MECHANISMS OF WORKING MEMORY AND THEIR MODULATION BY EMOTION

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DECLARATION

This thesis is based on research undertaken solely by the author who assumes all responsibility for its contents. The use of human participants in the studies reported in Chapters 6, 7, 10, 11, 12, 13 and 14, has been approved by the Ethics Committee (Department of Psychology, University of Warwick, UK) or the Human Subjects Committee (University of Wisconsin-Madison, USA). Informed written consent was obtained from all participants prior to their participation in experiments.

The following papers were based on the research reported in this thesis:

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Abstract

The aim of this thesis was to examine the possibility that sub-mechanisms of Short-Term or Working Memory (WM) can be selectively affected by task variables such as processing requirements, or situational variables such as positive or negative mood. The model of WM, developed by Baddeley and colleagues (Baddeley and Hitch, 1974; Baddeley, 2000) was taken as the basis for conceptualising the componential architecture of WM. It is proposed that individual WM components, i.e. the executive attention component, the verbal and the spatial storage components, could be systematically modulated by emotions.

The first 2 studies investigate the differential involvement of the Central Executive component in tasks that have been reported to be differentially affected by mood. It has been argued that analytical tasks make greater demands on the Central Executive (CE) and therefore alternative demands on the CE will disrupt such tasks. The detrimental effect of positive mood on analytical tasks is due to the disruptive effect of this type of mood on CE function. Using a dual-task paradigm, it was demonstrated that an analytical reasoning task was more disrupted by a concurrent WM task than was a creative task, i.e. a demonstration that the CE is more involved in analytical tasks. Measures of brain electrical potentials demonstrated a parallel effect at the cortical level.

The following studies examined other WM components, the verbal and spatial "slave" mechanisms and the possibility that they may be differentially modulated by emotion. Recent behavioural, psychophysiological and neuroimaging evidence suggests that

spatial, but not verbal, WM system is largely reliant on visual attention. It has also been shown that certain emotions, i.e. anxiety or fear, may be intrinsically associated with visual attention. On the basis of this overlap, it was predicted that induced anxiety/ fear would selectively modulate spatial WM, with little effect on verbal WM performance. An n-back task allowing of fine-grained dissociation of verbal and spatial WM was developed and three studies examined the effects of threat of shock on verbal and spatial n-back WM performance. The studies confirmed the prediction, showing that spatial WM performance was impaired in conditions of threat, while verbal WM performance remained unchanged. A number of analyses emphasised the relationship between anxiety and the decrement in spatial n-back performance. The presence of anxiety was objectively validated via physiological recordings.

The literature contains suggestions that, in contrast to the selective disruption of spatial WM in threat-anxiety observed in our studies, trait and test anxiety tend to affect verbal WM more than spatial WM. Therefore, in a subsequent study verbal and spatial n-back WM performance was contrasted in high vs. low trait anxiety individuals. It was found that verbal and spatial WM were not differentially disrupted in individuals high with trait anxiety.

The final study aimed to determine whether interhemispheric asymmetry models in emotion and WM could serve as a neuroanatomical explanation of the selective effect of anxiety on spatial WM. The study employed neuroimaging technology to compare the activation of regions of the frontal cortex in the two hemispheres in the verbal and spatial n-back tasks employed earlier. The anatomical regions of interest were chosen on the basis of neuroanatomical models of brain laterality in emotion. The results do not contain reliable patterns of frontal lateralization. Hence, they provide little support to laterality-based accounts of the interaction between spatial WM and anxiety.

These findings support the hypothesis that WM components can be selectively modulated by factors such as affective state. They also suggest that attentional-executive mechanisms may not be fully distinct from the storage systems, as claimed in the original characterisation of WM.

Outline of the organisation of the thesis

The present thesis attempts to examine specific influences of emotional states on affectively-neutral Working Memory (WM) processing. A reliable association is sought between the cognitive sub-mechanisms of particular emotional states on the one hand, and components of WM, i.e. Central Executive, verbal WM and spatial WM processes (Baddeley and Hitch, 1974) on the other hand.

The thesis comprises four parts, each of which contains several chapters which, in their turn, are divided into sections.

Part 1: Introduction provides a background on the main trends in the research on effects of emotion on cognitive processing *(Chapter 1)*. In Chapter 2 there is a discussion of the choice of the cognitive process investigated here (WM) and information-processing and neurobiological models of WM are introduced. Finally, there is a critical examination of the extant literature on the effects of emotional states or traits on individual WM components.

Part 2: Effects of positive emotion on analytical and creative tasks: a Central Executive account focuses on one of the relatively few reports of differential effects of emotion on cognitive tasks. Positive mood seems to facilitate creative problem-solving, but disrupt analytical performance *(Chapter 3)*. It has been proposed (Oaksford et al., 1996) that this difference is due to differential involvement of a WM component- the Central Executive (Baddeley and Hitch, 1974) in the two types of tasks. This perspective is consistent with biologically-founded models of the influence of positive mood upon cognition (Ashby et al., 1999) and biologically plausible computational models of WM (O'Reilly et al., 2000) *(Chapter 4)*. Although the studies reported in Part 2 *(Chapters 6 and 7)* did not manipulate emotion, they directly tested one of the core assumptions of the Central Executive/WM account of differential effects of positive mood on creative vs. analytical tasks, namely that the two kinds of tasks make different demands on the Central Executive. Our studies investigated this assumption at both the behavioural and electrophysiological levels. Finally, the limitations related to the use of complex cognitive tasks are also discussed.

