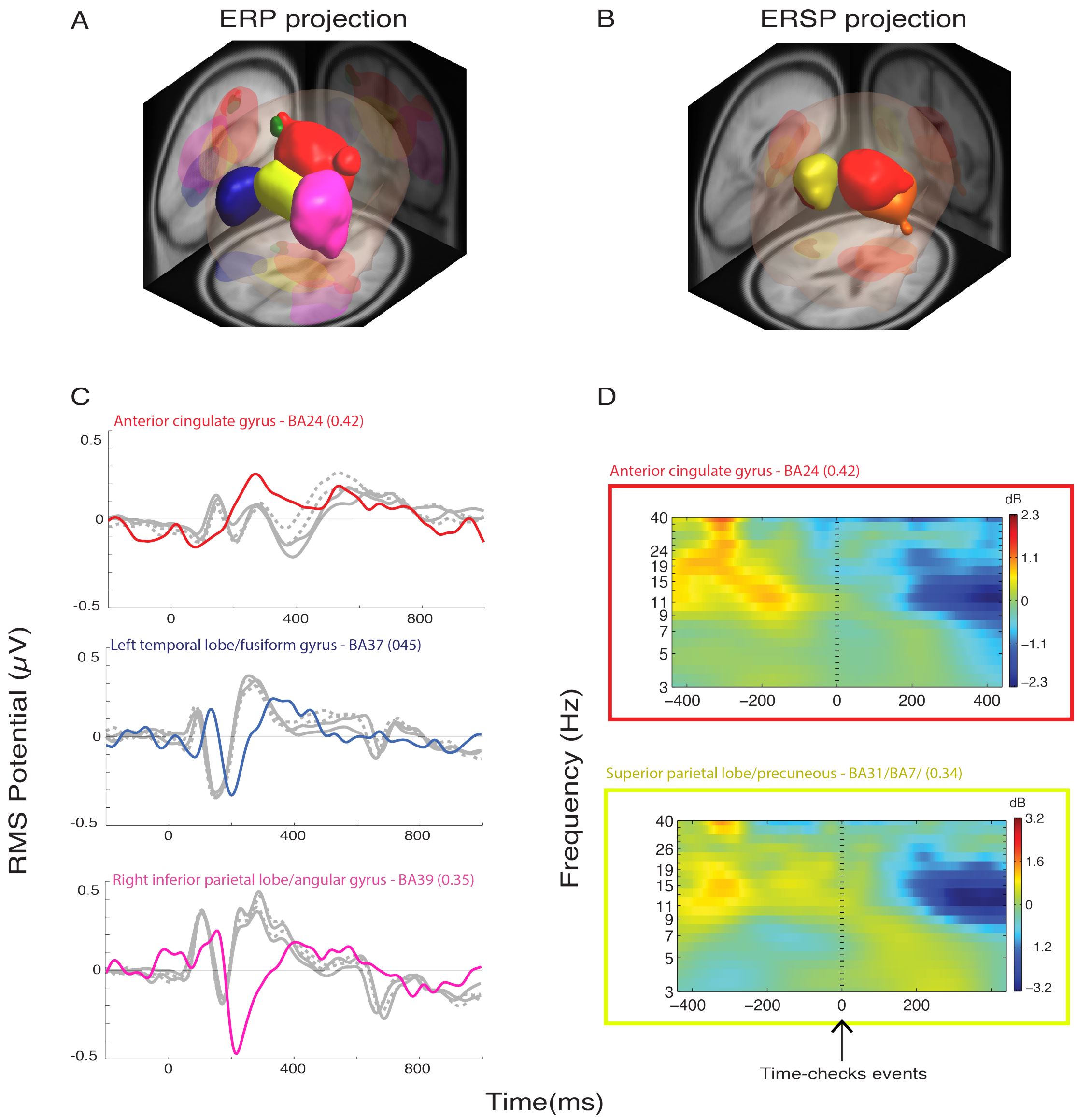


Figure 5-7. Measure projection analysis for the time-check events. (A) ERP measure projection revealed 5 brain domains. (B) ERSP revealed 4 regions, two in the temporal cortex, treated as one for overlap of main contributing ICs and similar resulting measures, and two in the anterior cingulate gyrus, also treated as one for the same reason. (C) ERP for three brain domains, which are also shown by the ERP measure projection analysis of the ongoing task events. ERPs from the ongoing task are depicted in grey as a reference. (D) Spectral perturbation obtained from the anterior cingulate and middle temporal domains showing increase in the spectral power of upper alpha (9-12 Hz) and beta (12-25 Hz) previous the time check and a decrease in similar frequency bands 200 milliseconds after time checks.

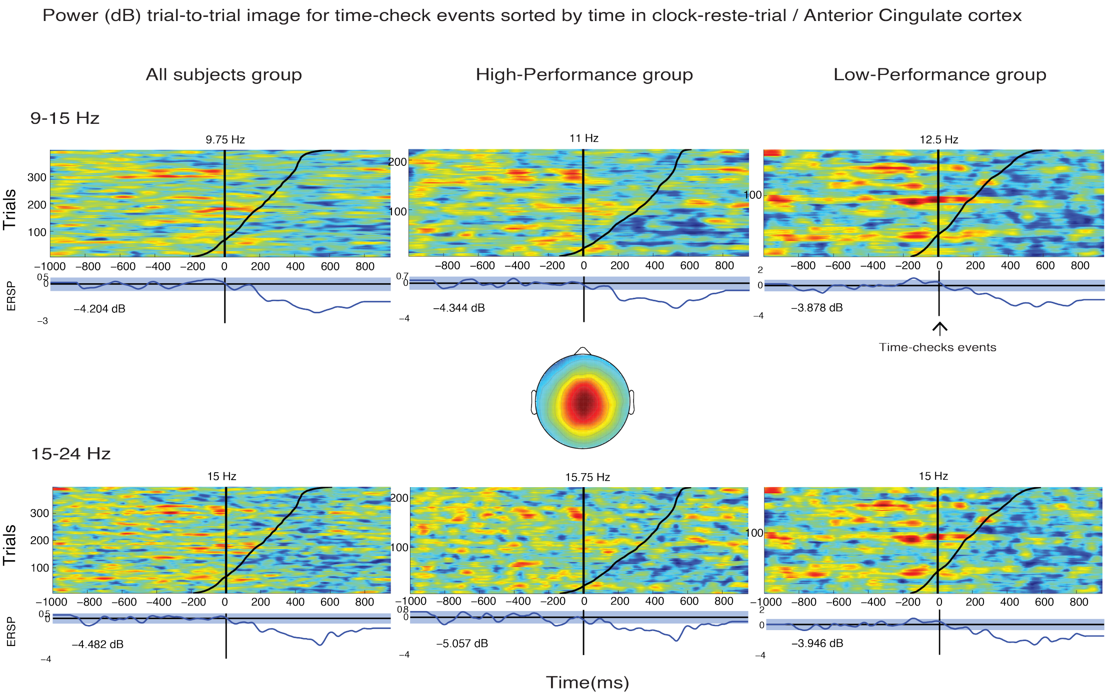


Figure 5-8. Power trial-to-trial image for time-check events sorted by time in clock-reset-trial. Smoothed trial-by-trial time courses of log power at 9-15 Hz (top) and 15-24 Hz (bottom). The power of the signal was calculated based on the peak frequency within the frequency band window. The peak frequency for each frequency band is indicated at the top of each plot. Power is shown before and after time-checks (time 0), sorted by time in the clock-reset-trial (black diagonal line, time is scaled to the figure). The first column represents the two groups, high- and low-performance, together. The other two columns show trials separated by performance group. All plots showed that alpha/beta power suppression was higher after the time-check. The high-performance group during the first 100 trials, showed greater alpha suppression, relative to the later trials (top-middle column). The blue lower traces give time courses of the frequency power for the frequency peak indicated at the top of each plot. Blue shading: Regions of non-significant difference from 0. Trials are smoothed with a 10-trial moving-average. Note that the number of trials differs for both performance groups. An average scalp map of the ICs topographic distribution per participant is depicted in the centre of the figure. Note that the number of trials in the y-axis is different for the all subject group, low- and high-performance group.

5.6 Discussion

The present experiment was design to clarify two main issues related to time-based prospective memory tasks: What are the attentional mechanisms required for maintenance of time-based prospective memory intentions? And what EEG measures are associated with the passage of time? A third question, related to intention maintenance mechanisms was also addressed: Are attentional mechanisms common to time-based and event-based prospective memory tasks?

5.6.1 Active maintenance of the intention during the ongoing task

The behavioural results showed that there was an interference effect in terms of a decrease in accuracy for the ongoing PM block. Error rate was calculated based only on ongoing task stimuli to which participants were able to give a response, incorrect responses in the ongoing task produced by time-checks and clock-resets were not considered in the final error rate. Thus, the decrease in accuracy is most probably explained by the maintenance of the time-based prospective memory task.

Two performance groups were defined based on the performance in the time-based prospective memory task. High-performers: people that reset the clock 4 times or more and Low-performers: people that reset the clock 3 times or less. We explored if the different performance in the time-based task, also affected differentially the performance in the ongoing task. The behavioural results showed that the decrease in accuracy was similar for both groups, thus the difference between the groups was not associated with the ‘amount of resources’ devoted to the time-based task, but to the strategic use of those resources. This idea is supported by two facts: first, the time-checks of the high-performance group were higher in number and strategically distributed, being more frequent towards the 4 minutes. In contrast, time-checks of the low-performance group were not correlated with the passage of time. Second, the timing of the error for the high-performance group was homogenous across the four-minute period, indicating that during the first minute they maintained performance in the ongoing task and did not get distracted by the time related task. In contrast, low-performance group showed greater number of errors at the beginning of the clock-reset-trials, maybe indicating that they were devoting attentional resources to the time-based task at early stages of the time estimation (as mentioned earlier, the total number of error across the ongoing PM block was the same for both groups).

In summary, the results showed that maintenance of the time-based intention had a cost in terms of accuracy of the ongoing task. The high-performance group showed strategic use of the resources pulled from the ongoing task, performing time-checks towards the end of the clock-reset-trial and maintaining similar error-rates across the clock-reset-time period. The accuracy of the low-performance group in the ongoing task was affected in a similar faction, but they did not make strategic use of the cognitive resources, this group obtained low number of clock-resets and most of the time-checks were performed in the first part of the clock-reset period.

5.6.2 Is monitoring associated with time perception in prospective memory tasks

The results showed that participants who strategically checked the time (closer to the target time) were more accurate in resetting the clock close to the 4-minute target. In addition, high-performance participants also checked the time a higher number of times. This is consistent with the test-wait-test-exit model (Harris & Wilkins, 1982). This model proposes that when people perform a time-based prospective memory task they enter a test-wait cycle, which consist on ‘tests’ to check whether it is time to perform and action and ‘wait’ until the next ‘test’, this cycle would be repeated until the time to execute the action is met. Harris describes a higher rate of time-checks as the critical period (the target time) approaches. This has been interpreted as that people rely more on internal time estimation during the initial part of the time-period and switch toward external time estimation (time-checks) toward the final part of the time period. When looking at the results according this model, we may propose that the high-performance group had better internal time-estimation, since they required less external time-checks during the first part of the clock-reset-trial. We decided to explore if the EEG dynamics of single time-checks were associated with the time of the check within the clock-reset-trial and if they showed modulations that may be associated with their capacity for time estimation.

Using the Measure Projection Analysis on time-based lock events, we observed that the anterior cingulate cortex was the area with highest convergence for both ERP and ERSP measures. We observed that the trial-by-trial time course of alpha power suppression (11 Hz) for the high-performance group seemed to be correlated with timing of the time-checks (Figure 5-8). The first 100 trials showed a marked increase in alpha desynchronisation, relative to the later trials. In comparison, the low-performance group showed an increase in alpha desynchronisation, similar across early and later trials. However, a clear correlation between the onset of alpha desynchronisation and the passage of time cannot be observed. One issue with this approach is the low number of time-check trials, the different number of time-checks per group and the variability in the performance of strategic monitoring. Figure 5-3 shows that participants belonging to the high-performance group performed a greater number of time-checks toward the end of the 4-minute period. However, not all participants showed this behaviour (Figure 5-3). Thus, even though behavioural results indicate that a strategic time-check distribution is associated with internal time estimation, we cannot offer a direct neural measure of this performance. The question of how time estimation is involved in prospective memory continues to be open. Another question is what is the relationship between time estimation and executive control of attention - we all know by personal experience that perception of time varies with the attention we are devoting to it.

Block (2006) proposes a theoretical framework for time-based prospective memory tasks that draws on elements from established models of time estimation. The core of this proposal is the ‘Internal clock theory’, which proposes that there is an internal clock that, after a start signal, produces a steady stream of pulses that are stored in an accumulator until a finish signal. The final count is stored in memory and becomes a representation of the time interval. The attentional counter theory (Block et al., 2010) extends this theoretical model proposing that attention influences time estimation, in the sense that the accumulator only updates the counts when attention is directed towards the passage of time. The paradigms used by Block differ from the classical paradigms in time estimation, where the explicit focus of the task is to keep track of time. In real-life activities, time estimation usually is required during the performance of a non-related additional task and it is not the primary focus of the performance. Thus, recent paradigms used to study time estimation are very similar to time-based prospective memory tasks.

A major focus of research in the field of time estimation relates to how time estimation is affected by simultaneous tasks that also require allocation of cognitive resources (attention). The evidence shows that the more demanding the non-temporal or secondary task, the more affected is the time estimation. This result leads to the idea that time estimation requires executive control of attention.

Research in prospective memory should consider the revisions of time estimation theories and models of executive control of attention, which may be associated with the idea of monitoring and active maintenance of intention in time-based prospective memory paradigms. More research is needed to generate and integrate evidence from imaging studies in prospective memory and the well-developed body of literature in time estimation (Block & Zakay, 2006).

One of the brain regions associated with executive control of attention is the anterior cingulate cortex, which was consistently revealed by ERP and ERSP measures of the two tasks performed in this study, word categorization and prospective memory. The next section discusses the role of the anterior cingulate cortex in the present time-based prospective memory paradigm.

5.6.3 Role of the anterior cingulate cortex

The anterior cingulate cortex was the area with the highest convergence in the ongoing and the time-based prospective memory tasks. It may be argued that the changes observed in this region, are due to the role of this area for both tasks, limiting the amount of resources available and explaining the decrease in the accuracy of the ongoing task during the prospective memory block.

The ongoing task events showed an increase in theta synchronisation, starting at 200ms after word onset. This synchronisation decreased during the ongoing plus prospective memory block, particularly for the frequency band between 5-7 Hz (Figure 5-5). In addition, activity in the anterior cingulate also showed a decrease of alpha synchronisation during the block, observed particularly for the lower alpha band (7-9 Hz). These results were similar for related and unrelated words when analysing the high- and low-performance groups together. The decrease in the theta band may be indicating that part of the activity of the anterior cingulate gyrus is devoted to time estimation, thus less resources are available to decide whether a word is related or unrelated. In addition, increase of alpha suppression may be indicative of increased ‘mental activity’ or neural activation (Klimesch, 1999), meaning that strong involvement of the anterior cingulate is required to perform both tasks simultaneously.

We inspected ERSP from the anterior cingulate cortex separately for high- and low-performance group. The results showed that theta synchronisation was significantly reduced only for the high-performance group and particularly for unrelated items. Whereas stronger alpha suppression was observed for both performance groups, but was significant only in small time windows, corresponding to the 200ms at the beta band (11-15 Hz) and close to 600ms for the lower alpha band (7-9 Hz) in the low-performance group. It may be argued that decrease in theta synchronisation for the combined task block, particularly for the high-performance group, may be a correlate of the strategic monitoring shown by this group, meaning that the high-performance group was devoting more resources to the time-based task compared to the low-performance group. Modulations showed by the ERPs of the ongoing task are also consistent with this hypothesis.

The decrease in theta synchronisation during the ongoing PM block was observed around 400 and 600ms. The same time windows showed a decrease in the voltage of the ongoing task events, for the high-performance group (Figure 5-6). The differences in the low-performance group are smaller. Thus, the same rationale used to interpret the ERSP results may apply to explain these differences.

The anterior cingulate cortex shares function between both tasks, and the high-performance group show more strategic use of the resources to perform the time-based prospective memory task relative to the low-performance group. This is reflected by: (1) neural activity of the anterior cingulate cortex in the domain of amplitude of the signal (potential) and frequencies (power) and (2) by the strategic monitoring behaviour shown through the distribution of the time-checks. In addition, the task requires an increase in the neural activation of the anterior cingulate cortex, reflected in the increase of alpha/beta suppression for both performance groups.

Previous ERP research in time-based prospective memory showed an increase in voltage in frontal electrodes, which the authors associated with a ‘monitoring effect’ indicating that this was a correlate of maintaining the intention ‘active in mind’ (Cona et al., 2012). We propose that this interpretation is unlikely, because there is no reason to think that time estimation tasks required enhance processing of a particular feature of the ongoing task events (as is the case in event-based paradigms). The results that we present in this study are associated with the effect of the time-based prospective memory task in the processing of the ongoing task events, in the sense that there is a reduction of the resources available to perform the task. We concordantly see weaker theta synchronisation in times windows were the voltage of the signal is also reduced. The increase of alpha suppression for the ongoing prospective memory block of all groups, may be considered as a general index of increased ‘mental activity’, which may be (or not) associated with the processing of the particular epoch event.

In relation to the time-based prospective memory task, activation in the anterior cingulate gyrus has been consistently found in different types of time estimation studies (Okuda et al., 2007; Pouthas et al., 2000; Rubia, 2006; Rubia & Smith, 2004). This brain region is also involved in executive control of attention (Cohen, Botvinick, & Carter, 2000; Gehring & Knight, 2000; MacDonald et al., 2000) and probably, more than specific timing functions, it may be supporting cognitive control of attention. This may also explain why we did not find a clear temporal correlation between onset of alpha desynchronisation and the time-on-trial variable (5-8).

The role of executive control of attention in time-based prospective memory is supported by involvement of the anterior cingulate cortex and alpha/theta modulations showed by this region.