Part 3: Effects of anxiety on verbal and spatial WM examines the ways in which other WM components, i.e. the "slave-systems" (verbal WM and spatial WM) can be differentially influenced by certain emotions. In particular, on the basis of several corpora of studies, it is hypothesised that intense anxiety (fear) can have a selective impact on spatial WM *(Chapter 8)*. It is aimed to probe this hypothesis by using verbal and spatial WM tasks, which are more transparent than complex cognitive tasks (e.g. insight and reasoning tasks) in terms of the recruited cognitive mechanisms *(Chapter 9)*. The employed verbal and spatial (n-back) WM tasks are rigorously piloted *(Chapter 10)*. Finally, the hypothesis of selective effects of acute anxiety on spatial WM is experimentally tested *(Chapters 11 and 12)* in paradigms that involve anxiety elicitation by means of threat-of-shock and physiological recordings as objective methods for establishing the presence of anxiety *(Chapter 9)*.

Part 4: Threat and spatial WM: the generality of the effect and its neuroanatomical correlates is devoted to further explorations of the association between anxiety and spatial WM, revealed in the studies reported in Part 3. Two investigations are presented. One aims to establish whether less acute forms of anxiety (e.g. test-anxiety) parallel threat-evoked anxiety (fear) in its differential effects on verbal and spatial WM *(Chapter 13)*. The second investigation aims to establish whether selective impact of anxiety on spatial WM can be explained at the neuroanatomical level by models of asymmetric pre-frontal activation in emotion and WM *(Chapter 14)*.

The thesis does not have a separate, general section on methodology, due to the multitude of utilised experimental methods and techniques. Instead individual methods/ techniques/ technologies are introduced before reporting the studies in which they were employed, often as separate chapters. Accordingly, in Part 2 the use of concurrent tasks is discussed and Event-Related Potentials (ERPs) are introduced *(Chapter 5)*. A detailed discussion of mood-induction techniques is contained in Part 3 *(Chapter 9)*. *Chapter 9* also introduces the physiological recordings (Electro-Myography and heart-rate) employed in Part 3 as tools for objective assessment of the emotional state. In Part 4 the utilised neuroimaging technology (functional Magnetic Resonance Imaging, fMRI) is introduced and relevant aspects of experimental designs used in fMRI are discussed *(Chapter 14)*.

Similarly, the three types of tasks employed in the present studies are introduced in the corresponding chapters, rather than all in one general section. Insight and reasoning tasks, whose modulation by positive mood and WM correlates are compared in Part 2, are introduced in *Chapter 6* (Part 2). N-back WM tasks, are introduced in *Chapter 9* (Part 3), prior to reporting the studies that employed them.

The thesis ends with a ***General Discussion***, which summarises the findings and conclusions of individual studies and, in addition, provides general conclusions that emerged from the synthesis of results from individual investigations.

PART I. INTRODUCTION

Chapter 1. Emotion and cognitive processing. Background

1.1. Research on mood biases

The influence of emotion on cognitive processes has always been a topic of considerable interest and there is an ample literature dedicated to this domain. In addition to the vast applicability of such knowledge in the clinical domain, it has important implications in the context of cognitive psychology. Emotions are important factors in human cognition. In particular, a perspective that will be investigated in depth in this thesis is that emotions can be powerful modulators of information processing mechanisms and that such modulatory influences can be very specific (i.e. specific to certain emotions and certain cognitive systems).

In what follows, I present some of the well-explored theoretical perspectives on the effects of emotion on cognitive processes. This discussion also contains some points regarding the limitations of these perspectives in relation to the aim of the current investigation, namely selective modulation of affectively-neutral cognitive mechanisms by particular emotions. Research of the affect-cognition interaction that attempts to circumvent these limitations is presented in Chapters 3, 4 and 8-12.

Mood biases and memory

One of the largest corpora of studies in this field has examined biases in cognitive processing due to the affective valence of the processed material, referred to as *mood biases* (Alexander & Guenther, 1986; Beck & McBee, 1995; Bower et al., 1978; Isen et al., 1978). This work can be further subdivided. A substantial number of investigations looked at mood biases in memory processing. One type of mood-biasing effects revealed in memory investigations is *mood congruency*, which refers to the bias to memorise/recall information whose affective valence is consistent with one's affective state (Fiedler & Stroehm, 1986; Isen et al., 1978). It is intuitively appealing that somebody in a happy state would tend to remember happy events and, conversely, that depression would prompt sad memories. Indeed, the results from a number of studies (Alexander & Guenther, 1986; Isen et al., 1978), with few exceptions (Bower & Mayer, 1985), have confirmed this intuition: depressed mood leads to a greater number of negative events recalled and to a smaller number of positive memories. This was found with autobiographic episodes (Alexander & Guenther, 1986), as well as with laboratory stimuli, whose recall followed relatively shortly after the presentation (Fiedler & Stroehm, 1986). Furthermore, the effect was documented with various stimuli (e.g. words, photographs). An interesting finding was that mood congruency is observed for isolated stimuli, but not for categorical material (Fiedler & Stroehm, 1986).

There have been investigations that gained insights into neurobiological mechanisms of mood congruency. Some psychopharmacological studies examined the effect of interventions at the level of neurotransmitter systems on the valence of the material retrieved from memory. For example, *haloperidol*, a drug known for its suppressing effects on dopamine transmission, as well as for its property of either flattening affect or inducing depressed mood, was shown to cause negative mood congruency effects, which emphasises the role of dopamine in retaining the affective valence of stimuli (Kumari et al., 1998).