5.6.4 Are attentional mechanisms common to time-based and event-based prospective memory tasks?

The ongoing task used in the present experiment was the same as the one used in Chapter 4. One of the modulations observed in Chapter 4 – associated with monitoring during the ongoing prospective memory block – was the increase amplitude in occipital regions with a source in the left temporal fusiform gyrus or BA37. This modulation was explained by the requirement, of the event-based prospective memory task, to evaluate the ongoing task events, for the occurrence of a prospective memory cue. In the present task, the left posterior domain (BA37) did not show difference between the activity for ongoing control and ongoing prospective memory task events, supporting the idea that the time-based prospective memory task did not require the assessment of the ongoing task events in order to fulfil the time-based intention. Thus, event- and time-based prospective memory tasks use different attentional mechanisms. This conclusion is also supported by the behavioural results.

The time-based prospective memory task produced a decrease in accuracy in the ongoing task (relative to the ongoing control block). However, no interference effect was observed in terms of the reaction time. Even more, reaction times during ongoing prospective memory block tended to be faster[1]. These results are the opposite of the effect produced by the event-based prospective memory task. In the event-based experiment we did not observed changes in accuracy but participants slowed down their responses during the PM block particularly for the unrelated events. The difference in this pattern also suggests that the prospective memory tasks used in this thesis require different monitoring strategies. Thus, different mechanisms explain monitoring and maintenance of intentions, depending on the context of the task.

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[1] Late significant differences between ongoing control and ongoing PM block in posterior brain domains may explain this reaction time difference; see figure 5-5.

Guynn's Monitoring Theory describes how prospective memory may operate – by means of retrieval mode and target checking – but it lacks a detailed description of what are the neural correlates or brain networks associated to monitoring, leading to the question of what strategic monitoring means in the context of time-based prospective memory tasks. Is it the same cognitive process engaged across different types of prospective memory tasks or does it involve mechanisms particular to time-based prospective memory?

We have shown that a general definition of monitoring can be applied to prospective memory tasks. However, the brain mechanisms supporting monitoring will be different depending on the particular nature of the task. Monitoring in time-based prospective memory tasks is based on time estimation and executive control of attention. The anterior cingulate cortex seems to support strategic monitoring in time-based prospective memory tasks.

5.6.5 Limitations

The requirement for time estimation can vary among different prospective memory tasks, depending on the availability of external indicators of time (for example, to have a clock continuously visible). To further explore the involvement of time estimation as a component of monitoring in time-based prospective memory task, would require use of tasks that allow different degree of internal time estimation.

Another limitation of this study may be related with the low number of time-check and clock-reset events, mixed with the different strategies that each subject may apply to performing the task. This situation makes it difficult to find consistent patterns across all participants. Despite this, all participants consistently showed involvement of the anterior cingulate region, the particular way in which this area is involved might be associated to particular subject performance.

5.6.6 Future work

The distinction between event-based and time-based prospective memory tasks has been useful for the development of theoretical models accounting for prospective memory. However, in real life situations it is not always clear whether an activity is purely event or time-based. For example, if we leave something in the oven for 30 minutes, there will be a series of environmental cues that could prompt the intention of ‘turning the oven off’, it can be the smell from the kitchen or by having a telephone conversation where you tell someone that you are cooking, then (prompted by the conversation) you may go to check or turn off the oven. In order to study prospective memory using experimental approaches we differentiate cognitive process involved in different forms of prospective memory. However in real life situations, a combination of cognitive processes and strategies support performance, depending on the particular nature of the tasks in progress. EEG has traditionally been used in very tightly controlled experimental paradigms – the question arises as to whether it can be used in more ecologically relevant contexts that allow us to study brain dynamics in naturalistic situations. This will be examined in chapter 6.

Chapter 6
Card Sorting and Toast Task (CSTT): A prospective memory EEG paradigm involving participant head and hand movements

5.1 Abstract

Different brain imaging techniques have been used to study cognitive functions and brain mechanisms underlying prospective memory. These approaches require very tightly controlled experimental paradigms and involve subtle finger movements in response to simple images or words. However, real life activity demands rarely match these conditions. The present chapter explores the question of whether neural correlates of prospective memory can be studied in more ecologically relevant contexts. If so, are brain sources and dynamics obtained in free-movement prospective memory tasks similar with the dynamics obtained in a classical non-movement prospective memory experiment? The present chapter explores this question by presenting a time-based prospective memory task in free-movement conditions. The rationale for the present study follows the previous experimental Chapter 5, in order to compare results of similar tasks performed under different experimental contexts. Participants were asked to toast pieces of bread (in a virtual toaster) over a period of 2 minutes, while sorting cards according to changing rules. We used independent component analysis to identify brain sources relevant for time-based prospective memory during the performance of the complex ongoing task. The brain region most associated with time-based prospective memory performance was the rostral anterior cingulate cortex, which is thought to mediate executive control of attention. Activity in the anterior cingulate cortex showed a decrease in the upper-theta band (5-7Hz) and strong alpha suppression (7-11Hz) during the 2-minute toasting period in the prospective memory condition. This pattern of activity was less evident during the first part of the toasting period, when people relied more on internal time estimation. By contrast, time estimation strategies switch towards using external cues to estimate the time, as the toasting time progresses, during which theta synchronisation decreased and alpha activity showed greater suppression.

5.1 Introduction

Prospective memory tasks have been studied in laboratory contexts in order to investigate the cognitive processes and brain mechanisms underlying different forms of prospective memory tasks. These studies have disentangled the main brain regions involved in prospective memory performance. fMRI and PET studies have shown specific involvement of the prefrontal cortex (BA10) in performing different types of prospective memory tasks (Burgess et al., 2011; Okuda et al., 2007). This brain region has been hypothesised to control the focus of attention either towards environmental stimuli or by contrast, to internally generated representations (thoughts or intentions), maintaining the intention actively in mind, while attending to, and executing, ongoing tasks (Burgess et al., 2007).

Most of the evidence in prospective memory has been collected using event-based prospective memory paradigms; when an external cue prompts the retrieval of the intention. Time-based prospective memory paradigms (driven by internal time estimation or demanding monitoring processes), have received less attention. The present PhD work has shown temporal correlates of prospective memory using both event and time-based prospective memory paradigms. We have shown electroencephalographic evidence of involvement of the anterior cingulate cortex, probably mediating attentional control in demanding prospective memory tasks (time-based or conceptually driven event-based tasks; see Chapter 4 and Chapter 5). We have also shown involvement of brain regions that are part of top-down and bottom-up attentional networks, for detection of prospective memory cues and retrieval of intentions, in low-demand (perceptually driven) event-based prospective memory tasks (Chapter 4).

All these non-movement experimental paradigms allowed us to explore cognitive process and mechanisms associated with different types of prospective memory tasks. However in real life situations, a combination of cognitive processes and strategies support performance, depending on the particular nature of the tasks in progress (Scullin et al., 2013). Contexts and environmental demands in real life situations are not controlled, thus unexpected situations can occur. During the delay period we deal with more than one task at the same time, which are usually demanding and prevent us from continuously attending to the prospective memory intention. In addition, the responses given in real-life situations usually involve considerable movement. Current paradigms require minimizing complexity of task materials and participant responses, usually involving subtle finger movements in response to simple images or words, which is far from the conditions faced in real-life situations.

In addition to the infrequent used of time-based prospective memory paradigms, the use of free-movement paradigms in EEG is not common and no experiments on prospective memory have used this approach. In the present experiment, we explored a new time-based prospective memory paradigm taking advantage of new approaches in EEG research (Makeig, 2009; Makeig et al., 2009). The aim of this study was to answer the following questions: Can we obtain physiologically meaningful brain activities in free-movement time-based prospective memory tasks? Are brain sources and dynamics obtained in free-movement prospective memory tasks similar with the dynamics obtained in a classical non-movement time-based prospective memory experiment? Is there any EEG measure associated with the performance of the time-based intention?

Participants undertook an ongoing foreground task and in addition, a time-based prospective memory task involving two computer screens. Unlike in most cognitive EEG experiments, they were allowed to freely move their arms and to rotate their head to view the two screens. As the foreground task we used an adaptation of the Wisconsin Card Sorting Test (WCST) (Nelson, 1976). The current time-based prospective memory task involved 'toasting bread' in a virtual toaster.

5.1 Materials and Methods

6.3.1 Participants

Twenty participants were recruited from the Swartz Centre for Computational Neuroscience (SCCN) subject pool, consisting mainly of undergraduates and graduates students from the University of California San Diego (UCSD). The mean age was 24.9 years with standard deviation of 5.4 years. Nine males and eleven females participated in the study, all of them right-handed. Written informed consent was obtained from all participants.

6.3.2 Procedure

Two research assistants provided participants with general information about the experiment and obtained the consent forms. They placed a 128-channel EEG cap on participants' head plus eye, muscle and reference sensors. Conductive gel was inserted into each electrode using a syringe with a blunt-tip needle, with the aim of establishing a proper connection between the scalp and the electrodes. The active EEG electrodes and amplifier used were part of a Biosemi2 system. The locations of all electrodes were measured using an ultrasonic system 'Zebris ELPOS' that allowed determining exact electrode position on the cranium. The whole procedure, including the experimental task, took approximately one hour. Participants were provided with towels and shampoo to clean the gel from their hair. They received 15USD as compensation for their time.

6.3.3 Task description

Participants were asked to toast pieces of bread on a virtual toaster while performing a card-sorting task. The toaster task measured the ability of participants to remember to do something after a delay, which defines a prospective memory task. The purpose of the card-sorting task was to continuously capture participants' attention so as to keep them from focusing on their concurrent time-based prospective memory task.

A computer screen was located in front of the participant with a keyboard to enter the responses for the card-sorting task. A second computer screen was located to the right of the participant displaying a virtual toaster. Participants could not see the screen to their right without completely turning the head (during the pilot sessions some participants used their peripheral attention to track changes or receive cues from the second screen). Participants used a computer mouse, located next to the 'toaster screen', to 'turn-on' and 'turn-off' the virtual toaster (Figure 1A).

Both tasks were programmed using Python and a Simulation and Neuroscience Application (SNAP). SNAP is a software environment developed in Python to program experimental protocols at SCCN (https://github.com/sccn/SNAP).

6.3.3.1 Ongoing task

As the foreground task we used an adaptation of the Wisconsin Card Sorting Test (WCST) (Nelson, 1976). The WCST requires people to change task settings continuously by categorising playing cards according different rules that they have to discover. The rules are discovered using the feedback given by the clinician or experimenter. Because of its cognitive demands, the WCST has been widely used to evaluate frontal lobe functioning (Chan, Shum, Toulopoulou, & Chen, 2008), particularly, cognitive flexibility, planning, mental set shifting and inhibition. We chose this test because it is demanding and requires changing context settings and sustained attention across the trials.

Participants were asked to unambiguously match a single card presented on the computer screen with one of four comparison cards also displayed on the screen (Figure 6-1B). The single card had only one common dimension with the comparison cards, either colour, shape or number, these three were the different rules that participants could apply to match the cards. For example, if the target card showed three blue **triangles** and the rule was **shape**, the correct match corresponded to the comparison card displaying one red **triangle**.

Visual feedback was given immediately after the response, with the words ‘Correct!’ or ‘Incorrect!’ displayed in green or red respectively. The rule changed unexpectedly after 6 to 10 correct responses. To discover the new rule participants had to respond using any of the remaining two rules, until they received the ‘correct’ feedback again. Participants were supposed to maintain or change the criteria used for matching the cards according to the feedback received. Feedback was displayed for one second, a new card was displayed immediately after and the participant had a maximum of 2 seconds to give a response. If no response was given a new card was presented. The speed of the card-sorting task was thought to be demanding and favour continuous involvement of the participant in the task, to avoid rehearsal of the time-based prospective memory task.

A ‘Correct!’ feedback meant that the participant should maintain the criteria for responding to the next card. ‘Incorrect!’ feedback could mean two different things, the participant either: had to change rule and try with the other two possible rules available or, he/she made an error. Two types of error were defined, following the description used in previous EEG experiments (Barcelo, 1999; Barcelo & Knight, 2002): (i) Distraction errors; meaning a difficulty to maintain the category and operationalized as any error committed posterior to the discovery of the correct rule and (ii) Perseverative error; meaning a difficulty to discover the new rule and operationalized as any error committed before the discovery of the rule for that category trial (see box 1).

All the trials performed under the same rule were considered as one series (Figure 6-1D), which started with an incorrect feedback categorised as a shift trial and indicating that a new rule had to be applied, the second trial could either be another shift (indicating that there is only one category left) or a correct trial, indicating that the participant found the right rule for the series. Any correct response given by accident at the beginning of a series was disregarded in the posterior analysis.

The Card Sorting Game had 200 trials during the baseline and at least 800 trials during the prospective memory block. Participants were allowed to take a break after the baseline block and then half way through the toaster block. As this paradigm did not involve head fixation or any maintained posture, participants did not feel the need for frequent breaks. The task was coded in a way that the card sorting task did not offer breaks or did not finish if the toaster was on, resulting in a variable number of trials per participants.

Box 1. Card sorting task – trial definition

Shift: Incorrect feedback that indicated the shift of rule or category.

Stay: Correct feedback that indicated that the person was using the right rule to sort the cards.

Perseverative Error: The person received two shift incorrect feedbacks and continued to try with the same incorrect categories.

Distraction Error: The person gave an incorrect response after having responded correctly for that series.

No Response: If the person did not give a response within two seconds a new card was shown.

Anticipation: The person responded with the correct category by chance without receiving a previous shift incorrect feedback.

Note: the feedback on the screen only showed correct or incorrect responses, the trial categorisation was performed off-line.

6.3.3.2 Prospective memory task

The time-based prospective memory task consisted on ‘toasting bread’ in a virtual toaster. Participants were asked to turn on the virtual toaster and then to turn it off after approximately two minutes. If they did not turn the toaster off in time, the piece of toast was ‘burnt’; if they turned it off too early, it was not ‘done.’ Their goal was to successfully toast as many pieces of bread as they could during the 30-minute experiment session (Figure 6-1C).

A delay time was enforced after using the toaster (toaster cooling off), so that the participant was prompted to continue performing the card-sorting task before starting with a new piece of bread. Only clicks between 95 and 115 seconds were considered as good. If they clicked the toast button before 95 second the toast was not ready, if they clicked the button after 115 seconds the toast was burnt, in both cases the toast did not count towards the total number of pieces of toast made. After 120 seconds the toaster went off automatically and it started to 'cool off' for the next toasting period. Participants did not receive any salient feedback if they forgot the toaster, and could only know the toaster status if they actively checked on it.

The colour of the slice of bread gradually changed from white to gold during the first 95 seconds, between 95 and 115 seconds the colour varied from light to dark gold and after 115 seconds the toast turned black (burnt toast). Participants did not receive any feedback about the state of the toasting bread, unless they pressed a 'check-toast' button on the keyboard, which displayed the piece of bread in the bottom-right corner of the card-sorting task screen (Figure 6-1B), the rest of the time the piece of bread was hidden. When participants clicked on the toaster button to turn it off, they received feedback by displaying the resulting toasted bread on top of the toaster (Figure 6-1C). Note that in general, feedback from the toaster task was given only when the participant decided to check the toast or click on the toaster button. Thus, the toaster task is considered as self-initiated: participants did not receive any environmental cue or reminder to prompt toast-checks or to press the toaster button.

Participants were instructed to check on the colour of the toast a maximum of two times per toast, to help them make the decision of when to turn off the toaster. They were previously shown pictures with the toast in different colours and emphasis was placed on the gold colour to indicate the ideal toast. They were told that the toast would get burnt towards the end of the two-minute period.

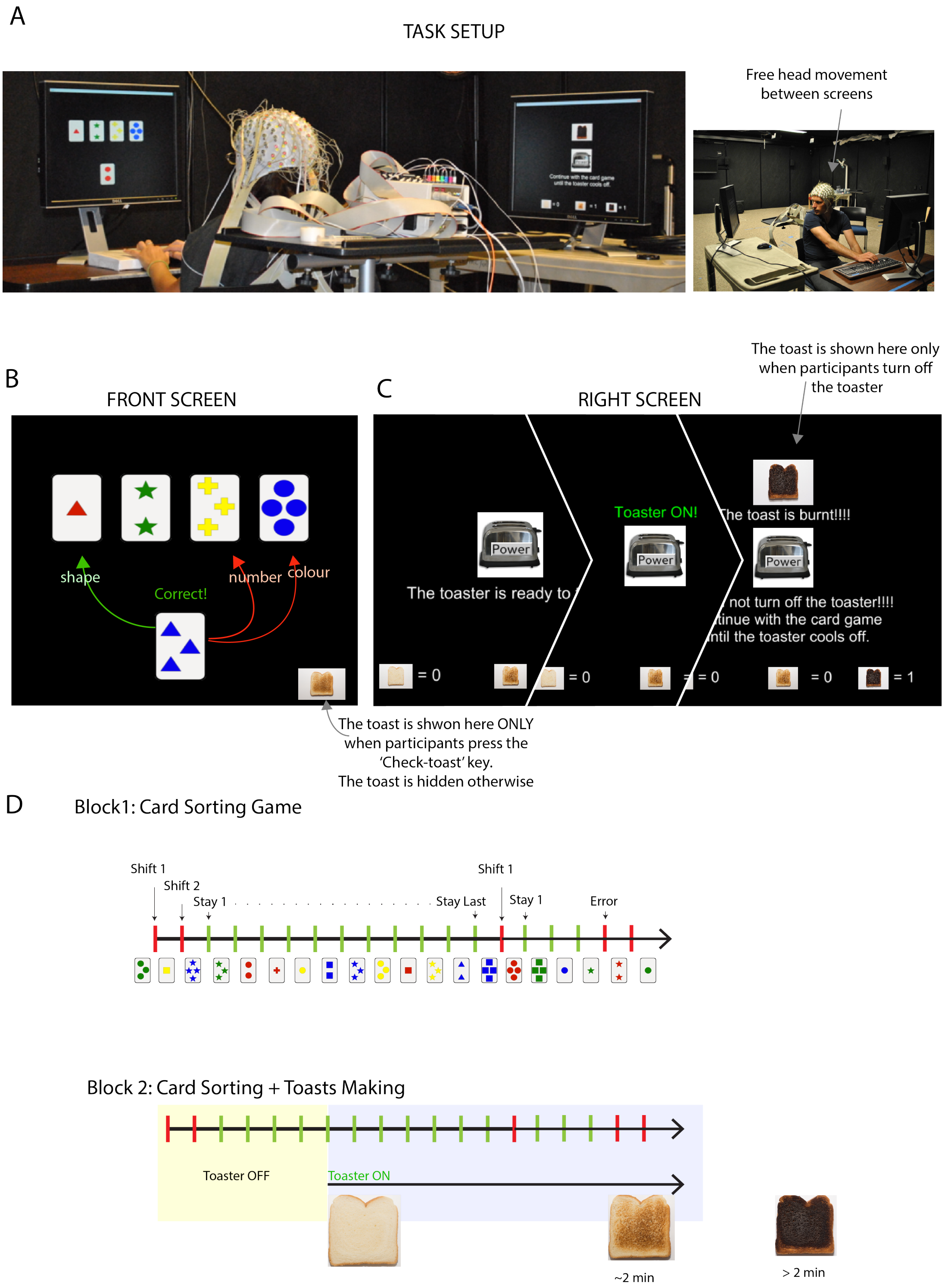

Figure 6-1. Experimental design (A) Task setup, participants were able to move their head and arms to change their point of gaze between the two screens. (B) The Front Screen display: Here, the matching rule in effect is 'Shape.' 'Correct!' feedback is displayed when the single card is matched to the first (upper left) comparison card. 'Incorrect feedback!' would indicate: an error or change of rule, to 'Number' or 'Colour' (red arrows). (C) Three different displays for the right screen, depending on whether the toaster is ready to toast, turned on and toasting, or 'Toast burnt!' (i.e., the participant forgot to turn off the toaster). A (successful) toast counter is shown at the bottom of the screen. (D) Only the card-sorting task was performed in the first 10-minute block (top): red bars indicate incorrect feedback; green bars indicate correct feedback. In the second block of the experiment participants performed the card-sorting task as well as the toast-making task (bottom).

During the pilot period of the experiment some participants checked for the toast continuously, thus the maximum of two checks per toast was established in order to avoid continuous rehearsal of the toaster task and to prompt strategic monitoring of the toast while they maintained their best performance on the card-sorting task. 'Toast-checks' is an important aspect of this paradigm; previous time-based prospective memory tasks (see Chapter 5) showed that people tend to strategically check for the passage of time towards the end of the delay period.

6.3.4 Data acquisition

EEG data were collected from 128 scalp electrodes, from two periocular electrodes placed at the edge of the outer canthus, two mastoid and two neck electrodes located 3 cm below mastoid and 3 cm lateral from midline, in order to detect head rotations (Sommerich, Joines, Hermans, & Moon, 2000). The data was collected at 24-bit A/D resolution and 2048 Hz sampling rate, down-sampled to 512 Hz. No analog processing was performed. Participants were allowed to rotate their heads and move their arms in order to operate both screens. All the events produced during the experiment were described using Hierarchical Event Descriptors (HED) tags (Bigdely-Shamlo, Kreutz-Delgado, et al., 2013), which is a system that proposes a uniform and detailed ontology for each of the events in an experiment, facilitating future analysis, sharing the data and comparing different experimental paradigms.

6.3.5 Behavioural data analysis

Performance in the toast-making task was examined based on two variables: number of good pieces of toasts and timing of the toast-checks. The first variable represents the accuracy in the performance of the time-based prospective memory task, and the second variable represents the monitoring behaviour, which is associated with the time estimation function (Mioni & Stablum, 2014). Performance in the card-sorting task was examined based on accuracy and reaction times of the different event types (box 1). Performance in the card-sorting task in parallel with the toast-making task represents the 'task interference effect' or, the cost of maintaining the intended action. Each of these variables is detailed below:

6.3.5.1 Accuracy for time-based delayed intentions

The goal in the prospective memory task was to toast as many pieces of bread as participants could while performing the card-sorting task. An accurate performance was defined as to turn off the toaster when the piece of bread was ready: participants were previously informed using images of what was considered a good piece of toast (gold colour) and they were told that the toasting time was approximately 2 minutes. The maximum number of good pieces of toasts was 9, if participants performed accurately along the whole experiment.

6.3.5.2 Monitoring behaviour

Previous time-based prospective memory studies have described monitoring behaviour as the self-initiated action of checking the time. As the target time approaches, participants check the time more frequently. The experiment performed in Chapter 5 of this thesis showed that strategic monitoring behaviour is a strong predictor of good performance in the prospective memory task. This result is consistent with previous studies of time-based prospective memory (Mantyla et al., 2007; Mioni & Stablum, 2014).

Monitoring behaviour has been associated with time estimation ability. If time checks are performed towards the end of the target time period, it can be interpreted as during the first part of the period people are relying more on an internal clock estimation, thus require less external clock checking. When the response period (or target time) is getting closer, people rely more on external time checking in order to give an accurate response (Block & Zakay, 2006; Mioni & Stablum, 2014). In the present experiment, participants checked time by checking the colour of the toasting bread. Participants were allowed to check the bread a maximum of two times per toasting trial and strategic monitoring behaviour was defined as performing the toast-checks close to the response time (turn off the toaster). Each of the toast-checks was tagged with the exact time when people performed the check.

6.3.5.3 Task interference effect

We also compared performance in the card-sorting task among three toaster stages, (1) NO Toaster; corresponding to the first block of the experiment, (2) Toaster ON; card sorting trials between clicks to turn the toaster on and off and (3) Toaster OFF; card sorting trials after turning the toaster off and before turning it on again. The idea was to explore any effect on the performance of the background card-sorting task while devoting resources to the toaster task.

Reaction time and accuracy were subjected to analysis of variance (ANOVA) using two repeated measure factors: Response type (shift, stay, distraction error, perseverative error and no response), and Blocks (No toaster, toaster ON and toaster OFF).

6.3.5.4 Index of strategic monitoring

Participants were instructed to maintain a high performance in the card-sorting task, while they toasted the bread. The relationship between the error rate and the correct number of toasts corresponds to the index of strategic monitoring. An ideal performance consisted of someone obtaining at least 8 pieces of good toast during the whole experiment, checking the toast towards the end of the toasting period and maintaining a good performance in the background card-sorting task.

6.3.6 EEG data analysis

6.3.6.1 Data processing

All experimental events were tagged with detailed information of the card-sorting task and toast-making task: Using a MATLAB code we classified the responses to the card-sorting task within the following categories: shift, stay, perseverative error, distraction error and anticipation (see box 1). Card stimuli previous to the response were tagged with the same information. In addition, all stimuli were tagged with timing information indicating when exactly the card stimulus and response occurred. This time information allowed classifying the card-sorting task events according to different time contexts. The format of this new information followed the hierarchical event descriptor (HED) tags for analysis of EEG data (Bigdely-Shamlo, Kreutz-Delgado, et al., 2013). An example of a HED tag for a card presentation, response and feedback is provided below:

Card presentation:

Stimulus/Visual/Shape/Rectangle/Playing Card/ [card name] – *Three_Red_Triangle*
Stimulus/Visual/Screen Location/Lower Center,
Stimulus/Visual/Background/Uniform Color/Black
Custom/Time-on-Toaster/#[time in seconds]

Response:

Response/Button Press/Keyboard/ [key]
Response/Button Press/Keyboard/Reaction Time/ #[time in seconds]
Custom/Active Rule/Color [or /Shape or /Number]
Custom/Response Type/Incorrect/Shift1 [or /Shift2]
Custom/Block/PM Card/PM1/ [card name]
Custom/Time-on-Toaster/#[time in seconds]

Feedback:

Stimulus/Feedback/On Accuracy,
Stimulus/Visual/Language/Latin/English,
Stimulus/Visual/Language/Sentence,
Stimulus/Visual/Uniform Color/Green,
Stimulus/Visual/Background/Uniform Color/Black,
Stimulus/Visual/Screen Location/Bottom
Stimulus/Visual/Word/Correct
Custom/Time-on-Toaster/#[time in seconds]

Data were visually inspected for bad channel removal. A high-pass filer at 1Hz (cut-off frequency of 0.5Hz) was applied to continuous EEG. The continuous data were cleaned as follows: Short-time high-amplitude artifacts were removed by statistically interpolating – in a sliding 1-second window – any principal components of the short-time EEG window. Criterion for removal was variance above a threshold of 15 or more standard deviations from the variance of uncontaminated EEG (taken from the cleanest part of the data). Each affected time point of EEG was interpolated by multiplying it by the interpolation matrix $I = M(V' \circ T)^{+}V'$ where M is a mixing matrix calculated from clean EEG, V are the principal components in the 1-second window, and T is a matrix of 0's for every principal component above the variance threshold and 1's for every component below the threshold, respectively. Infomax

ICA algorithm was performed on the continuous data to decompose into source-resolved activities. Equivalent current dipole estimation was performed using a Boundary Element Model of MNI head model (DIPFIT). After pre-processing, data were subjected to different data segmentation, in order to answer the questions of the present experiment (Figure 6-2).

6.3.6.2 Data segmentation

The aim of the analysis was to find electrophysiological features relevant for the time-based prospective memory task performance. In order to explore how the toast-making task interfered in the processing of card-sorting task stimuli, we examined changes in source-resolved event-related potentials (ERP) and event-related spectral perturbations (ERSP), time-locked to ongoing task events. Grand-average ERPs were computed for each stimulus type, card presentation and response/feedback. Note that each button press produced an immediate visual feedback, thus response/feedback events may contain activity associated with the response preparation and feedback processing. We studied card presentation events and response/feedback events separately, because previous EEG studies using card-sorting showed differential modulation of activity for these two events type (Barcelo, 1999; Barcelo & Knight, 2002). The EEG continuous data (previously submitted to ICA and dipole estimation) was segmented into two epoched datasets: One contained only activity locked to the card presentation, using 1 sec baseline and 2 seconds post-stimulus (card dataset), and other containing only response/feedback related activity, using the same time length (response dataset).

6.3.6.3 Clustering

It starts by identifying ICs from each dataset to be entered into the clustering process. Each dataset contributed 100 to 128 ICs, however, only 5 to 7 ICs per participant were retained for clustering, based on the dipole residual variance threshold (below 15% residual variance), resulting in 136 ICs for clustering.

The pre-clustering function, pop_preclust.m, available through the EEGLAB website (http://sccn.ucsd.edu/eeglab/allfunctions/pop_preclust.html), computed a *condition mean measure* used to determine the cluster 'distance' of ICs from each other. The condition mean measure was calculated based on the weighted combination of ERPs (weighting: 1), ERSP (weighting: 1) and dipole location (weighting: 8), the last one received the highest weight. IC clustering was performed using the k-means method in EEGLAB generating 7 clusters (http://sccn.ucsd.edu/eeglab/allfunctions/pop_clust.html). The number 7 was chosen based on the numbers of ICs selected for clustering (136) and number of participants (18 subjects, two participants were not included because of very noisy signal), allowing the maximum chance for each cluster to include one IC from each subject. Both datasets, card dataset and response dataset, we subjected to the clustering processes, resulting in the same clusters. These clusters were further inspected manually to check consistency, and some manual adjustments were performed to ensure both datasets contained the same clusters with the same ICs within each of them.

6.3.1.1 Statistical analysis

Data epochs from both datasets, card and response, were analysed comparing brain dynamics of the events under different time contexts defined using two EEGLAB study designs:

- ***EEGLAB study structure 1 or design 1:*** we defined three different contexts where card locked events and response locked events occurred. Context 1: ‘No Toaster’, ongoing task performance without toast making; Context 2: ‘Toaster On’, ongoing task performance plus toast making when the toaster was on. Context 3: ‘Toaster Off’, ongoing task performance plus toast making when the toaster was off. Each of the card and response events were tagged to indicate the current toasting condition: No Toaster, Toaster On, or Toaster Off. ERP and ERSP locked to card and response events were subjected to permutation one-way ANOVA with factor ‘contexts’ (No Toaster, Toaster On and Toaster Off) separately, False Discovery Rate (FDR) was used for multiple correction with α-level = 0.05. Post-hoc comparisons were performed using permutation t-test with FDR for multiple comparisons. The block effect is shown shaded in gray for the ERP differences and the difference between

No Toaster and Toaster On effect was reported for ERSP masking the difference at α-level = 0.01 (Figure 6-9). An additional single subject analysis was performed for two reasons: First, neither of the clusters included ICs from each of the 18 participants, moreover, the cluster with more significant differences (rostral anterior cingulate cortex) only contains 9 subjects, for this reason, we consider necessary to explore how consistent is the activity shown by each contributing IC. Second, as we identify a great variance in the behavioural performance (Figure 6-7), we considered it necessary to explore if any variability within the participants contributing to the cluster is associated with the variability in the performance. To carry out single subject analysis we measured average frequency power (dB) locked to 'No Toaster' card events and 'Toaster On' card events, for each participant in the cluster, in three frequency bands: upper-theta (5-7 Hz), lower-alpha (7-9 Hz) and upper-alpha (9-11 Hz) bands at two time windows: 200-400ms and 500-600ms (regions that showed statistical differences in the previous analysis). This analysis was performed with the card-locked dataset only (Figure 6-10 and 6-11). Only descriptive statistics are performed for this analysis.

- ***EEGLAB study structure 2 or design 2:*** In order to investigate how card-sorting task trials (card and response datasets) are affected by time estimation we studies ERSP in different time stages of toast-making, here the 2-minute toasting period was divided into 4 Toasting Segments of 30 seconds each. Each of the card-sorting task stimulus presentations was tagged with the Toasting Segment during which it was presented. This analysis was performed on the Rostral Anterior Cingulate Cluster only, the one that showed statistical differences according the EEGLAB study structure 1 analysis. ERSP locked to card and response events were subjected to permutation one-way ANOVA with factor ' time segments' (Time1, Time2, Time3, Time4), False Discovery Rate (FDR) was used for multiple correction with α-level = 0.05. Post-hoc comparisons were performed using permutation t-tests with FDR for multiple comparisons, α-level = 0.05. All the comparisons were performed against Time1 segment (Time1 vs. Time2, Time1 vs. Time3 and Time1 vs. Time4), in order to identify any change in the ERSP that may be associated with the progression of time (figure 6-12).

Figure 6-2 shows a graphic representation of the pipeline followed for the processing and analysis of the data. All data analysis was performed using EEGLAB (Delorme & Makeig, 2004) and code written in matlab.

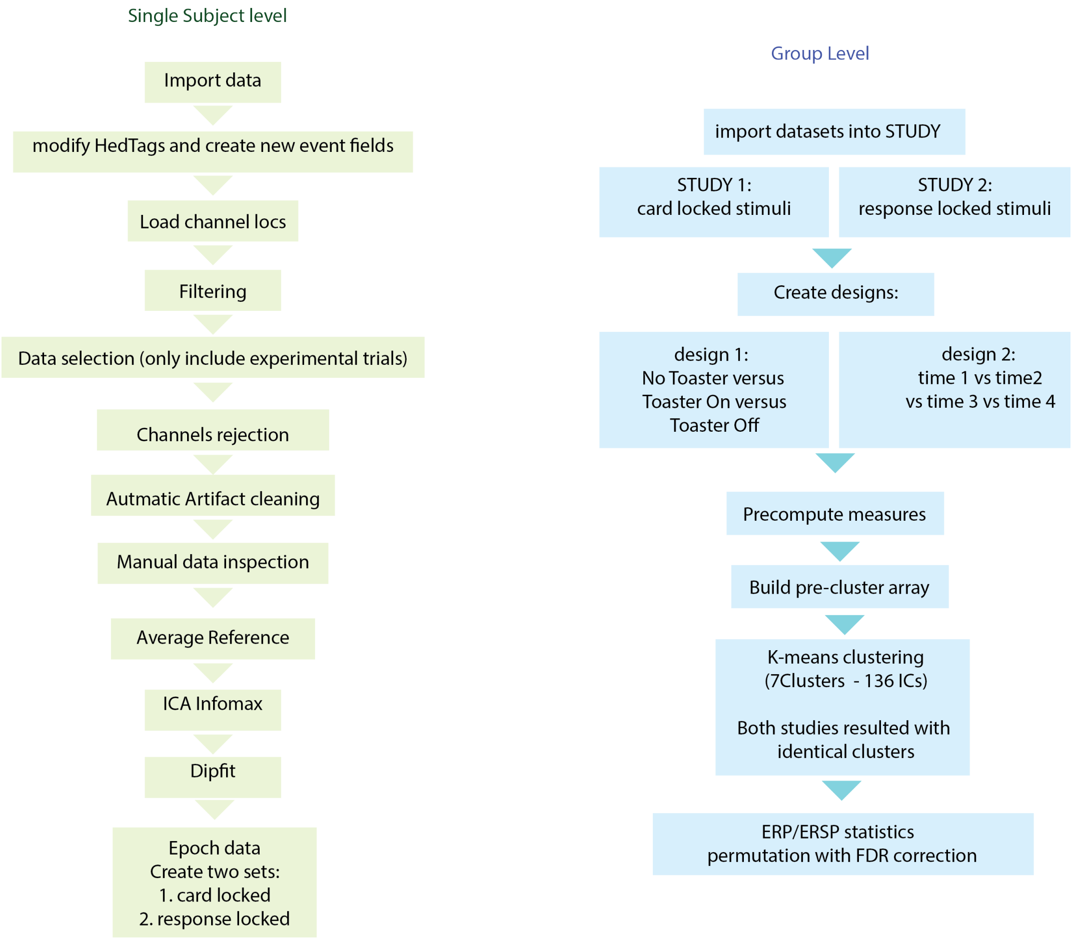

Figure 6-2. Pipeline followed for data processing and analysis.

Two datasets were discarded because of low quality data (subject 1 and subject 17). Datasets were imported into two STUDY functions of EEGLAB for the following group level analysis. One STUDY corresponded to the card epochs and the other to the response/feedback epochs. Both studies followed exactly the same computing measures parameters and used the same pre-clustering criteria: power spectrum, dipole location and scalp maps. The two designs described above were created for both studies. The resulting ERP and ERSP measures were compared using repeated measures ANOVA with permutation and FDR correction for multiple comparisons. For design 1 the ANOVA factor was ‘contexts’ (No Toaster, Toaster On and Toaster off). For design 2 the factor was time segments (from segment 1 to 4).

6.4 Behavioural results

6.4.1 Toasts-making task performance

The median performance of the group was 6.5 successful pieces of toast (Figure 6-3). In the group, five participants toasted 9 successful pieces of toast and 4 participants obtained 8 successful pieces. Participants with lowest performance produced 2 or 3 pieces of correctly toasted bread. 19 of the 20 participants forgot to turn off the toaster at least once. Figure 6-4 shows the mean time per participant for each toast-making task category.