In addition to mood congruency, another phenomenon documented in the literature on mood biases in memory processing is *mood dependent memory*, which refers to facilitation of memory when the mood states at encoding and recall are the same (Eich & Metcalfe, 1989). Although the evidence of mood dependent memory has been less consistent than that of mood congruency (Bower and Mayer, 1989), recent studies, employing a more rigorous methodology, have confirmed the effect (Beck & McBee, 1995). The most influential model of mood biases in memory, based on spreading activation associative models of memory (Anderson, 1976), is the *semantic network model* (Bower, 1981). It proposes that networks containing semantic information about stimuli, also include nodes encoding affective information and that activation of the latter facilitates retrieval of particular semantic information. Recent studies of mood biases in memory (Varner and Ellis, 1998) provided support for the model.

Mood biases and attention

Mood biases have been investigated not only in relation to memory processes. A large corpus of studies have examined attentional biases in emotional states and disorders. In particular, attentional biases in highly anxious individuals have been systematically investigated for some time (MacLeod & Rutherford, 1992; Mathews & MacLeod, 1994; Mogg et al., 1994). Mathews and colleagues (MacLeod & Mathews, 1988; Mathews et al., 1997; Williams et al., 1988) made one of the earliest attempts to condense the results of numerous studies in a theoretical framework. *Trait anxiety* has been conceptualised as one of the basic dimensions of personality (Gray, 1982), reflecting the proneness of the individual to experiencing anxiety states. The model by Mathews and co-workers postulated that highly anxious individuals (i.e. individuals with high trait anxiety) show a facilitatory attentional bias in processing material with (even mild) negative affective content, referred to as *attention to threat* (Mathews et al., 1997). In contrast, individuals with low trait-anxiety show the opposite bias for mildly negative stimuli- an avoidance bias; only for stimuli perceived as highly threatening do individuals with low anxiety also show a facilitation bias. The model explains the difference between high- and low-trait anxiety groups in terms of the reactivity of the mechanism that allocates resources to the processing of threat. Considerable evidence was amassed in support of the theory from designs utilising various stimuli (words, pictures, etc., see Mathews et al., 1997).

A similar model of *attention to threat* was proposed by Mogg, Bradley and colleagues (Mogg & Bradley, 1998; Mogg et al., 1994). Both models distinguish between a component that evaluates how threatening various stimuli are and another component that allocates cognitive and physiological resources (e.g. attention) to threat processing. The only significant difference was that one model explained the difference between high- and low- anxiety groups in terms of the evaluation mechanism (Mogg & Bradley, 1998), whereas the other model explained that in terms of resources allocated to threat processing (Mathews et al., 1997).

Studies of mood biases in memory and attention provided significant insights into the role of emotion in prioritising information. Theoretical accounts formulated in the domain (e.g. the *semantic network* model or *attention to threat* theories) developed useful conceptualisations of the interaction between semantic information and affect. Moreover, psychopharmacological studies have begun to unravel the neurobiological correlates on mood-induced selectivity in memory (Kumari et al., 1998). However, the current thesis is concerned with the effects of emotion on affectively-neutral cognitive processes. The literature on mood biases is less conclusive with regard to material that does not have affective valence.

1.2. Emotional disorders and cognitive processing

A number of studies have examined performance on a variety of affectively neutral cognitive tasks in individuals with affective disorders, especially depression (Brown et al., 1994; Henriques & Davidson, 1992; Watkins et al., 1996). This approach had several motivations. Firstly, it was expected to reveal the cognitive profiles of emotional traits and disorders. Secondly, additional insight could be gained from the consideration of the neurobiological and neuroanatomical substrates of emotional disorders and how these could be related to information-processing deficits in affective disorders. Such a perspective has been strengthened significantly by the utilisation of modern neuroimaging technologies (Bench et al., 1992; Drevets & Raichle, 1995; Drevets et al., 1992). Finally, cognitive profiles of emotional disorders have been used as models of the effects of emotional states on cognition in a more general context. This can be exemplified by the well-documented relationship between the hyperthymic (manic) episodes in bipolar depression on the one hand, and creativity on the other hand. Several influential studies have reported strong associations between manic affective states/episodes and creativity (Andreasen, 1987; Andreasen & Canter, 1974), though see Shapiro & Weisberg (1999) for a more moderate interpretation of these and similar results in terms of increased productivity, rather than creativity.

Although investigations of cognitive profiles of affective disorders have proven informative, significant difficulties in this field have been related to generalisation to normal emotion. It may be tempting to regard disordered and normal affect as quantitatively different, but it is increasingly clear that there are qualitative differences between the two (Drevets & Raichle, 1995). Furthermore, affective changes in emotional disorders are largely explicable in terms of major neurochemical changes in the brain. However, among these neurochemical changes some would have little influence on affect per se, but may have a considerable impact on cognitive functioning.

1.3. Investigations of the overlap between the anatomical substrates of emotion and cognition

A complementary perspective, embraced by many researchers, was to consider biochemical and neuroanatomical models of normal emotion in relation to the functional anatomy of certain cognitive processes (Bartolic et al., 1999; Gray, 2001; Tucker, 1999). Consequently, predictions could be formulated on the basis of the overlap between the biochemical or neuroanatomical substrates of certain emotions and of certain cognitive processes. For example, models of interhemispheric asymmetry in emotion have been particularly prolific in generating such predictions.

These models exploited the left vs. right coordinates of the brain anatomy, ascribing differential involvement to left vs. right (Davidson, 1992, 1995, 1998; Tucker, 1981; Tucker & Williamson, 1984) cortical regions in dichotomously defined basic emotions (e.g. approach vs. withdrawal, Davidson, 1992). Numerous studies have been conducted in order to test such hypotheses. They have utilised behavioural (Tucker, 1981; Liotti & Tucker, 1992), neuropsychological (Bruder, 1989; Morris et al., 1996), psychophysiological (Davidson et al., 1990; Gotlib et al., 1998; Sobotka et al., 1992), and, more recently, neuroimaging (Sutton et al., 1997), techniques and gathered substantial amounts of empirical evidence.

The interest in the functional-anatomical overlap between emotion and cognitive function has not diminished over the recent years (see Gray, 2001). More importantly, some of the recent behavioural studies were in remarkable consensus with regard to their findings of differential effects of emotion on certain cognitive processes, predicted on the basis of models of interhemispheric asymmetry in emotion and cognition (Bartolic et al., 1999; Gray, 2001, see Chapter 14 for a more detailed discussion). However, a significant drawback of this approach is that neuroimaging studies have so far provided only limited support (Lawrence & Murphy, 2001; see also Chua et al., 1999 and Rauch et al., 1998 for divergent results) for one of the most widely held models of functional anatomy of emotion, namely the prefrontal cortex asymmetry model (Davidson, 1992, 1995, 1998). A more fundamental limitation of this perspective is its relative muteness with regard to the information-processing mechanisms underlying the effects of emotion on cognitive processing and, hence, on the evolutionary role of these effects. The overlap between cortical regions that represent a certain type of affect and a particular cognitive function can predict interactions between particular types of affect and cognition. However, some fundamental questions, e.g. "why is there overlap in cortical representation of emotions and cognitive functions?", would still remain unanswered. For example, an influential psychophysiological study (Henriques & Davidson, 1997) proposed to investigate the role of interhemispheric asymmetries in the interaction between depressed mood and verbal vs. spatial cognitive performance. The study employed verbal and spatial cognitive tasks, which were well matched for difficulty. However, although the tasks appeared to involve several cognitive functions (perception, long-term memory, Working Memory, etc.), the authors made no attempts to explore the cognitive aspects of the utilised tasks. The investigators only indicated that previous studies found differential involvement of brain hemispheres in the employed verbal and spatial tasks. This was regarded as sufficient for the purpose of testing interhemispheric models of emotion and its effect on cognition. A similar approach was taken in a recent behavioural study (Bartolic et al., 1999). The authors examined how frontal lobe interhemispheric asymmetries in emotion would account for the effects of induced positive and negative mood on tasks claimed to predominantly involve left (verbal fluency) and right (spatial fluency) frontal regions. Although careful consideration was given in this study to the neuroanatomy of verbal and spatial fluency in relation to the neuroanatomy of emotion, the cognitive processes contained in the two kinds of tasks and their functional role in the interaction with emotion were not examined.

1.4. The Resource Allocation framework

There are studies which attempted to address some of these issues, in particular the information-processing mechanisms underlying the influence of affect on cognitive processes. A number of investigations amassed support for the rather influential *resource allocation* theory (Ellis & Ashbrook, 1987). The theory explained the detrimental effects of depressed mood and the associated affective states (e.g. sadness) and disorders (e.g. clinical depression) on cognitive tasks in terms of cognitive resources being preferentially allocated to processing mood-related, but task irrelevant, cognitive material. Studies employing different mood induction procedures for eliciting depressed (sad) mood in healthy participants supported the resource allocation model in its application to memory encoding (Ellis et al., 1984) and memory retrieval (Ellis et al., 1985). It has also been shown that the more mood-related thoughts participants had, the more impaired was their memory performance (Seibert & Ellis, 1991). Similar effects of induced mood were observed on text comprehension (Ellis et al., 1997). Interestingly, although it had been previously found that the association of a piece of information with a negative affective state increases the likelihood of its retrieval in a similar affective state (*mood dependent memory*, Beck and McBee, 1995; Eich & Metcalfe, 1989), the overall memory efficiency in conditions of depressed mood is decreased for both encoding and retrieval (Ellis & Ashbrook, 1987; Ellis et al., 1985).

In its original formulation, the model was only intended to account for the effects of depressed mood on memory processing. One of the model's limitations is that it made little use of the knowledge of neurochemical and anatomical correlates of both depressed mood and memory. Consequently, the concept of *resource allocation* is sometimes difficult to apply in relation to functional-anatomical data. For example, one influential neuroimaging study examined the effects of induced depressed mood on verbal fluency (Baker et al., 1997). In the most commonly used versions of the verbal fluency task (e.g. Controlled Oral Word Association Test, Benton & Hamster, 1983) participants are given a letter of the alphabet and asked to generate during a certain time interval as many distinct words as they can that start with that letter. In the above-mentioned neuroimaging study, prior to performing the verbal fluency task, participants were asked to read aloud verbal statements with elated, sad or neutral content (first used by Velten, 1967, hence referred to as Velten statements), e.g. "People annoy me, I wish I could be by myself". A control group did the task with no exposure to Velten statements. The results showed decreased activity after depressed mood induction in the left prefrontal region- the most active cortical area during verbal fluency in the absence of mood induction. This finding raises questions with regard to the resource allocation account. If depressed mood were to re-allocate resources within certain cortical regions from verbal fluency to sad thoughts, the activation in these areas should not have decreased. A possible reconciliation of these results with the resource allocation framework is that, as a consequence of mood change, resources are re-distributed from one brain area to other brain areas. Indeed, there were brain regions outside the territories activated by verbal fluency that showed more activity in the depressed compared to the neutral conditions (Baker et al., 1997). The important point here is that neuroanatomical and neurochemical data can and should be used to constrain the information-processing models and to define their key concepts more precisely (e.g. the notion "cognitive resources" could be re-defined in terms of activation of brain areas). This was done in biologically plausible cognitive models of the effects of emotion on cognitive processing (e.g. "dopamine theory", Ashby et al., 1999, see Chapter 3). The definition of notions used in such models in neurobiological terms increases their expliecative value.