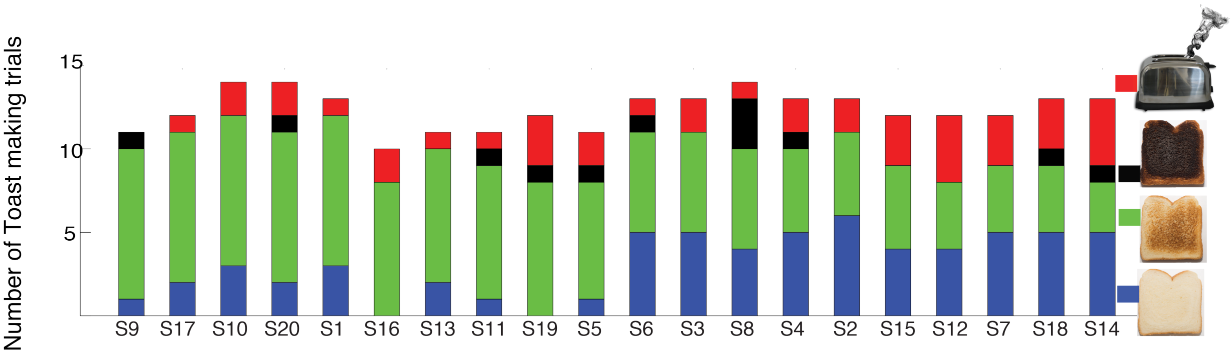

Figure 6-3. Toast-making task performance. Total number of pieces of toast successfully created by each participant; stacked bars indicate the numbers of Early, Correct, Late, and Forgot toast trials respectively.

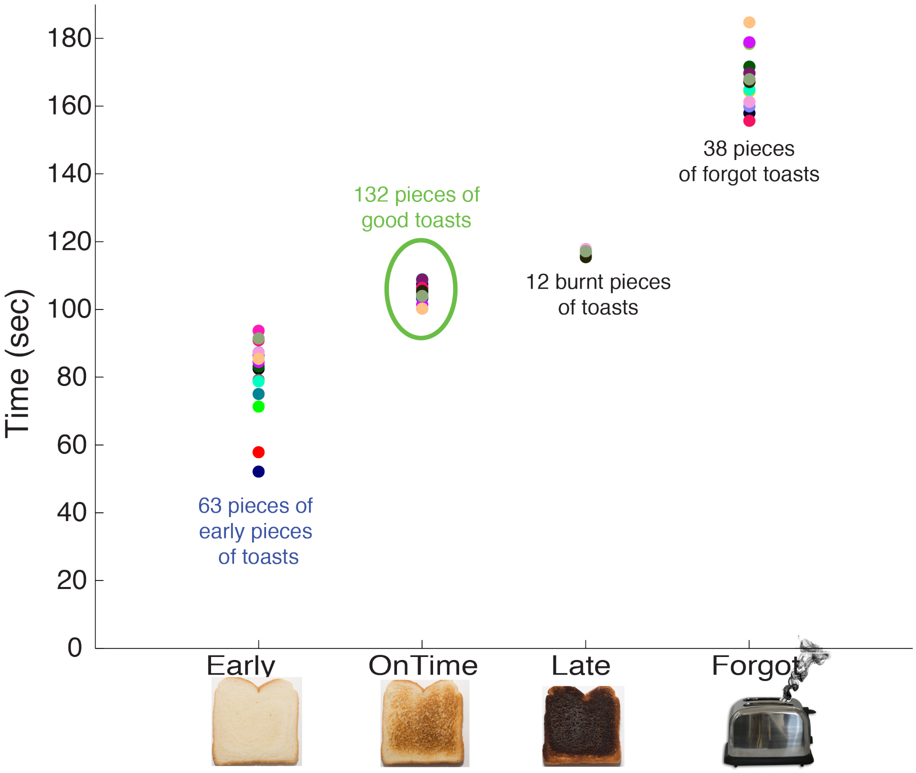

Figure 6-4. Mean time to Turn Off the toaster per participant for the four different toasting-result trial types. Values for 'Forgot' were calculated based on when participants turned on the toaster again after the two-minute trial had elapsed.

6.4.2 Monitoring behaviour

Good monitoring behaviour is associated with greater number of toast-checks towards the end of the toast-making time. It was hypothesised that participants would rely on their internal time estimation during the first part of the toast-making period and would switch to rely more on external time estimation (by checking the toast colour) as the toast-making time progressed.

Only two toast-checks were allowed in order to avoid continuous toast checking and to force participants to strategically use the two checking opportunities. The repeated measures ANOVA, using the number of the toast-checks as dependent variable and the time segments as main factor, showed a significant effect of time segments, F(1.8,48) = 35.6, p<.0001, partial eta squared = .69 (Greenhouse-Geisser reported). Participants checked the bread mainly between 60 and 90 seconds (mean=8.7, SD=0.5). Time segment 2 (mean=5.2, SD=0.7) and 4 (mean=5.6, SD=0.4) had similar means, whereas time segment 1 (mean=0.7, SD=0.2) was the time period were participants performed the lowest number of toast-checks (*post hoc* pairwise comparisons adjusted by bonferroni) (Figure 6-5). The repeated measures ANOVA also included a between factor ‘performance group’ (above and below the median), to explore if both performance groups presented similar pattern for toast-checks. The results showed a significant interaction effect ‘Time segments x performance groups’, F(3,54) = 9.668, $p<.001$, partial eta squared = .349, indicating that the groups performed differently. The ‘Below median group’ made most of the toast-checks in the middle time segments (between 30 and 90 seconds). In contrast, the ‘above median group’ made most of the toast-checks in the second half of the toast-making period (between 60 and 120 seconds), (Figure 6-5).

We also explored the timing of the errors in the card-sorting task within each toast-making trial, to see in which time segment participants were more distracted. The ANOVA used error rate as the dependent variable, time segments as a main factor and ‘performance group’ as between-subjects factor. The results showed a significant main effect of time segments, F(3,57) = 11.34, $p<.0001$, partial eta squared = .37. The highest error rate was shown in the first time segment (mean=.33, SD=.02) and the lowest in the last time segment (mean=.15, SD=.02). The error rate during the second and the third time segment was very similar (mean=.26, SD=.02). *Post hoc* pairwise comparisons were performed with Bonferroni correction (Figure 6-5). The results did not show a significant ‘Time Segments x Performance group’ interaction, F(3,57) = 1.36, $p>0.05$.

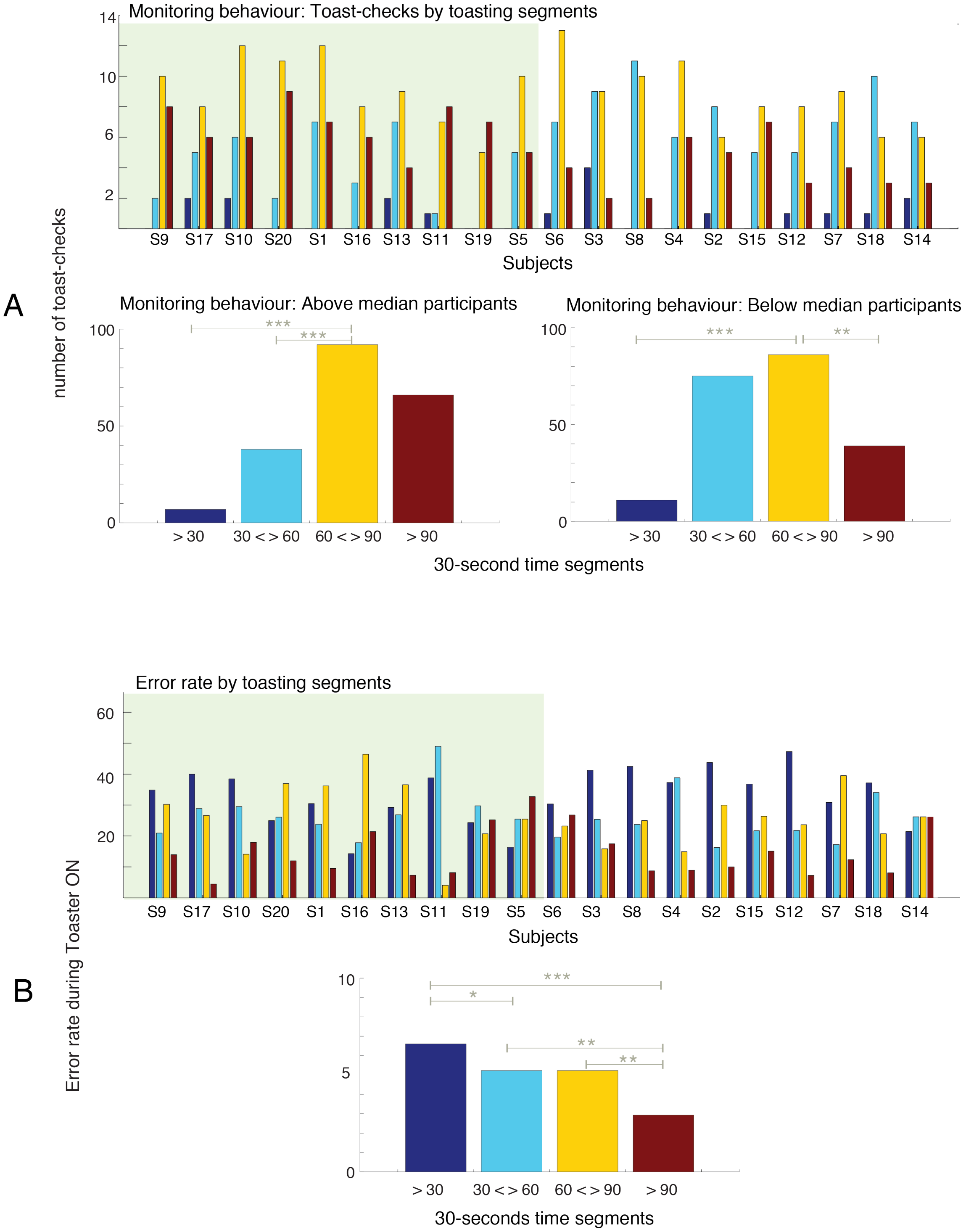

Figure 6-5.Monitoring behaviour. (A) Distribution of toast checking across the four Toasting Segments for each participant (top) and for the group (bottom). Note that participants that obtained accuracy above the median in the toast-making task, performed more toast-checks at between 60 and 90 seconds (yellow bar). (B) Distribution of card-sorting errors during the four Toasting Segments; participants tended to commit more errors during the first 30-second Segments (blue bar). Area shaded in light green shows subjects that performed above the median. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

6.4.3 Task interference: Effects of toast-making on card-sorting task error rate

We predicted that participants would commit more errors in the card-sorting task during concurrent toast making than when there was no prospective memory task, or at times when the toaster status was off. However, a repeated-measures ANOVA showed a marginal effect of the factor Block (baseline, toaster on, toaster off) with a small effect size, F(1.2,38) = 4.2, p=.05, partial eta squared = 0.18 (with Greenhouse-Geisser correction). Participants committed more errors during the first task block when the toast-making task had not yet been introduced (see Table 6-1 and Figure 6-6).

In terms of reaction times, the repeated measures ANOVA showed significant main effects for Blocks, F(1.4,38) = 7.5, p< .01, partial eta squared = .283 (Greenhouse-Geisser reported) and Response type, F(2,57) = 46.9, p< .001, partial eta squared = .712 (with Greenhouse-Geisser correction), *post hoc* analysis revealed that reaction times were faster during both toaster-on and toaster-off blocks compared to the single-task baseline.

These results showed that, in behavioural terms, the toast-making task did not interfere with performance in the card-sorting task, since responses to this task were quicker and more accurate when participants performed both tasks simultaneously.

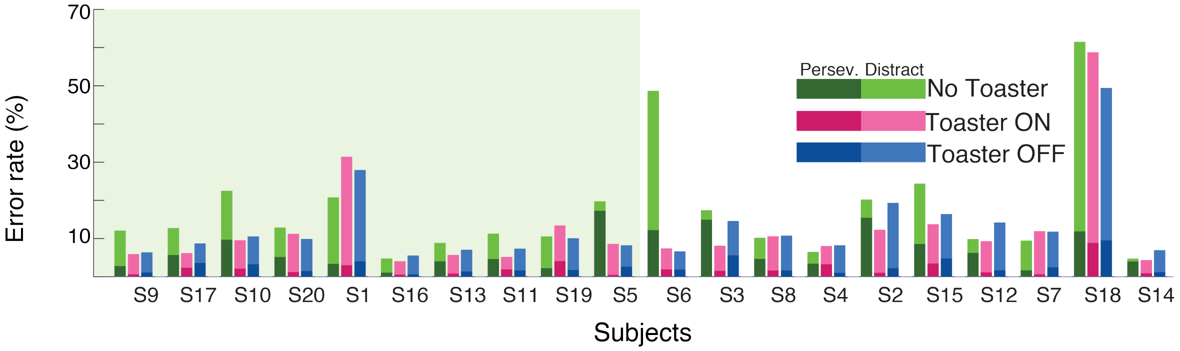

Figure 6-6. Task interference effect. Error rate in the card sorting task during the different Toasting Segments: Baseline (no toasting), Toaster On, and Toaster Off; stacked bars show the numbers of two types of errors: Distracted (light) and Perseverative (dark).

Table 6-1. No prospective memory task interference on card-sorting accuracy

	Error rate (%), mean (std).		
	Baseline	Toaster On	Toaster Off
Distracted	10 (12)	10 (11)	10 (8)
Perseverative	7 (5)	2 (2)	3 (2)
No Response	3 (3)	3 (2)	9 (5)

Table 6-2. No prospective memory task interference on card-sorting response times

	Reaction time (ms), mean (std)		
	Baseline	Toaster On	Toaster Off
No Rule Shift (correct)	932 (136)	864 (88)	875 (93)
Rule Shift (incorrect)	962 (148)	886 (88)	874 (112)
Distracted (incorrect)	1010 (243)	1000 (115)	1086 (134)
Perseverative (incorrect)	1206 (164)	1078 (153)	1022 (150)

6.4.4 Index of strategic monitoring

In time-based prospective memory tasks, an index of strategic monitoring can be operationalized as the relationship between error rate and performance. Someone who successfully created many pieces of toast and made a low number of errors in the card-sorting task would have a more efficient performance and could be said to have had a high index of strategic monitoring or a low monitoring cost, compared to someone making the same number of pieces of toast, but a higher number of card-sorting errors. To calculate the index of strategic monitoring we divided number of successful pieces of toast by the card-sorting task error rate during ‘Toaster On’ periods, the final value for each participant normalized to that of the best performer (Figure 6-7). Participants who obtained higher number of correct toasts (performed over the median) were also the ones with high index of strategic monitoring, with exception of two participants (S1 and S19) that made more pieces of toast but also increased the error rate during ‘Toaster On’ periods (see Figure 6-7).

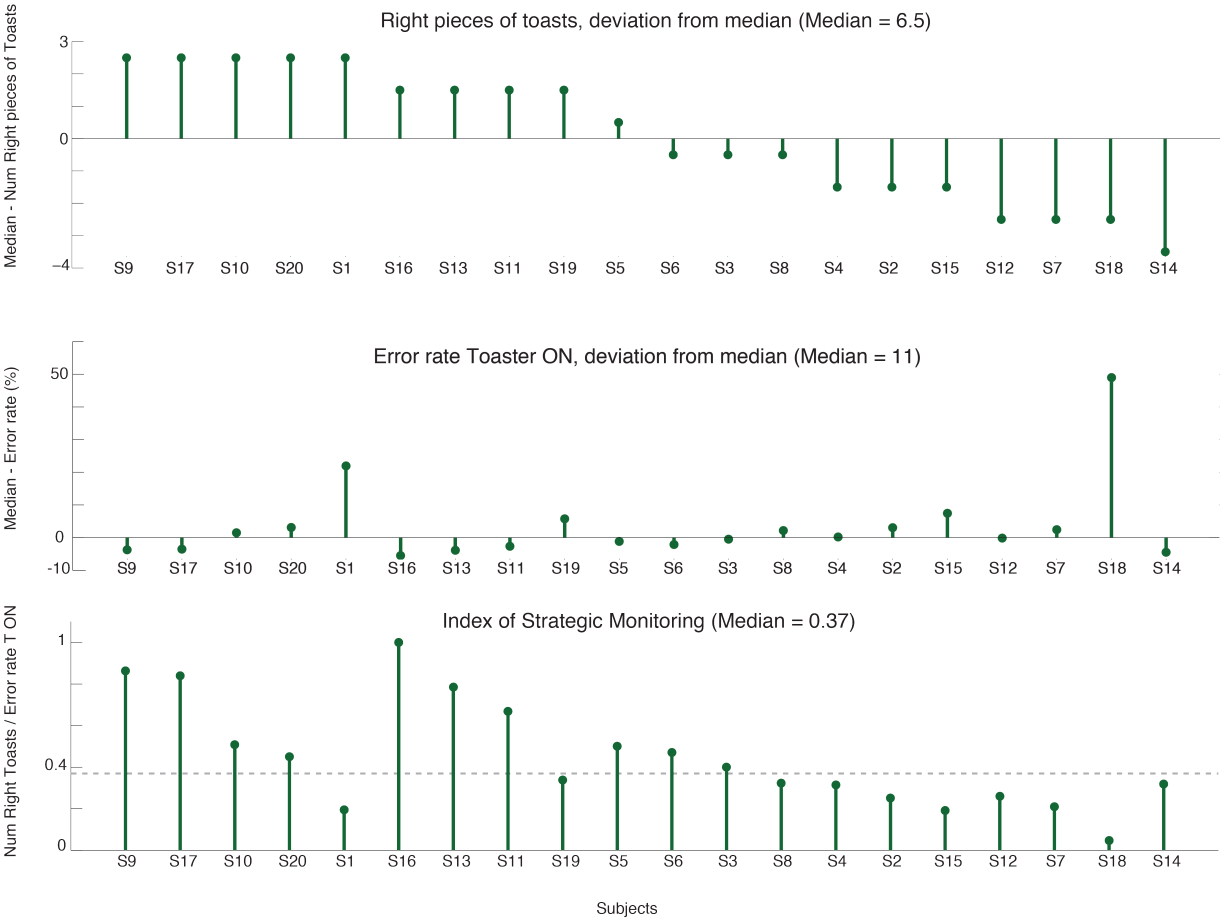

Figure 6-7. Index of Strategic monitoring and inter-subject variability for toast-making and card-sorting task. (top) Number of correct pieces of toast per participant relative to the median of the group. (middle) Error rate during Toaster On segments, relative to the median error rate of the group. (bottom) Index of Strategic Monitoring, measured as the relationship between the number of correct pieces of toasts and the error rate during the toast-making trials (toaster ON). A high index of strategic monitoring represents a good performance. The dashed line indicates the median. Subjects are sorted by number of right toasts as a first criterion and index of strategic monitoring as a second criterion (from left to right).

In summary, the behavioural results showed that: (i) Inter-subject variability in performing the toast-making task was high compared to performance of the card-sorting task. (ii) Response accuracy and reaction time in the card-sorting task improved when participants also performed the toast-making task. (iii) Participants ‘checked the toast’ most frequently in Toasting Segment 3 (60 - 90 seconds), consistent with the fact that ‘the toast was done’ between 95 and 115 seconds (i.e., early in Toasting Segment 4). The lowest frequency of toast checking was during Toasting Segment 1 (0 – 30 seconds) and (iv) the card-sorting task error rate was higher during Toasting Segment 1, the time segment where people relied more on internal time estimation (smallest number of toast-checks).

6.5 EEG results

6.5.1 Relevant brain clusters and dipole location

The k-mean cluster analysis revealed six brain clusters plus one cluster containing eye movements and one cluster containing muscle activity. Three of the six resulting brain clusters are located in the prefrontal cortex; the most anterior cluster centroid is located in or near right Brodmann area 46 (Cluster 1 in Figure 6-8). The second cluster seems to have its centroid in or near right anterior cingulate cortex, close to the motor area, right Brodmann area 24/6. Whereas the third frontal cluster seems to be part of the rostral anterior cingulate cortex, Brodmann area 24/32/34 (rACC cluster). However, this latest cluster is located deep in the brain and some of its components seem to lie in subcortical structures. Note: In equivalent dipole fitting, depth is the dimension of least certainty (Akalin Acar & Makeig, 2013).

Of the other three clusters, one cluster showed its centroid located in the left precentral gyrus (Brodmann area 4). The cluster that shows an occipital scalp distribution has equivalent dipoles located close to the right temporo-parietal junction (Brodmann area 37) and posterior cingulate cortex (Brodmann area 30). The left occipital cluster showed equivalent dipoles located in the middle temporal gyrus (Figure 6-8). The cluster containing eye movements is not shown.

Event-related measures for only three of the seven clusters exhibited differences between card events and responses in the different toast-making contexts: No Toaster, Toaster On and Toaster OFF (Figure 6-9). Activity in these clusters was further explored to evaluate if these changes were associated with strategic monitoring (changes across the 30-second time segments).

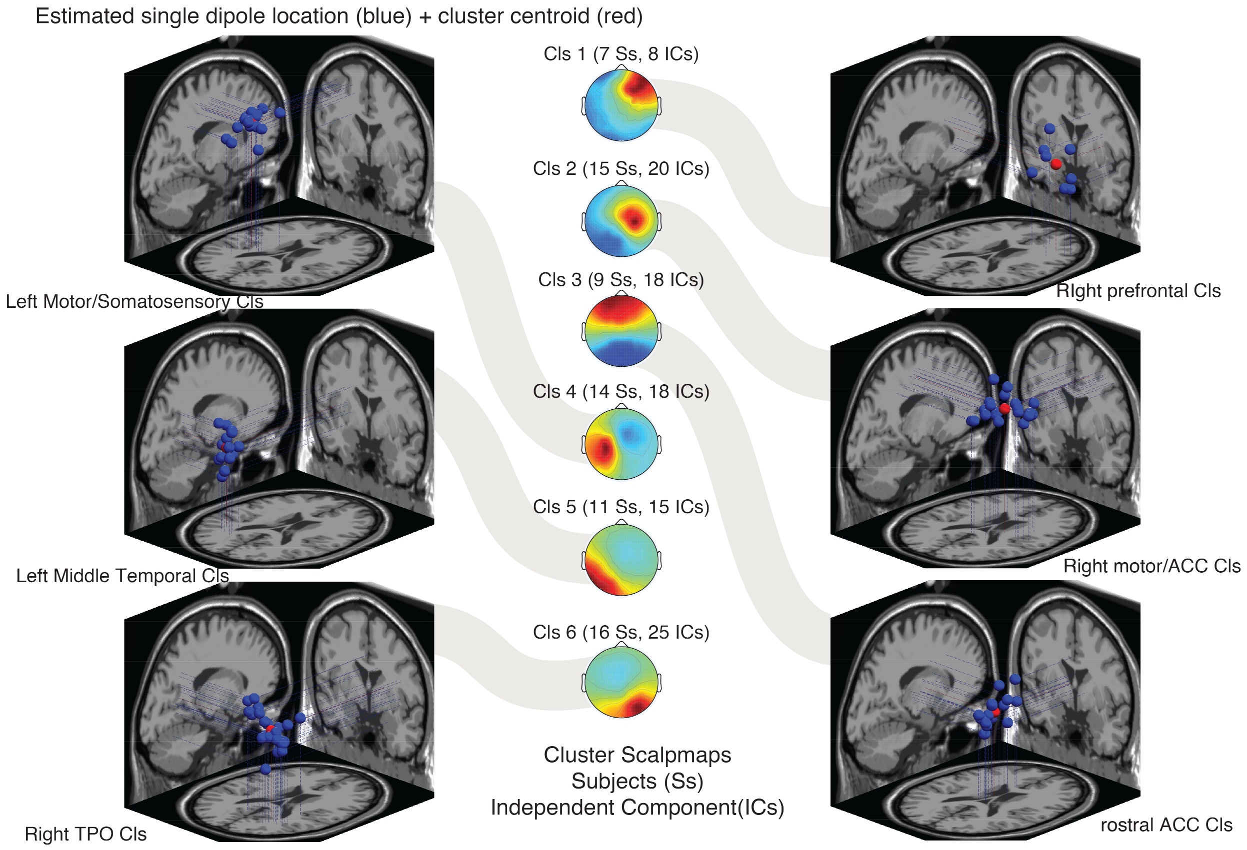

Figure 6-8. Scalp maps and estimated equivalent dipole locations. The central column of this figure shows the mean component topographic projection (scalp map) for each of the clusters, which were obtained using log power spectra, equivalent dipole locations and scalp maps in constructing the component distance metric used in clustering. For each of the clusters, the number of subjects included (Ss) and the number of independent components (ICs) are indicated. The equivalent dipole locations are also shown; blue balls represent individual IC locations and red balls, the cluster centroids.

6.5.2 Effects of the toaster task on brain activity during the card sorting task

6.5.2.1 Ongoing control (No Toaster) versus Ongoing PM (Toaster on)

ERP and ERSP comparisons were performed within a latency window from 200 msec before to 800 msec after the time-locked events. The results showed that two frontal and the right occipital clusters exhibited differences between card-sorting only (No toaster) and card sorting plus the prospective memory task (Toaster On). All comparisons were performed using a one-way repeated measure ANOVA using task blocks as a factor (No toaster, Toaster On, Toaster Off) with non-parametric statistics using permutation bootstrap with FDR correction. The analysis was performed for card presentation events and response/feedback events separately.

For both measures, ERP and ERSP, Cluster 3 (rACC) showed the strongest condition differences (Figure 6-9B). The amplitude of the ERP was larger following card presentations during No Toaster (card-sorting alone) compared to either Toaster On or Toaster Off (card-sorting plus toast-making), particularly at latencies near 200 msec and between 300 and 600 msec. For the response/feedback event measures, task condition differences were stronger near 200 msec. The ERP of the Right Occipital cluster only showed significant differences when time-locked to card presentations (Figure 6-9C).

In general, ERSP measures for the three clusters showed stronger alpha suppression following card presentations in the ‘Toaster On’ PM condition than in the single-task ‘No Toaster’ condition. Rostral ACC and right motor/ACC clusters showed decrease of upper theta power during ‘Toaster On’ condition.

Response/feedback events produced the opposite effect: an increased of power in the lower (7-9 Hz) and upper alpha (9-11 Hz), for the ‘Toaster On’ condition (Figure 6-9).

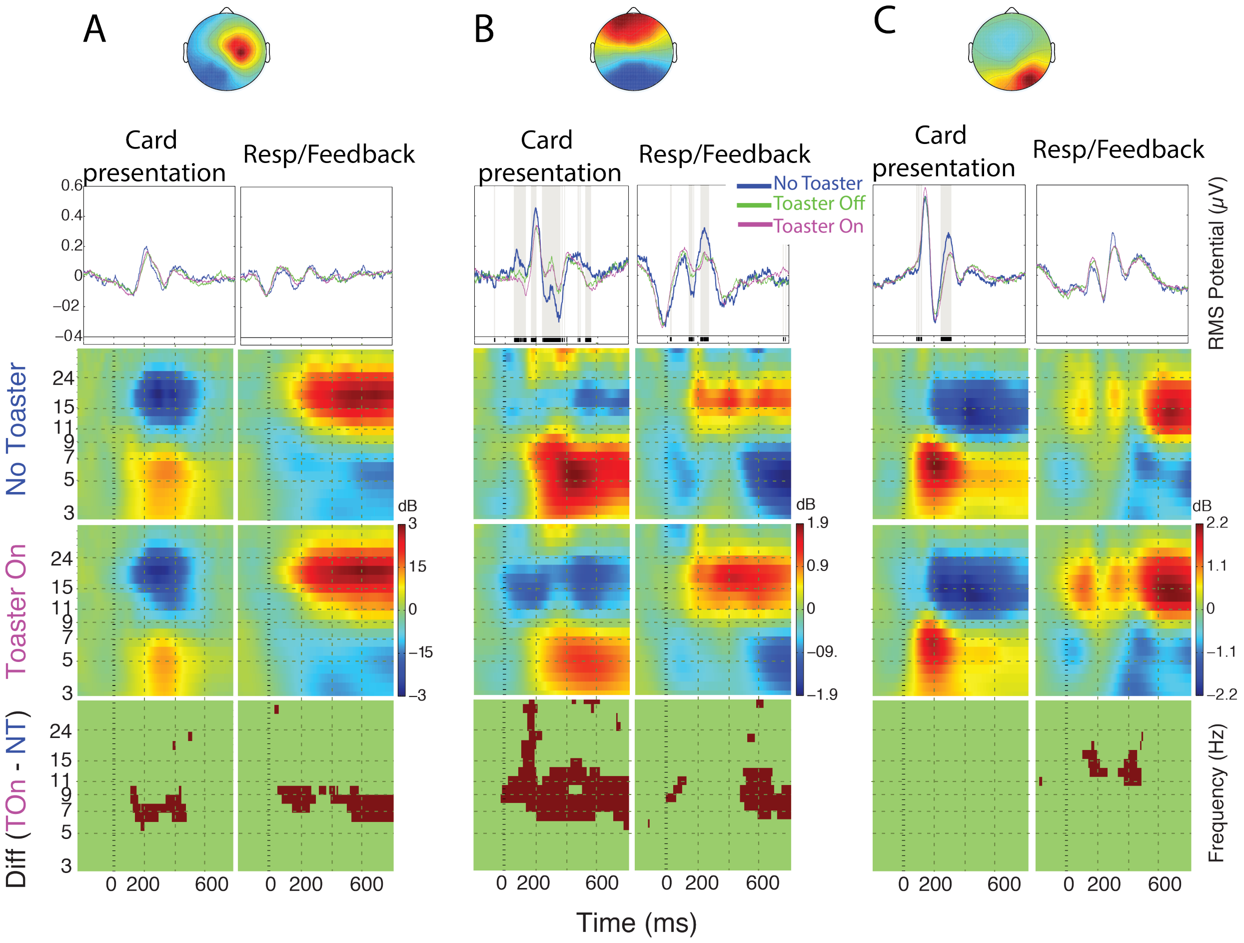

Figure 6-9. Comparison of card sorting task events during 'No Toaster' and 'Toaster On' task conditions. For Cluster 3 (middle column) and Cluster 6 (right column), trial-average Event Related Potentials (ERPs) were larger (blue line) during 'No Toaster' card-sorting-only task periods. Grey areas and timeline highlights (below) show significant differences at $p < .05$ by permutation bootstrap with FDR correction. In epochs time-locked to card presentations, upper alpha suppression was stronger during dual-task 'Toaster On' periods. In contrast, the power of alpha increases for response-locked epochs during dual-task 'Toaster On' periods. All statistics were computed using permutation bootstrap with FDR correction for multiple comparisons. Differences were masked at $p < 0.01$ for comparisons for Cluster 3 (middle column), and at $p < 0.05$ for comparisons for Clusters 2 and 6 (left and right columns). Response/Feedback trials are time-locked to button presses in response to card presentations; each time the participant made a response, he or she received immediate visual feedback, either 'Correct!' or 'Incorrect!'.

The rostral ACC is the cluster that showed the most consistent changes between Ongoing control (No Toaster) and Ongoing PM (Toaster on), with significant differences for ERP and ERSP. However, the rACC contained only 9 of the 18 participant's datasets that were included in the analysis (two datasets were excluded because of noisy signal).

We performed a *post hoc* analysis to examine whether the decrease in theta power and increase of alpha suppression during the 'Toaster On' condition was consistent across participants included in the rACC cluster. We focused on the differences in upper-theta (5-7 Hz), lower-alpha (7-9 Hz) and upper-alpha (9-11 Hz) bands at single subject level. Power was calculated at the frequency with maximum power at the given frequency range. Figures 6-10 and 6-11 shows average power (dB) for the frequency range already indicated in two time windows: 200-400 ms and 500-600ms respectively. Both figures showed activity locked to card presentation.

Even though the rACC did not contain all participants, the results showed that it contained participants representative of the different performance levels (Figure 6-10). Topographic distribution of the source-resolved activity was similar among subjects, only three ICs showed topographic projections reflecting dipoles with a different orientation. Most of the participants showed stronger upper-alpha suppression, for both time windows, during 'toaster On' segments. It seems that alpha suppression was stronger in the late time window 500-600ms (Figure 6-11). Two participants, 20 and 12, showed smaller desynchronisation in lower and upper alpha bands. Note that these participants did not show clear improvement in the performance of the card-sorting task during 'Toaster On' as most of the participants did (Figure 6-6) and had a low index of strategic monitoring, relative to other participants performing similarly in the toast-making task.

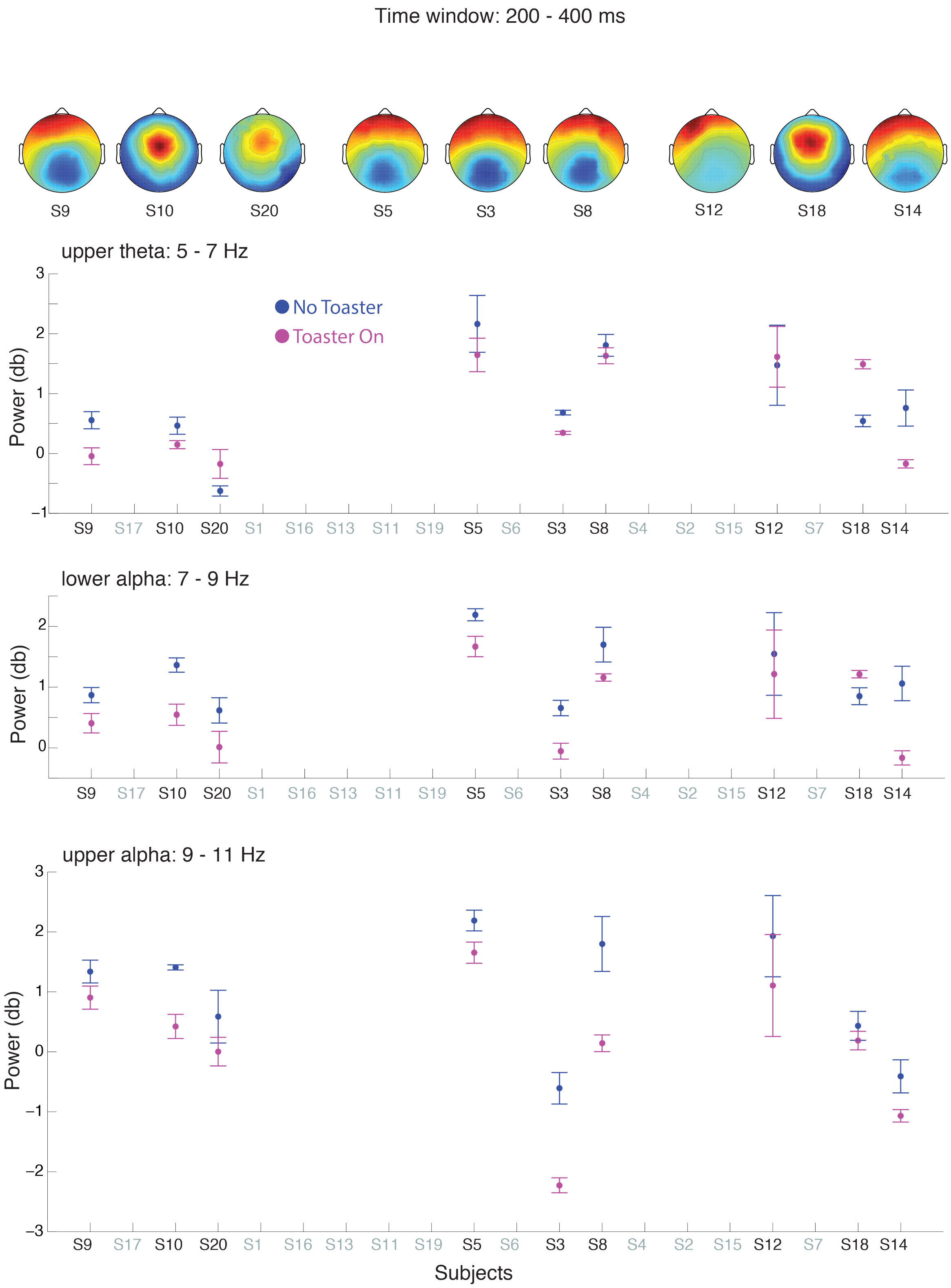

Figure 6-10. Single-subject power in upper-theta (5-7 Hz), lower-alpha (7-9 Hz) and upper-alpha (9-11 Hz) bands at 'No toaster' and 'Toaster On' segments. Calculated from rACC cluster. Each circle represents average power (dB) and standard deviation for the frequency range indicated. Scalp distribution of the 9 participants contributing to the rACC cluster are depicted at the top of the figure.