Despite limitations, the resource allocation theory can serve as an elegant conceptual framework, which was subsequently used for accounting for the effects of other types of emotion on several cognitive processes/ tasks (e.g. reasoning and Central Executive tasks, Oaksford et al., 1996).

1.5. The Processing Efficiency theory

A theory that makes similar assumptions as the *resource allocation* framework is the model of the effects of trait anxiety on Working Memory (WM; Part II of the thesis is dedicated to the description of the most influential cognitive and neurobiological models of WM.), the *processing efficiency* theory (Eysenck & Calvo, 1992; Eysenck, 1997). A number of studies have concurred in finding WM deficits in individuals with trait-anxiety (Calvo & Alamo, 1987; Darke, 1988; Eysenck, 1989; Markham & Darke, 1991). Importantly, these individuals seem to be more impaired on WM tasks than on other tasks. A recent study by Tohill & Holyoak (2000) found that state and trait anxiety depleted the capacity to perform complex analogies. Since the authors linked the complexity of analogies with the WM capacity, they interpreted the impact of state and trait anxiety on analogy in terms of the disruptive effects of anxiety on WM. The model by Eysenck and colleagues explains WM deficits in high trait anxiety individuals in terms of WM capacity being saturated by task irrelevant anxiety-related thoughts, e.g. worries (*ruminations*, Eysenck & Calvo, 1992). Although the theoretical approach of Eysenck and co-workers is conceptually related to the resource allocation framework, it is qualitatively different in at least three respects.

Firstly, it is more specific than the original resource allocation model with regard to the cognitive processes modulated by emotion. For example, in addition to predicting what cognitive tasks would be influenced by trait anxiety (the ones involving WM), it also predicts weaker effects on tasks that do not make substantial WM demands (Eysenck & Calvo, 1992). Secondly, rather than simply assume that anxiety reduces the amount of WM resources available to the task, the processing efficiency model proposes that this reduction in resources is largely compensated through additional effort. The latter means that the absolute amount of cognitive resources available to the task does not change in conditions of anxiety. Rather, the proportion of resources allocated to the task out of the global pool of cognitive resources decreases because of irrelevant anxiety-related processing, hence the term *processing efficiency.* Accordingly, the processing efficiency model predicts that only tasks that make large demands on WM resources would be visibly impaired by trait/ test anxiety. Thirdly (and this is closely related to the previous point), the processing efficiency theory predicts that the Central Executive component of WM is the mechanism that manages the compensatory resources and, consequently, it is more affected than WM slave-systems, though some disruption of the phonological loop is also thought to occur. Therefore, in contrast to the resource allocation model, concerned with the depletion of memory resources, processing efficiency proposes that anxiety affects primarily attentional / executive resources. In Chapter 13 the processing efficiency theory is discussed in more detail, and some of its predictions tested.

As it will be shown below (Chapter 2), the neurobiological substrate of the cognitive process examined in the processing efficiency theory (WM) is well investigated. Unfortunately, this advantage has not been capitalised upon by the theory or the studies that tested it. Moreover, the majority of the studies upon which the theory is based employed verbal WM tasks. The influence of anxiety on spatial WM is less documented. This is important in the context of the present investigations whose focus is the selective interaction between emotion and sub-mechanisms of WM (e.g. verbal vs. spatial WM components).

Chapter 2. The choice of the cognitive process: Working Memory

2.1. Information-processing models of WM

The present thesis examines the modulation of affectively-neutral cognition by affective states and the cognitive function under scrutiny is Working Memory. Several reasons determined the choice of Working Memory as the object of investigations. As was argued above, some of the most prominent research perspectives on effects of mood on cognitive processing, such as *interhemispheric asymmetry models* or the *resource allocation* theory, did not provide detailed accounts of the cognitive processes whose modulation by affect was investigated. Therefore, one important motivation for choosing here to investigate Working Memory is the following: Working Memory is well characterised in terms of its cognitive architecture.

WM as a multi-component system

Working Memory (WM) was first conceptualised by Baddeley and colleagues (Baddeley & Hitch, 1974, Baddeley, 1986, 2000) as a system for temporary maintenance and manipulation of information. Although WM acts as a memory mechanism, its functional significance for on-line, goal oriented processing makes it more than merely a memory system. It has been proposed that WM integrates motivational and instrumental aspects of behaviour. In other words, at any point in time WM represents the information about goals as well as about potential ways they can be accomplished. The prioritisation of goals and response alternatives is performed by the Central Executive component of WM, or, as conceptualised by other authors, the Supervisory Attentional System (Norman & Shallice, 1986). The Central Executive operates independently of the type of information, or the modality through which information is acquired, and is therefore said to be modality-independent. In addition, given its role of ultimate decision-making instance, the Central Executive is at the top of the hierarchy of WM components. Two other components that are part of WM, unlike the Central Executive, are defined by the types of information they process. The Verbal component of WM, also referred to as the *phonological loop* (Baddeley & Hitch, 1974), stores verbal material, putatively in the form of articulatory or phonological codes. The Spatial component of WM, also referred to as the *visuo-spatial sketchpad* (Baddeley & Hitch, 1974), is assumed to hold visuo-spatial information that reaches WM.

The model by Baddeley and Hitch (1974) represents a development of earlier models of short-term memory (Broadbent, 1958, Atkinson & Shiffrin, 1968). Nevertheless it is qualitatively different from the latter in at least two ways. Firstly, the early models of short-term memory viewed memory as a unitary store, whereas Baddeley and Hitch proposed a non-homogeneous, multi-component model. Secondly, the Baddeley and Hitch model of WM is more than a memory store, as suggested by the role of its Central Executive component. The Central Executive is involved in prioritisation of any non-routine (i.e. deliberate) behaviour. The non-storage character of the Central Executive is further evidenced by the lack of maintenance capacity, postulated in the early version of the model (Baddeley & Hitch, 1974) and reiterated subsequently (Baddeley, 1986, 2000). Hence, the Central Executive has to use external storage capacity, represented in Baddeley and colleagues model by two "slave-systems": the phonological loop and the visuo-spatial sketchpad.

In addition to the integration of processing and storage dimensions, a factor that also contributed to the model's recognition is that considerable evidence from various areas of cognitive science and neuroscience supported the multi-component character of the model. There is substantial behavioural evidence supporting the distinctiveness of the verbal and spatial sub-components of WM (Baddeley, 2000). Although somewhat less consistently, neuroimaging data also suggests relatively distinct substrates of verbal and spatial WM in the brain (Smith & Jonides, 1999). As it will be discussed later, recently an additional storage system, the episodic buffer, was added to the original WM model (Baddeley, 2000).

By far the most investigated component of WM has been the phonological loop, proposed to maintain verbal and acoustic information. In the original version of the WM model, the phonological loop was further sub-divided into the phonological store and the articulatory rehearsal mechanism. The function of the rehearsal mechanism was to enhance the on-line maintenance capacity for verbal information. Evidence for the phonological loop as a distinct component of WM comes from different domains. Memory experiments with phonological material showed that it is easier to remember a sequence of letters or words when these are phonologically dissimilar and, conversely, memory performance for sequences decreases with increasing phonological similarity between items (Conrad & Hull, 1964, Baddeley, 1966). For example, the sequence *g, c, b, t, v, p* is harder to remember than the sequence *f, w, k, s, y, k* (Baddeley, 2000). In contrast, semantic or visual similarity has little effect (Conrad & Hull, 1964, Baddeley, 1966). This suggests that even when these items are presented visually, they are remembered as acoustic or phonological codes.

Furthermore, participants find it easier to recall sequences of short words (*wit, sum, harm* compared to *university, auditorium, constitution*). This phenomenon, referred to as the word-length effect, has been interpreted in terms of polysyllabic words taking longer to rehearse, which allows the memory trace to deteriorate (Baddeley, 2000).

Articulatory suppression is a particularly interesting phenomenon in the context of the phonological component of WM. When people are prevented from rehearsing the items that have to be remembered (e.g. by being asked to repeat continuously an irrelevant word with little semantic content, such as *the*) performance is impaired significantly. Moreover, articulatory suppression eliminates the word-length effect, so that it does not make much difference how long the words in a sequence are. Indeed, if the words are not verbally rehearsed, it does not matter how long it takes to articulate them. Interestingly, articulatory suppression can also substantially reduce the effect of phonological similarity. For instance, in conditions of concurrent articulatory activity it does not seem to matter how phonologically similar the items are. However, this only holds for the visual presentation of items; articulatory suppression does not eliminate the disadvantage for phonologically similar items in auditory presentations. The explanation for this is straightforward if it is assumed that articulatory suppression disrupts the transfer of information from visual to phonological codes (Murray, 1968). Such transfer is likely to be ubiquitous because the phonological loop is efficient and people choose to subvocally rehearse visually presented items (Baddeley, 2000).

There is persuasive neuropsychological evidence for the distinctiveness of the phonological loop within WM. Among patients with speech impairments, some do and some do not have rehearsal deficits. Importantly, patients who have intact rehearsal are the ones whose speech impairments are known to be of peripheral nature (Baddeley & Wilson, 1985), supporting a more "central" character of the rehearsal code (Baddeley, 2000). Further evidence concerning the phonological loop comes from well-documented cases of individuals who have relatively spared memory for visuo-spatial information, but impaired phonological WM (Vallar & Shallice, 1990).

The second slave-system, postulated in the Baddeley and Hitch (1974) model of WM, the visuo-spatial sketchpad, is less investigated and understood. As with the phonological loop, it is believed to be further fractionated into a visual, a spatial and, possibly, a kinaesthetic component (Baddeley, 2000). Despite the scarcity of behavioural data on the visuo-spatial store, what is available seems to support its specialised character. For instance, in the same manner the phonological loop was tested with articulatory suppression, interference paradigms were employed to probe the existence of visuo-spatial WM, and with similar results. Simple tasks believed to load the processing resources of the visuo-spatial sketchpad (e.g. tapping the corners of a square with one's fingers) were found to disrupt the WM for spatial information, but not the WM for verbal or acoustic information (Baddeley, 2000). Although more rare, selective neuropsychological impairments of visuo-spatial WM have also been documented (Hanley et al., 1991).