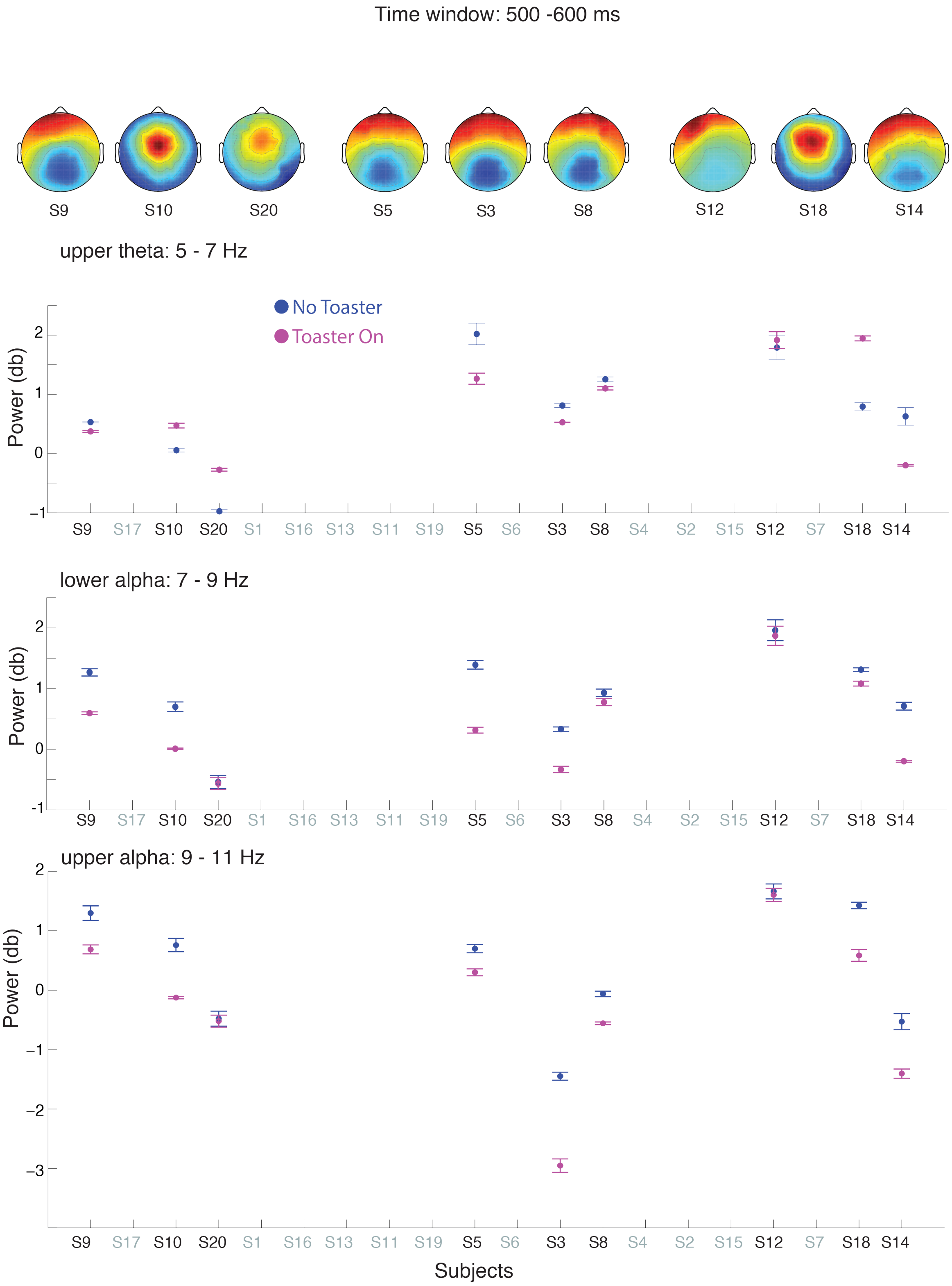

Figure 6-11. Single-subject power in upper-theta (5-7 Hz), lower-alpha (7-9 Hz) and upper-alpha (9-11 Hz) bands at 'No toaster' and 'Toaster On' segments. Calculated from rACC cluster. Each circle represents average power (dB) and standard deviation for the frequency range indicated. Scalp distribution of the 9 participants contributing to the rACC cluster are depicted at the top of the figure.

6.5.2.2 EEG dynamics in Toasting Segments 1 and 3

To evaluate the effect of the time-based prospective memory task on EEG dynamics occurring during the card-sorting task alone, we compared card-sorting task events depending on when the card presentations occurred during the 2-minute toasting periods. The analysis was performed on the ERSPs of Cluster 3, which showed the most consistent difference between the card sorting events during 'No Toaster' and 'Toaster On' conditions (Figure 6, middle column). A one-way repeated measure ANOVA, with permutation bootstrap and FDR correction at $p < 0.05$, revealed changes in theta and lower-alpha band power across the four Toasting Segments in ERSPs time locked to card presentations (Figure 6-12A). *Post hoc* analysis revealed differences between Toasting Segments 1 and 3, showing a reduction in theta power near 300 msec for the time segment 3. A repeated-measures ANOVA performed on the ERSPs time-locked to button-press responses showed some differences in upper alpha/beta frequency bands. These differences were equal across Toasting Segments (Figure 6-12B).

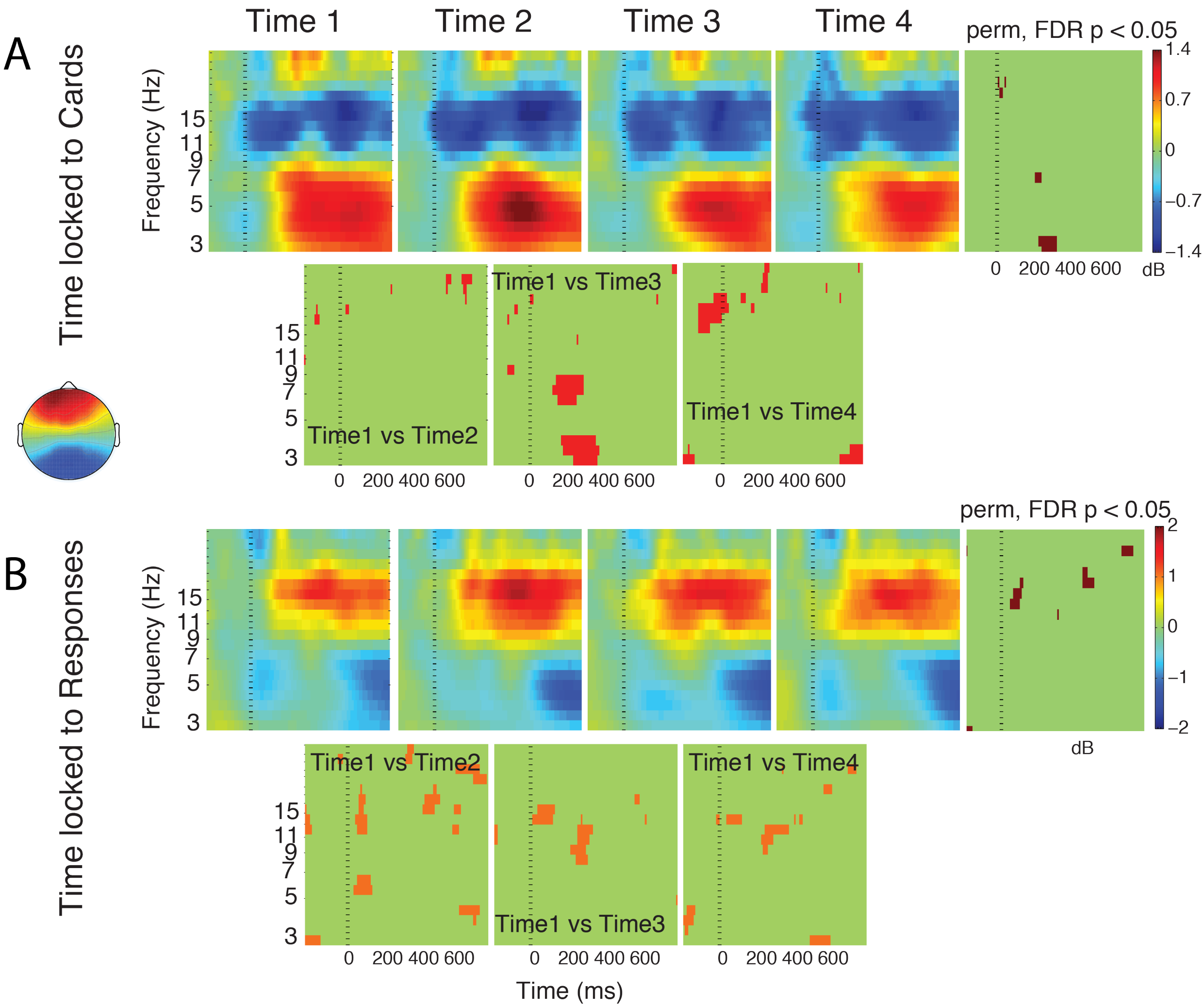

Figure 6-12. **Event Related Spectral Perturbation (ERSP) across four time chunks**. (A) ERSP locked to the card presentation during different time contexts of the toaster task. The results of the repeated measure ANOVA (permutation and FDR) masked at $p < 0.05$, showed a decrease in the theta power around the 300 ms, led by the difference between Time1 and Time3. Note that Time3 was the time chunk when people performed the highest number of toast checks (see Timing of toast check section and figure 3D). (B) ERSPs locked to the response, the main differences are observed in the upper alpha/beta band. However, we did not observe a clear contribution of any of the time chunks to this difference. Time1: 0-30 secs, Time2: 30-60secs, Time3: 60-90secs, Time4: 90-120secs. All post-hoc analyses were performed using paired t-test with permutation, masked at $p < 0.01$

6.6 Discussion

The present experiment was performed with the aim of contributing towards the development of a new naturalistic approach in the study of cognition using EEG. The questions addressed by this experiment were: (i) Can we obtain physiologically meaningful brain activities in free-movement time-based prospective memory tasks? (ii) Are brain sources and dynamics obtained in free-movement prospective memory tasks similar with the dynamics obtain in a classical non-movement time-based prospective memory experiment? (iii) Is there any EEG measure associated to the performance of the time-based intention?

The results showed that: (i) the present paradigm and ICA are suitable to study meaningful electro-physiological brain activity during a time-based prospective memory task. (ii) The brain dynamics observed during the current time-based prospective memory task are similar with the one obtained in Chapter 5, a decrease in theta synchronization (5-7Hz) and increase of alpha suppression are observed for ongoing trials during time-based prospective memory task performance (7-11 H), particularly for the activity obtained from the rostral anterior cingulate cortex. (iii) This pattern of activity was less evident during the first part of the toasting period (time segment 1), when people relied more on internal time estimation. In contrast, time estimation strategies switch towards external time reference points as the toasting time progresses (more toast-checks), during which period, theta activity decreased and alpha activity showed greater suppression (time segment 3).

6.6.1 Behavioural results: High variability in toasting task performance

Figure 3B shows the error rate in the card-sorting task and with the exception of two participants (S1 and S18), the performance among participants can be considered homogeneous, with participants obtaining similar error rates. However, the results for the toaster task showed a high variability in performance (Figure 6-7). The literature on time estimation states that time based tasks are, in general, more affected than non-temporal tasks when the time estimation has to compete with another task, unless the time task is prioritised. Probably, in the current experiment, cognitive resources were devoted preferentially to the card-sorting task, so the variability in the performance of the toast-making task can be interpreted as the ability of the participants to deal with a secondary task when the primary one has been covered, in the specific case, as the ability to strategically monitor the toasting-time. Some of the participants seem to be more effective (S9) than others (S1), see Figure 6-7.

The variability in the results of the toaster task may also be the result of the different strategies that participants implemented, the motivation they had during the experiment, the engagement with the task, the level of attention, skills for time management, multitasking and many other factors. While all these factors are present in any experiment, when paradigms are more controlled, or the responses required are simpler, the performance among individuals is more homogeneous, as was the case of the previous experiments presented in this thesis (Chapter 4 and Chapter 5).

No clear sign of a task interference effect between the card sorting and the toaster task was found. The number of errors did not increase as expected (table 6-1) and the reaction time seemed not to be affected (table 6-2). Furthermore, a practice effect was observed, with participants being more accurate and faster during the Toaster On periods. These results are contradictory with the concept of ‘cost’ (Smith, 2010), which indicates that an ‘effortful’ prospective memory task would require attentional resources dragged from the ongoing task. Thus, the performance of the ongoing task would be affected in terms of a decrease in accuracy or an increase in reaction times.

Regarding strategies for time monitoring, we observed that most of the toast-checks were performed in the time segment 3 (60-90 secs), which makes sense considering that the toaster was considered good from 95 seconds onwards. This pattern of activity was clearer for the group that obtained higher number of good pieces of toast. In addition, time segment 1 showed the highest error rate. These behavioural results are consistent with the idea that participants relied more on internal time estimation during the first period of the toast-making trial and shifted to more external time estimation (toast-checks) towards the completion of the toast-making trial.

Participants who obtained a higher number of correct toasts (performed over the median) were also the ones with high index of strategic monitoring, with the exception of two participants (S1 and S19) who made more pieces of toast but also had greater error rate during ‘Toaster On’ periods (see Figure 6-7).

6.6.2 Brain clusters relevant for the card-sorting task

All brain dynamics in this experiment were analysed time locked to card sorting events (card-locked events and response/feedback-locked events). The focus was on examining how these events can be affected or modulated by the time-based prospective memory demands. The cluster analysis revealed six brain clusters (Figure 6-8), three of them located in frontal areas. This is relevant considering that the card-sorting task is traditionally known as an assessment of frontal lobe function. Imaging studies reveals frontally distributed networks involved during the performance of the card-sorting task, as well as areas of the prefrontal cortex, inferior parietal lobes, temporo-parietal association cortex and association visual cortex (Nyhus & Barcelo, 2009).

The cluster that showed more consistent changes between ongoing task ‘No Toaster’ and ongoing task ‘Toaster On’ was the rostral anterior cingulate cluster (rACC). This cluster showed differential activity associated with the card-sorting task, depending on the time context when the card-sorting events occurred. These results are discussed in the following section.

6.6.3 Decrease in ERPs amplitude and changes in theta and alpha frequency bands as a correlate of the time-based prospective memory task

The right frontal and right posterior clusters showed differences in ERSP and ERP activity when comparing, (i) the card-sorting task during No Toaster with (ii) the card-sorting task during Toaster On. However, the most consistent one was the cluster located close to the anterior cingulate cortex. Interestingly the effect produced on the ERPs was a significant reduction of the amplitude of the modulations time locked to both card presentation and response (a similar result was obtained in Chapter 5). The amplitude of the ERP, when having the same source origin, can be interpreted as a reflection of the cognitive process engaged or as the probability of engagement of certain brain processes. In any of the cases, the decrease in the amplitude during the Toaster On period may be reflecting that cognitive resources relying on the same area (rACC) are being simultaneously devoted to the time-based prospective memory task, resulting in less resource available for the processing of the card sorting events. Another alternative would be that the reduction in the ERP amplitude is reflecting practice effect, we consider that this alternative is less probable, based on three facts: First, we observed a greater increase in alpha suppression in the same area during 'Toaster On' periods, reflecting greater information processing (Klimesch, 1999). Second, we observed a relationship between the activity in this area and time-based performance when inspecting brain dynamics by time segments (Figure 6-12). Third, the previous experiment (chapter 5), showed similar dynamics with decreased accuracy of the ongoing task. For this design, we did not use counterbalanced control, PM blocks, to avoid potential interference effect of the Prospective Memory Task over the control blocks (West et al., 2007).

ERP were not the only measure affected, we also observed changes in the Event Related Spectral Perturbations (ERSP). The same rACC cluster showed a decrease in the power of the upper-theta band (5-6 Hz) and an increase of alpha suppression (7-11 Hz). The decrease in theta power may be explained by the same phenomena that account for the reduction of the amplitude in the ERP. In addition, alpha suppression is widely known as a correlate of mental effort (Klimesch, 1999). Thus, increase in alpha suppression may reflect higher cognitive effort to perform the card-sorting task during the toaster on period. The subsequent event, the responses, showed the complementary pattern (an increase in the power of upper alpha) maybe modulated by the increase in the alpha suppression during the cards presentation. An increase in alpha synchronisation has been previously observed after giving a response (Pfurtscheller & Klimesch, 1990). The greater increase in synchronisation may be responding to the greater alpha desynchronisation during the processing of the previous card event. Finally, when comparing the ERSP by time segments for the same cluster we found that the main differences in theta and the upper alpha frequency bands are found when comparing the time segment 1 with time segment 3 (Figure 6-12). Interestingly, time segment 3 was the time period when more toast checks were performed, without an increase in the error rate. The fact that participants performed the toast-check preferably during time segment 3 reflects that during that time period, people were relying more in external time estimation. Thus, it is plausible to think that the rACC brain cluster is the one most closely associated with the performance of the time-based prospective memory task.

Chapter 5 in this thesis also showed that the cluster most associated with the time-based prospective memory task and executive control of attention was the anterior cingulate cortex. However, the clusters found in Chapter 5 and the one in the current experiment are different. The current ACC is located toward the rostral portion of the cingulate cortex and the equivalent dipole centroid is located deep in the brain. Based on the scalp map, the direction of the dipoles seems to be pointing to the frontal regions of the scalp. However, some of the components in this rACC cluster resemble the cluster found in Chapter 5 (centro-medial distribution). It is possible that the rACC cluster in the present experiment contains ICs located in Brodmann area 24 and 30, whereas the ACC cluster found in Chapter 5 has its centroid in Brodmann area 24.

Even though the rACC did not contain all participants, the results showed that it contained participants representative of different performance levels. When single subject activity was inspected, we observed that the results observed in the group analysis were present at single-subject level. However, not all participants showed the same pattern of activity.