Limitations of the Baddeley and Hitch (1974) original WM model

Despite the impressive record of the Baddeley and Hitch (1974) WM model in accounting for various data, it soon became apparent even to its proponents that some significant phenomena were beyond its scope. For instance, it was evident from the outset that the phonological loop could not be the only system responsible for WM for verbal material (Baddeley, 2000). Indeed, if it would be the only mechanism for short-term retention of verbal information, then articulatory suppression should have catastrophic effects on verbal WM. While the effects of articulatory suppression are significant, people still preserve a substantial proportion of verbal WM capacity. Moreover, patients with deep impairments of short-term phonological memory, who have a digit span of one for verbal material in auditory presentations, have a digit span of four in visual presentations. One could resort to the possibility that verbal material could also be visually coded in the visuo-spatial sketchpad. This would predict that there would be significant visual similarity effects for verbal material (similar to the above-mentioned phonological similarity effects). Such effects were indeed found (Logie et al., 2000), but they are too small to account for the capacity to retain verbal material when the phonological loop is disrupted (via suppression or neurological damage).

Further questions were raised by studies of sentence and text comprehension, which showed that the phonological loop does not provide an adequate account of WM for verbal material in text comprehension (Gathercole & Hitch, 1993). This is well illustrated by memory for prose. It has been known for a long time that when verbal material can be organised into "chunks", then chunks, rather than individual words, are digits in the digit span (Miller, 1956). Chunks can be easily shown to exceed the capacity of the phonological rehearsal mechanism. Moreover, the assumption that WM for chunks is phonological in nature imminently leads to a contradiction of the above-discussed word-length effect (long words are harder to remember). It seems obvious that the chunking effect is due at least to some degree to the semantic information from long-term memory. It could even be argued that the span for chunks could be entirely a long-term memory phenomenon. However patient data are not consistent with the latter proposal. For instance, a patient with verbal WM impairments and intact long-term memory, described by Vallar and Baddeley (1984), had a sentence span of five words, which was more than the single digit span of one word, but considerably less than the normal sentence span of approximately 16 words. Therefore, it is concluded that, although the chunking effect is driven by semantic information retrieved from long-term memory, chunks are stored in WM (Baddeley, 2000).

To summarise, it became increasingly clear that verbal information is not solely stored as phonological codes in WM. On the other hand, as memory for prose suggested, semantic information from long-term memory may be incorporated into the representations stored in WM. These lines of evidence are problematic for the Baddeley and Hitch (1974) model of WM in at least three ways. Firstly, none of the model's components is suited for the storage of semantic information. Secondly, none of the components was capable of storing integrated information of different types (e.g. phonological and semantic). The Central Executive could perform such integration but had no storage capacity. Thirdly, the model did not explicitly postulate any on-line exchange between WM and long-term memory. An additional limitation of the initial model of WM concerns rehearsal mechanisms. While the phonological loop was assumed to have a rehearsal sub-mechanism based on the rehearsal of articulatory codes, the latter evidently could not be applied for the rehearsal of visuo-spatial information. Yet, the model did not specify any other rehearsal mechanisms.

Three developments of the model have attempted to address these limitations (Baddeley, 2000). A new slave-system component, the episodic buffer (also referred to as the back-up store), was added to the WM model. Its function is to store information that is integrated across different types (e.g. visual, phonological, etc), including semantic information exported into WM from long-term memory. In addition, the three slave-components (i.e. the storage components) of WM were assumed to have reciprocal connections with similar sub-divisions of long-term memory: the phonological loop to the linguistic knowledge in long-term memory, the visuo-spatial sketchpad to visual semantics and the episodic WM buffer to episodic long-term memory (Baddeley, 2000). Finally, rehearsal in the visuo-spatial sketchpad was proposed to be mediated by shifts of attention from one item (or spatial location) to another (Smyth & Pelky, 1992; Smyth, 1996, see Chapter 8 for an extensive discussion of the role of attention in spatial WM).

A Central or a specialised Executive?

Although rehearsal in the visuo-spatial sketchpad is proposed to be mediated by shifts of attention, it is not clear how these shifts are related to the Central Executive (which is an executive and attentional system). Attentional shifts may be performed by the Central Executive, implying that the Central Executive takes an active part in spatial WM rehearsal. Since rehearsal in the phonological loop is believed to be largely independent of the Central Executive, this would imply a stronger association between the Central Executive and spatial WM, as compared to Central Executive and verbal WM. Furthermore, the WM model assumes that the Central Executive is by essence a non-storage system (Baddeley, 1986). An alternative is to postulate specific executive (attentional) capacities in the slave-components. A related, but more drastic, revision has already been proposed by some authors (Daneman & Tardif, 1987, Shah & Miyake, 1996). These investigators opt for multiple executive (attentional) systems in WM, which are specifically associated with the storage components (e.g. verbal attentional resources, spatial attentional resources), instead of the Central Executive. The evidence cited in support of a multi-component executive system instead of a unitary one is that spatial span tasks that tax both storage and execution components of spatial WM, correlate with measures of spatial ability (e.g. spatial visualisation), but not with measures of verbal ability (Shah & Miyake, 1996). Similarly, verbal WM tasks taxing both storage and processing (reading span) correlate with verbal, but not spatial, ability measures. At the same time, it has been claimed that verbal and spatial tasks that only tax storage are poor predictors of complex verbal and spatial tasks (Daneman & Carpenter, 1980; Perfetti & Goldman, 1976; Turner & Engle, 1989). This suggests a distinction between verbal and spatial modalities not only in low-level storage processes, but also in attentional-executive processes.