6.6.4 Limitations

Two variables indicated the passage of time in the present experiment: the colour of the toasting bread and the two-minute period. The emphasis was put on the colour of the bread and the two-minute period was given to offer a reference point in order to estimate when to do the toast-checks. People showed strategic performance when deciding to leave the toast-checks for the ‘critical’ period of response. This situation made the task more difficult, since, not only was time a criterion but also the colour of the piece of toast.

To maintain a demanding ongoing task, the card-sorting task presented card events continuously and participants obtained feedback immediately after giving a response. Thus, these epochs may contain activity associated with response preparation and feedback processing. This is a crucial difference of this paradigm with previous card-sorting paradigms, when brain activity associated to card presentation, response and feedback, is analysed separately for each event. The present paradigm is not appropriate to study detailed dynamics associated to card-sorting tasks.

In order to study prospective memory in the laboratory is necessary to create experimental paradigms that emulate tasks, as they will be encountered in daily life. A major characteristic of prospective memory is that once an intention has been created and encoded it is necessary to retain the intention over a delay period in order to perform the task at a later moment in time. During this retention interval we are involved in unrelated activities. Thus, the intention cannot be continuously rehearsed. The complexity of real-life prospective memory tasks is difficult to reproduce in controlled, experimental conditions. The present work represents an attempt to approach more complex paradigms. However, this experimental paradigm is still far from the activities we face in real life conditions and can be seen as an intermediate point between traditional EEG experiments and future more complex and real-life like experiments. More research is needed to extract more useful information from complex EEG paradigms and to develop tasks that closely resemble our daily life activities.

The aim of performing a free-movement time-based prospective memory paradigm was to explore the feasibility of exploring neural correlates of prospective memory and to see to which extent modulations of the task are similar with non-movement task. However, there is a great amount of information that was not considered in this first stage of analysis, which is related to movement. Thus, an interesting question not explored yet, relates to whether head rotations influenced the EEG dynamics shown by this first analysis.

Chapter 7
General discussion

7.1 Integrative summary

The studies presented in this thesis are intended to contribute to a better understanding of what cognitive resources are required for maintenance and execution of prospective memory, a cognitive ability relevant for the performance of our daily life activities.

Three questions were addressed: Is attention required to retrieve delayed intentions? What does monitoring mean in the context of prospective memory? Is prospective memory a discrete memory system or it is based on established attentional and memory mechanisms? To answer these questions prospective memory was studied using different types of prospective memory paradigms, covering event and time-based prospective memory tasks, using traditional EEG paradigms and a free-movement EEG paradigm.

We studied prospective memory using EEG because this technique offers a direct measure of brain activity, providing a close temporal correlate of what is happening at different stages of prospective remembering. We also used Independent Component Analysis (ICA), a mathematical method that separates the independent sources (ICs) that contribute to the mixed brain activity detected at scalp electrodes level. ICA increases the spatial resolution of the EEG, by finding dipole locations that nearly perfectly match the scalp distribution of the ICs. Studying brain activity at source level also increases the signal-to-noise ratio of the dynamics studied and enables a focus on signals that are more sensitive to the cognitive processes of interest (Makeig, Debener, et al., 2004; Onton et al., 2006). In addition, EEG is potentially suitable for use in free-movement conditions. New research (Gramann, Jung, et al., 2014) shows that it is possible to study brain dynamics in more natural contexts. However this approach is still uncommon in experimental paradigms and so far, it has not been used to study prospective memory. Prospective memory is critical for daily life activities (Brandimonte & Ferrante, 2008; Guynn, 2008), thus to study brain sources and dynamics associated with prospective memory in more natural behaviour situations allows us to understand prospective memory beyond laboratory conditions. It may also lead to applications of techniques such as brain computer interfaces or neurofeedback in the rehabilitation of cognitive functions.

For traditional EEG paradigms, the same ongoing foreground task was used with different types of prospective memory task embedded. This design allowed the use of the ongoing task as a control to compare the involvement of different brain sources and dynamics depending on the type of prospective memory task. The ongoing task consisted of a continuous word categorisation task, in which responses were categorised as Related – when the word on the screen belonged to the same semantic category as the previous one – and Unrelated – when the word on the screen did not belong to the same category. The ongoing task was performed under two conditions: ongoing baseline task (without the prospective memory task embedded) and ongoing PM task (with the prospective memory task embedded). Three different types of prospective memory tasks were performed, two event-based and one time-based. The two event-based prospective memory tasks were: (1) press a key when you see words written with the first letter in upper case; and (2) press a key when you see animal words. The time-based prospective memory task was: (3) press a key when you think that four minutes have passed. All three prospective memory tasks corresponded to a minority of the experimental trials and had in common that an action, different from the ongoing task, had to be performed after a delay when a particular retrieval context was identified.

The free-movement time-based prospective memory task followed the same rationale as the non-movement time-based prospective memory experiment. People were allowed to move their arms and head as they needed. This paradigm can be seen as an intermediate step in the process of performing and analysing experiments in naturalistic conditions.

The results identified different brain sources underlying prospective memory performance, depending on the type of intention that has to be maintained. We suggest that prospective memory always requires attention, at least in experimental contexts, and monitoring will involve different mechanisms depending on the particular features of the prospective memory task. In addition, prospective memory is not a discrete memory system, but relies on systems involved in the executive control of attention and retrospective memory.

The current chapter discusses in detail how we responded to each of the research questions of this thesis and how these results contribute to understanding prospective memory in light of a new model presented in Chapter 1, section 1.6. We finally present some outstanding questions for future research.

7.1.1 Attention is required in experimental paradigms of prospective memory

7.1.1.1 Event and time-based prospective memory tasks using traditional EEG paradigms

Different theoretical perspectives on prospective memory agree that there are certain prospective memory tasks that require sustained attentional control to be successful. For example, when the right moment to retrieve the intention is difficult to identify or the ongoing task activity is demanding. Attentional demands required by the prospective memory task would draw on the limited attentional resources available, thus it would have an impact on accuracy and/or reaction times in the ongoing task. This effect has been defined as the prospective memory 'cost' (Smith, 2010).

Experiments in chapter 4 showed that neither of the two event-based prospective memory tasks affected accuracy in the ongoing task. However, we observed an attentional modulation in the EEG signal of early visual components (at around 200ms) for the processing of the ongoing PM task events (related and unrelated) relative to the ongoing baseline events (Figure 4-3). These results lead us to suggest that attentional modulation was required, even in situations where the prospective memory task seemed not to interfere with the ongoing task.

In contrast, the time-based prospective memory paradigm, in Chapter 5, did not affect the early processing of the ongoing task events; the amplitude of the negativity observed at 200ms was similar for ongoing PM events and ongoing baseline events (Figure 5-5). This makes sense considering that, in this case, the detection of the retrieval context was not associated with the ongoing task stimuli. Instead of early ERP modulations, we observed reduced ERP amplitudes at around 400 milliseconds for the ongoing task events relative to the same ongoing events in the baseline condition. Modulations at 400ms are associated with semantic processing of words, reflecting the nature of the ongoing task. We also observed increased alpha suppression (alpha desynchronisation), modulation traditionally associated with ‘mental activity’ or active cortical information processing (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999; Klimesch et al., 2008). Alpha desynchronisation has been described as a local phenomenon produced over task relevant areas, while task irrelevant areas would show the opposite pattern. We observed that the anterior cingulate cortex cluster (Figure 5-5) showed strong alpha suppression during the ongoing PM condition, perhaps reflecting an increase in attentional demands of the task (Klimesch, 1999). This interpretation is consistent with the fact that during ongoing PM blocks participants had to perform the ongoing and prospective memory tasks simultaneously. These results may be reflecting increased neural activation (greater cortical information processing) in the anterior cingulate, to be able to respond to the ongoing task in parallel with the time estimation task. In addition, time-checks were also shown to be mediated by activity in the anterior cingulate cortex (Figure 5-7). The slight reduction in theta synchronisation during the prospective memory PM blocks suggests that the time-based prospective memory task pulled cognitive resources away from the ongoing task. In line with this finding, decreased accuracy in the ongoing task was observed when performed with the time-based prospective memory task.

These results support the idea that attentional control is required throughout the retention interval for prospective memory tasks in traditional EEG experimental settings.

7.1.1.2 Prospective memory paradigms in free-movement conditions

For this task we obtained fewer brain components (n=136) than typically obtained under traditional EEG experiments (n=288). However, we were still able to find brain sources relevant for the task being performed. Interestingly, the brain source that showed most consistent involvement in the time-based prospective memory task was located close to the anterior cingulate cortex (Brodmann area 24/32), and the estimated location of the centroid of this cluster was similar to that found in the non-movement time-based prospective memory task. However, the scalp topography of the ACC cluster showed a different pattern between the non-movement time-based task (Figure 5-8) and the free-movement time-based task (Figure 6-8). The differences may be explained by the involvement of ICs with different scalp distribution in the free-movement experiment (Figure 6-10): some ICs showed exactly the same central pattern as the ones shown in the non-movement time-based experiment, whereas other ICs showed more anterior distribution, the latter being the dominant pattern shown by the scalp map for the free-movement experiment cluster. Independently of the differences in the scalp topographies, both clusters showed similar equivalent dipole locations, with the free-movement experiment dipole located slightly deeper in the brain to that in the non-movement experiment.

Source localisation in EEG experiments has to be interpreted with caution, due to localisation error (4-6mm) when not using accurate head models. In addition, in equivalent dipole fitting, depth is the dimension of least certainty (for more detail see (Akalin Acar & Makeig, 2013). However, activity of a cluster in or close to ACC seems to be consistent across studies (Figures 4-6, 5-8 and 6-8). The anterior cingulate cortex has been traditionally associated with the executive control of attention (MacDonald et al., 2000).

The ERP modulations of the ACC showed a reduction in amplitudes during the ongoing plus prospective memory task. As concluded from the previous time-based experiment, it may be that the time-based prospective memory task pulled attentional resources away from the ongoing task, though in this case participants' accuracy was not impaired and even shows a practice effect for some of the participants. It is unlikely that the ‘practice effect’ observed in the behavioural results of this task explain the differences in amplitude, since a similar effect was observed in the previous time-based prospective memory task that did not show practice effects. However, this alternative cannot be completely ruled out.

The results also showed a strong increase in alpha suppression for the ERSP results (similarly with that shown by the ACC in Chapter 5). It may be that the strong increase in alpha suppression observed during the ‘ongoing toaster on trials’ reflects a compensatory strategy (increased mental activity) to maintain performance. However, more research is needed to address this question.

Evidence that the anterior cingulate cortex is providing some form of attentional or cognitive control in the free-movement time-based task, comes from the fact that: we observed an increase of alpha (7-11 Hz) suppression and reduced theta synchronization (5-7 Hz) in the ongoing task events (card-sorting events) during time segment 3, relative to time segment 1. This is relevant if we consider that during time segment 3 (close to the time to turn off the toaster), there was a high dual-task demand. This dual-task demand is shown by two aspects: firstly, participants increased the number of toast-checks during this time segment, indicating ‘active’ time monitoring. Secondly, participants continued performing the ongoing task (card-sorting task) without increasing their error rate. By contrast, time segment 1 did not require evaluating any external event or actively tracking time (low number of time-checks), since participants knew that they were still in an early stage of the toast-making trial.

It may be argued that the modulation in alpha/theta frequency band in the anterior cingulate cortex, was associated with greater neural activation in order to respond to both ongoing and time-based tasks simultaneously. This may be interpreted as following; attentional control is required throughout the retention interval for time-based prospective memory tasks in a naturalistic EEG experimental settings.

7.1.2 What does monitoring mean in the context of prospective memory? Different mechanisms for maintenance of intentions depending on the type of prospective memory task

One of the variables associated with the nature of prospective memory tasks is the distinctiveness of prospective memory cues to indicate the right moment to execute intentions. The experiments presented in this thesis used perceptual cues, conceptual cues and time as indicators for prospective memory retrieval. Our results are consistent with previous work suggesting that different cognitive demands are made depending on subtle changes in the features of the prospective memory tasks (Okuda 2007). However, Okuda distinguished only between time- and event-based prospective memory tasks. We extend this conclusion to distinguish between different types of event-based prospective memory tasks.

We observed that the maintenance of both types of event-based prospective memory tasks did not affect the accuracy of the ongoing task. But particularly for the case of the conceptual condition (identifying animal words), it affected the reaction time of the unrelated words in the ongoing task. The detection of the conceptual prospective memory cue seemed to occur at around 400 milliseconds, and the ERP modulation of the conceptual cue was very similar to the ERP modulation of the unrelated words (Figure 4-6). This makes sense if we consider that each of the unrelated words in the conceptual condition could potentially be a prospective memory cue. By comparison, for the perceptual condition (identify upper case letter), the identification of the prospective memory cue did not require processing of the meaning of the words and the detection of this target occurred earlier, as shown by the ERP modulation around 300 milliseconds (Figure 4-5). We concluded that different mechanisms facilitate cue detection depending on the nature of the event-based prospective memory cue, extending previous findings based only in perceptual event-based prospective memory tasks (West 2011).

The main differences in brain sources and dynamics for the different types of prospective memory tasks were:

Event-based prospective memory task: The left occipital clusters showed an enhanced negativity during the performance of the ongoing task, reflecting a processing bias in favour of task-relevant stimuli. When the perceptual PM cue was detected, it elicited a negativity over occipital regions, probably mediated by activity in the superior parietal cluster, which is part of the dorsal attention network, associated with top-down attentional modulation. By contrast, detection of the conceptual prospective memory cue elicited a later negativity similar to detection of unrelated items (N400).

Time-based prospective memory task: The left occipital cluster was activated for the processing of the ongoing task stimuli (in the non-movement time-based PM task). However, the enhanced negativity was not observed, meaning that top-down attentional modulation was not required to enhance processing of ongoing task stimuli features (in this case the prospective memory cue was not part of the ongoing task stimuli). By contrast, we observed reduced amplitude in the ERP of the component cluster with centroid in or near ACC, plus stronger alpha suppression. The anterior cingulate cortex is related to cognitive control at a late level of processing (van den Berg et al., 2004), and possibly response selection or response execution. Reduced activity in this region plus an increase in the error rate of the ongoing task suggests that resources were dragged from the ongoing task and devoted to the time-based prospective memory task, which also required activity from the same cluster.

These results can be used to explain the discrepancies between theories of prospective memory. The first point to make relates to the idea that monitoring and preparatory attention cannot be used as synonyms. Preparatory attention in prospective memory is defined as devoting attentional resources to evaluate the environment in order to detect a prospective memory event. This definition of preparatory attention may be understood as one possible mechanism of monitoring (Chapter 4). However, monitoring may involve other mechanisms, not only associated with early evaluation of environmental events, but also with: (i) verification of the prospective memory cue (is this the right moment to execute the intention?) and (ii) execution of the correct response (inhibit the ongoing response and perform the corresponding delayed action). These may also be considered as monitoring of behaviour, with the anterior cingulate cortex being one of the areas underlying these mechanisms.

Based on these results we conclude that monitoring will involve different mechanisms depending on the features of the retrieval context of the prospective memory task.

7.1.3 Prospective memory: not a discrete memory system

The idea of prospective memory as a particular cognitive ability is practical in clinical terms, where people suffering different neurological conditions complain about forgetting to do things. In this sense, prospective memory can be evaluated using questionnaires (Crawford et al., 2006) and table-top assessments (Fish et al., 2010) that give an idea of the capacity to maintain delayed intentions. However, it seems clear that prospective memory is not a distinct memory system, but utilises established attentional and retrospective memory mechanisms (Knight et al., 2010; West, 2011). The brain dynamics investigated in this thesis support this idea. Perhaps the term prospective memory is misleading in this sense, as memory is only one of the components involved. Ellis (1996) made this point previously, proposing the term ‘realization of delayed intentions’ as an alternative to prospective memory. The neural correlates of prospective memory and associated functions revealed in the present PhD work support this proposal.

Based on brain sources and dynamics observed across experiments, we suggest that prospective remembering requires coordination of different sensory and cognitive processes in order to fulfil a goal. EEG signatures, rather than reflecting processes specific to prospective memory, are the signatures of the collective coordination of all those processes (Figure 4-4). For instance, the parietal positivity observed at sensory level in the perceptual condition seems to be a combination of top-down attentional regulation (parietal sources) and monitoring of response (ACC source) (Figure 4-5). On the other hand, the parietal positivity in the conceptual condition may reflect word categorisation and response monitoring (ACC source;

Figure 4-6). In both cases, a similar scalp ERP is observed over parietal and frontal electrodes.

Prospective memory tasks by definition are demanding non-routine activities that require switching back and forth between alternative behavioural options. Thus prospective memory tasks require involvement of the frontopolar cortex (FPC). However, it has also been shown that the involvement of the FPC is gradually reduced when tasks are learned or practiced (Koechlin & Hyafil, 2007). A prospective memory task that shows reduced activation of the PFC may be reflecting that the prospective memory task is becoming a habit. Along the same lines, the complete absence of monitoring may be an example of ‘utilization behaviour’ (Shallice et al., 1989). We propose that activities that involve the performance of habits, for example brushing one’s teeth, are not prospective memory tasks. When remembering to brush one’s teeth becomes a problem, this suggests that this activity is not longer a habit and it becomes a prospective memory task, or a task that requires a certain degree of performance monitoring to be performed.

Imaging research in prospective memory has been centred on the prefrontal cortex, particularly Brodmann area 10 (BA10) (Burgess et al., 2008). The functional role of this area has been associated with control of the focus of attention that can be strategically directed towards the internal cognitive state (lateral activation in BA10) or towards external stimuli (medial activation in BA10). However, this region is hard to access using EEG. In the present thesis we did not consistently see activity in the FPC (as it may have been if using fMRI). However, we found the involvement of brain sources that participate in ventral (Temporo-Parietal Junction) and dorsal (Superior Parietal Lobule) attentional systems. The dorsal attentional network is associated with internally driven attention, whereas the ventral network is associated with externally driven attention (Shomstein, 2012), similar to the role of BA10 in prospective memory.

These findings lead to the idea that prospective memory is not a discrete memory system, as it is sometimes treated (Crawford et al., 2006; West & Krompinger, 2005; West & Wymbs, 2004) and can be explained based on general models of cognitive control in humans, beyond the activation in PFC or BA10. The contribution of the present work to understanding prospective memory within new theoretical models is presented in the following section.

7.2 Contributions to models

7.2.1 Contributions to a new model

The initial Chapter of this thesis presented a detailed revision of the models used to explain prospective memory, particularly related to the requirement of attention and memory processes. We also presented a new model, integrating well-known theories of attention, monitoring and working memory. In the present section we explain how the research work carried out to answer the research questions of this thesis, contributes to understanding prospective memory within this new model.

In Chapter 1 we proposed that the mechanisms that 'activate' an intention can be internally or externally initiated. The Preparatory Attentional and Memory Process (PAM) theory states that we do not require constant engagement of monitoring (preparatory attention), but it will be required at some point during the prospective memory process (Smith & Bayen, 2004). However, an important issue in relation to this hypothesis is that monitoring and preparatory attention are not synonyms. We propose that preparatory attention may be just one possible mechanism of monitoring in prospective memory tasks, for example, by being ready to respond to a prospective memory target (early visual ERP modulation, Figure 4-3). This mechanism is represented in Figure 1-1D, which illustrates how top-down modulations may maintain continuous evaluation of the ongoing task in order to detect the prospective memory context (purple arrows). Another possible mechanism is one reflected by the modulation of activity in the anterior cingulate cortex. This mechanism is represented in Figure 1-1E - the ongoing task is not continuously evaluated but some self-initiated processes maintains internal time estimation (red arrows) until the clock is checked. We consider that attentional control in this case, may be produced by top-down modulations (not necessarily conscious) and executive control of attention. The attentional control may be implemented in response to the task instruction, such as being asked to identify particular cues or events or to keep track of time. Even when people do not maintain the prospective memory task continuously in the focus of their attention (as they continue responding to the ongoing task) the mechanisms necessary for performing the task are operating (in the background or in the second level of storage according the model presented in Figure 1-1).

It may be then argued that attentional mechanisms necessary to perform prospective memory tasks are activated when the prospective memory intention is held in mind (as is the case of prospective memory in experimental conditions). A recently published theory, the dynamic Multiprocess Theory (Scullin et al., 2013), offers a similar approach to our proposal of involvement of attentional mechanisms in prospective memory. This theory proposes that monitoring is required only when people enter a context where prospective memory cues are expected. This theory proposes that spontaneous retrieval of intentions is prompted by environmental cues and as a result, people enter a retrieval mode, and monitoring mechanisms are implemented in order to execute the intention. The difference between this proposal and our theoretical model is that we propose that not only environmental cues can 'activate the intention'. As we detail in figure 1-1A, other motor schemata, thoughts or even unconscious cues (brushing teeth in Figure 1-1C) can activate the intention and trigger monitoring systems in order to execute the intention or postpone it again.

We speculate that the role of the Supervisory Attentional Gateway is to allow 'the transit' of the intention between the different layers of storage (Figure 1-1). In other words, the SAG may help keep the intention in the focus of attention or maintain it so that it is accessible if it is not immediately required. In Preparatory Attentional and Memory Processes (PAM) Theory terms (see section 1.3.2), the former would be analogous to bringing the intention to the focus of attention and the latter would result in the phenomenological report of 'keeping the intention in the back of the mind'. If the information is stored in the second layer (not in the focus of attention but readily available), activation of the intention (or memory representation) would be less demanding than when the information is stored in the third layer (long term memory mechanisms). In laboratory conditions, the repetition of prospective memory cues and the short delays used for the retention interval can act as prompts to enter the 'retrieval mode' and maintain the intention 'active' even in the absence of explicit instructions. Thus, the model we have presented would only show the transit between the focus of attention and the layer of storage of immediate access. We would need a paradigm that force people to completely disengage from the prospective memory task and to store it in long-term memory while executing an ongoing task. A possible way to do this would be to create a paradigm where people are not expected to perform the prospective memory task.

Another aspect that we highlighted in our theoretical proposal is the idea that monitoring would involve different mechanisms depending on the features of the prospective memory task. The results presented in this thesis support this statement. We proposed that the supervisory attentional system (Shallice & Burgess, 1996; Stuss et al., 1995) offers a good framework to understand how different mechanisms for monitoring and executive control underlie prospective memory performance across its stages. The requirement for monitoring can be described at different processing levels (van den Berg et al., 2004), for example, stimulus encoding, target detection, target recognition, response selection and/or response execution. Some of these mechanisms may entail top-down modulation of attention in the processing of visual targets (Chapter 4), strategic allocation of attentional resources (Chapters 5 and 6) and inhibition/activation of motor schemata (Burgess et al., 2007). These mechanisms would be implemented depending on the nature of the task. Examples of attentional control as a mechanism for monitoring are given in section 7.2.3 ‘The role of the anterior cingulate cortex in prospective memory’.

Elucidating the relationship between the requirement for executive functions and components of prospective memory tasks (maintenance of the intention, cue detection and response retrieval) under different task conditions (time or event based) helps us to better understand how the brain deals with delayed intentions. We propose that the cognitive demands of holding the intention during the ongoing task are mainly associated with the context of retrieval, specifically with the characteristics of the cues that signal the moment to execute an action (as shown by the behavioural results of Chapter 3). In other words, if a cue is easier to detect, fewer resources will be required during the retention interval to successfully identify the cue when it occurs. However, it is necessary to have certain amount of attentional resources available in order to engage cognitive processes that allow the identification of the salient cue. Figure 1-1 from C to D schematises how monitoring during the retention interval would change according the retrieval context.

7.2.2 Prospective Memory and hierarchical models of cognitive control

The results showed by this thesis also indicated the relevance of attentional systems (particularly parietal areas) and control of attention (anterior cingulate cortex) in the execution of delayed intentions. The findings discussed in the previous section of this Chapter lead us to explore wider models of cognitive control, which consider the involvement the same brain networks and regions.

We propose that one challenge in prospective memory research is to understand prospective memory within an integrated system involving: Prefrontal cortex (BA10), dorsolateral cortex, premotor areas, anterior cingulate cortex and other brain regions involved in attentional networks such as superior and lateral parietal cortex. It may be worth considering how models of cognitive control proposed by Koechlin (Koechlin & Hyafil, 2007; Koechlin, Ody, & Kouneiher, 2003; Koechlin & Summerfield, 2007), Cohen (Cohen, Botvinick, & Carter, 2000; Gehring & Knight, 2000) and Brade (Badre, 2008) can be used to explain prospective memory.

Koechlin et al. (2007) proposes the concept of 'cognitive branching', which corresponds to the cognitive function of the frontopolar cortex (FPC). The branching process allows maintenance of a task that is temporarily suspended while another is being performed, by switching in and out of 'branches' or behavioural options. These processes would be implemented in multitasking contexts, when a series of activities to be performed are not serially organised or coordinated by a pre-established plan. Activity in the frontopolar cortex would be part of a rostro-caudal organization (cascade model) of cognitive control (Badre, 2008; Koechlin et al., 2003). The cascade model proposes that more complex tasks would recruit more rostral regions, going from: sensory control and selection of motor responses (pre-motor regions);

contextual control or stimulus-response association (caudal LPFC) and; episodic control or stimulus-response associations in relation to previous events or to internal goals (rostral LPFC). Perhaps the greatest difference between this cascade model of cognitive control and the supervisory attentional system, is that the latter proposes that control is executed by a central executive system over multiple ‘slave systems’, whereas the cascade model presents the executive control as a multistage cascade that involves different regions that are required depending on the complexity of the task. The question of how the FPC is regulated (the apex in the executive control of cognition) is still subject of research. One of the hypotheses that explain the decision of which task to perform and which one to put on hold may be associated with rewards and motivated behaviour (Koechlin & Hyafil, 2007). However, this question has not yet being clearly answered.

Activity in the anterior cingulate cortex has also been associated with executive control of attention, raising the question of how this region is involved in the rostro-caudal organization of the prefrontal cortex. Cohen et al. (2000) proposes that the ACC would detect the requirement for increased cognitive control or monitoring and it would communicate with PFC to exert top-down control over posterior brain regions (Cohen, Botvinick, & Carter, 2000; Gehring & Knight, 2000). One mechanism by which the PFC may execute cognitive control would be through the involvement of selective attention, which favours processing of a particular task-relevant stimulus type or dimension.

Prospective memory may well be explained by the involvement of the mechanisms previously described. These integrative theories of cognitive control continue to be developed, and studying prospective memory in the context of these theories may be a next stage in research on prospective memory..

7.2.3 The role of the ACC in prospective memory

A great variety of tasks show involvement of the ACC, these tasks usually require; response monitoring (Gehring & Knight, 2000; Sheth et al., 2012), working memory load (Onton et al., 2005), socially driven interactions (Lavin et al., 2013) and control of attention (Carter et al., 1999; MacDonald et al., 2000). The participation of the ACC in this wide variety of cognitive functions has given it the reputation of a regulator of attention and behaviour in complex cognitive tasks. In particular, two roles are associated with the ACC: (1) detection of conflict at the level of planning or execution of actions; and (2) control of attention indicating the degree of involvement of top-down control (Botvinick et al., 2001; Carter et al., 1999).

The role of the ACC in detecting conflict is based on involvement of the ACC in tasks that present some sort of conflict (carter 1999), such as the classical *stroop paradigm* or the *flanker tasks*. In these tasks, error detection is one example of a conflict situation. The experiment in Chapter 4 shows an example of conflict response. People were instructed to detect animal words, which corresponded to 10% of the trials. Targets were embedded in a list of words belonging to many different categories. For most of the trials participants responded indicating if words were related or unrelated semantically, but in a minority of trials, when they saw an animal word, they had to inhibit the 'unrelated' response and to give a target response; 'animal word'. ERP activity with source in the ACC was shown to underlie this process (Figure 4-6).

The role of the ACC in control of attention seems to be associated with signalling the requirement for attentional control (engaging top-down attentional mechanisms). This idea is based on the involvement of the ACC in different tasks that require some sort of selective attention, such as dual-task paradigms, inhibiting responses, novel versus practiced tasks (Carter 1999). And it is by means of this function that the ACC has been linked to wider models of cognitive control (Cohen, Botvinick, & Carter, 2000; Gehring & Knight, 2000). Thus the ACC, more than exerting attentional control itself, has the role of regulator of attentional control, modulating activity of other brain regions that exert the attentional control. The regulatory function of the ACC in the control of cognition is consistent with its anatomical location. The ACC has strategic connections with different parts of the brain; it connects with dorsolateral frontal, parietal, temporal, enthorinal cortex and amygdala (Devinsky, Morrell, & Vogt, 1995).

In addition, activation in the anterior cingulate cortex has been consistently found in different types of time estimation tasks (Okuda et al., 2007; Pouthas et al., 2000; Rubia, 2006; Rubia & Smith, 2004) and also in time based prospective memory tasks (Okuda et al., 2007). However, the ACC has not been related to any particular theory of time estimation and it may be more related to cognitive control during time estimation tasks than a specific timing function. The experiments in this thesis showed that the ACC is accessible by EEG, thus it is an interesting candidate to understand the requirement of executive control during prospective memory.

7.3 Outstanding Questions and Future Outlook

Previous sections in this final discussion chapter have raised issues that need to be further explored.

7.3.1 Prospective memory and models of cognitive control

Perhaps one of the most relevant issues is how to study prospective memory in the context of models of cognitive control. As we previously mentioned, to be able to test the theoretical model we initially proposed we would need to develop a theoretical paradigm that includes the encoding of prospective memory intentions in long-term memory, so we can study the 'transit' of the intention across different layers of storage.

In order to extend our proposal to explain prospective memory within hierarchical models of cognitive control (Koechlin & Hyafil, 2007; Koechlin, Ody, & Kouneiher, 2003; Koechlin & Summerfield, 2007; Cohen, Botvinick, & Carter, 2000; Gehring & Knight, 2000; Badre, 2008) we would need to explore activity in frontal structures, such as as Brodmann area 10, which is very difficult using EEG (eye movement noise and the high signal-to-noise ratio in frontal electrodes). Some of the participants in the current experiments showed independent brain processes close to BA10, although ICs in BA10 were not consistent across participants. An approach to exploring activity in the FPC, in relation to other structures in the prefrontal cortex and to well-described attentional networks, may be to combine EEG and fMRI methods. MEG may also be a good alternative to obtain a balance between temporal and spatial resolution. Alternatively, obtaining an MR image for each participant in EEG research would be ideal, because it would increase the accuracy for source localisation.

7.3.2 Prospective Memory and other cognitive tasks

Based on the idea that prospective memory tasks require the orchestration of already known attentional and executive system, classical cognitive paradigms can contribute to resolve specific questions associated with prospective memory process. For example, paradigms of task switching and error monitoring can be similar to the demands that prospective memory task has at the moment of recognising the right moment to perform the task and execute the intention. On the other hand, paradigms that require sustained attention and time estimation may be similar to the demands of prospective memory tasks during the intention maintenance period, during which the intention has to be held while performing an ongoing task. In other words, the use of classical cognitive tasks may help to estimate the performance in prospective memory tasks that may require some of the same executive functions. However, this approach would break down the different components of prospective memory in different tasks without giving a direct measure of the performance of delayed intentions. One limitation of all theses paradigms, including the ones used to measure prospective memory, is that they may not measure the ability to activate delayed intentions, retrieved from deep levels of memory storage (i.e. the third level in the three-layer-models). On the other hand, generalisation of the results obtained from laboratory settings to real-life prospective memory tasks is limited, since prospective memory tasks require repetition of the context for retrieval, in order to study brain dynamics associated to it. Thus, even though the number of prospective trials is low, the interval may be short enough to allow continuous rehearsal of the prospective memory task and to maintain activation of the attentional control mechanisms for prospective memory task performance. Future research in prospective memory may focus in investigating the mechanisms for performance of delayed intentions when the intention has been stored in long-term memory and it is not readily available for retrieval, as it may be the case of classical PM paradigms.

Particularly for the case of time-based prospective memory and time estimation tasks, more research is needed to elucidate if the participation of the anterior cingulate in prospective memory tasks reflects mechanisms associated with executive control of attention or if it is reflecting particular mechanisms for time estimation. One possible approach would be to further analyse the time-based prospective memory tasks to explore any parametric relationship between time estimation and the brain dynamics of the ACC cluster (for example, by studying changes in power of frequency bands using a regression model)

Future research can explore what is the role of time estimation in time-based prospective memory paradigms. Is there a difference between maintenance of the time-based intentions and the demands of time estimation? To examine this question we would need to create experimental conditions with the same time-based prospective memory tasks, but with different demands in terms of time estimation. For example, one condition may rely on internal time estimation to give a response, meaning that no clocks or external cue will be available, while a second condition may allow participants to regularly check a clock and a third one could have a clock visible continuously. The goal across the three conditions would be the same, but the strategies implemented would be different. This can be complemented with a control task that only requires prospective time judgement. For example, people perform the same ongoing task and are told that they will be asked for their time judgment during the task, after a variable interval the task can be interrupted and they will be asked how much time they think has passed.

7.3.3 Towards naturalistic paradigms and brain computer interfaces

We implemented a free-movement prospective memory paradigm in an attempt to explore neural signatures associated with prospective memory in a more natural behaviour context.

The ongoing task selected for the experiment was based on the Wisconsin Card Sorting Test. One of the reasons for selecting this task was that it has been widely studied using different imaging methods (Barcelo, 1999; Barcelo & Knight, 2002). However, there is a number of more naturalistic tasks, that have been developed for clinical research that may also be interesting to study using electroencephalography, for example the Hotel Task (Manly et al., 2002), Six Elements Test, Multiple Errands Test and others. However, studying these tasks with EEG requires further development in interpretation and analysis of complex data. The task presented here used repetitions of events and we focused the analysis on how the brain dynamics locked to the events were affected by the maintenance of the intention, with the advantage that we had a high number of events to locked brain signals and also that we had previous information of ERP and brain regions associated with the Card Sorting Task. The uses of new naturalistic tasks, that do not allow multiple repetitions of events, represent a major challenge for EEG studies that certainly needs to be addressed in future research.

To find brain sources associated to the maintenance of intentions under natural motor behaviour may contribute to a new understanding of prospective memory in our daily life, where the consequences of prospective memory failures are measured. It also opens possibilities of exploring the use of technologies such as Brain Computer Interfaces (BCI) in the field of cognitive rehabilitation. The free-movement study presented in this thesis is a first approach to free-movement prospective memory tasks, and the analysis performed targeted the main questions addressed by this thesis. However, there is more information offered by this paradigm that has not yet been explored, such as characterising the brain dynamics in relation to the movements executed during the experiment. Particularly in relation to head rotations, one of the outstanding questions is whether brain dynamics described in this experiment are modulated by head rotations. This question goes beyond the scope of the present thesis, but is an important issue.

Identifying neural signatures associated with prospective memory is the first stage in applying these signals in brain computer interface experiments. Brain computer interface (BCI) systems provide online feedback of the brain activity that can be used to control external devices only using brain activity. Originally BCI implied that a subject sends voluntary and directed commands toward an external device. More recently, research in BCI has focused on real-time monitoring of the cognitive state, particularly in error detection and work-load indices (Zander & Kothe, 2011). This approach may be useful in the field of cognitive rehabilitation. For example, passive BCI could be used as an ‘unspecific organizer’ monitoring activity of the fronto-parietal sustained attention network or the anterior cingulate cortex and signalling those changes, in order to prompt re-engagement of attention. A group of ERP modulations commonly used in BCI paradigms associated with monitoring of performance is the error related negativity (ERN), whose more likely generator is the ACC that has been consistently shown by the present experiments.

7.4 A final thought

In summary, use of EEG in the study of prospective memory might follow two paths: One path would be oriented to developing ‘clean’ experimental paradigms that are able to characterise key brain areas involved in prospective remembering and participation of fronto-parietal networks in the monitoring of the performance at different processing levels. These paradigms will tend to be more reductionist and tightly controlled (Chapter 4 and 5). However, these paradigms may not be representative of the mechanisms applied in real-life situations, which are more complex, unpredictable and involve constant changes in task contexts. Thus, the second path would be to develop EEG paradigms that involve more naturalistic context, exploring what sort of brain signatures are associated with prospective memory tasks in real-life situations. Whilst these paradigms may be more difficult to analyse and interpret, we have shown that steps can be taken in this direction.

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