An amodal, homogeneous WM

A radically different way of resolving the problem of rehearsal as well as the other problems of the early multi-component WM model (Baddeley & Hitch, 1974) discussed above, is to assume a unitary pool of WM resources used for different tasks (Engle et al., 1992). Indeed, if executive resources are equally available for different processes, then rehearsing different types of material does not seem a problem. Similarly, in a unitary WM devoted to different processes and different types of information, it does not seem problematic to store semantic information and integrate it with other types of information (e.g. phonological and visuo-spatial). For example, in several studies by Engle and colleagues (Engle et al., 1992; Turner & Engle, 1989) digit span was measured with different types of information as digits (words or numbers as digits). In addition, verbal ability was measured in a set of separate tasks. It was shown that digit span correlated equally well with measurements of verbal ability when the items to be remembered were words or numbers.

However, such an account would still need to explain in more detail how rehearsal for different types of information works, which has already been done quite successfully for some types of information (e.g. phonological) within the multi-component WM framework. Some clarification of how an amodal WM could work comes from recent biologically plausible computational work by O'Reilly and collaborators (Frank et al., 2001; O'Reilly et al, 1999). These authors propose a gating mechanism that modulates shifts to new contents in WM. Such gating, instantiated in the brain by the dopaminergic circuits that project from basal ganglia into the prefrontal cortex (PFC), could support rehearsal of various types of information, or information modalities. However, studies of sub-vocal articulation show that rehearsal in verbal WM is associated with mechanisms of speech which do not appear active in spatial WM (see above the discussion of articulatory suppression). Conversely, neuroimaging literature indicates that rehearsal in spatial WM, and not verbal WM, tasks activates primary visual areas (Awh et al., 1999, see Chapter 8). Even if one assumes that one mechanism supports rehearsal, it seems that the latter would need some internal differentiation, or at least differentiation at the level of its connections to the peripheral systems (i.e. speech (motor) output in verbal WM and visual perception in spatial WM).

Furthermore, critics of the unitary WM account argue that much of the evidence in its support come from verbal and numerical processing tasks rather than verbal and spatial processing tasks (Shah & Miyake, 1996). Finally, the unitary WM model would have to explain a number of phenomena (phonological similarity and word-length effects, articulatory suppression and its correlates, etc.) which were elegantly accounted for by the multi-component WM model. The proposal of the WM as a unitary system has also been made in the literature on the functional neuroanatomy of WM, with some recent neuroimaging studies reporting no marked differences between the cortical regions (in particular, prefrontal regions) activated by verbal and spatial WM tasks (Nystrom et al., 2000). However, as it will be mentioned in the next section, the evidence of cortical activity specific to WM components (e.g. Broca's area in verbal rehearsal) is rather persuasive.

In conclusion, despite the limitations of its early version and the speculative character of some of the recent developments of the model, the multi-component WM model (Baddeley & Hitch, 1974; Baddeley, 1986; 2000) has accounted for a wide range of behavioural, neuropsychological and neuroimaging data with a relatively limited number of assumptions. Importantly, amongst neuroanatomical models of WM, which will be discussed in the next section, the most successful are also based on the multi-component cognitive model of WM.

2.2. Neuro-anatomical models of WM

It has been said above that one important reason for choosing to investigate WM is the accumulated knowledge regarding its cognitive architecture. Another incentive for choosing WM as the cognitive mechanism whose manipulation by affect would be studied is its functional neuroanatomy. It is a matter of consensus that the Prefrontal Cortex (PFC) is intimately involved in WM (Fuster, 1995; O'Reilly et al., 1999; Smith & Jonides, 1999). Several PFC areas, such as the dorso-lateral, inferior-lateral areas and also the anterior cingulate, appear to be involved in WM tasks (Smith et al., 1998), as well as in the generation, perception and maintenance of most emotional states (Drevets & Raichle, 1998). Another consensus, reached in the neuroimaging literature on emotion, is that the prefrontal cortex is intimately involved in the generation, maintenance and control of affect (Davidson & Irwin, 1999; Raichle & Drevets, 1998). Furthermore, there is significant overlap in the neurotransmitter systems subserving some forms of emotion and also believed to be involved in WM. For example, the processing of reward is largely reliant on dopaminergic pathways (Schultz et al., 1993), which are particularly dense in the PFC. The same neurotransmitter, dopamine, is proposed to be critical for updating WM contents (Frank et al., 2001; O'Reilly et al., 1999). Consequently, there are good neurobiological reasons to expect powerful interactions between affect and WM.

There are several neuro-anatomical models of WM. Perhaps not surprisingly, these models address the same issues as WM theories in the cognitive literature, namely the existence of modality-specific components in WM, the dissociation between retention and executive processes, the differentiation between storage and rehearsal functions and the nature of rehearsal in verbal and spatial WM.

Primate studies

The first neuroanatomical evidence for the presence of a mechanism for retaining information over short delays was provided from single-cell cortical recordings in non-human primates. A typical investigation of WM in non-human primates is exemplified by the following experiment by Goldman-Rakic and colleagues (Funahashi et al., 1989). Monkeys were shown a small square in one of several locations. A short, e.g. 2.5 sec, delay followed the presentation of the square, after which the monkey was cued to shift its gaze to the location where the square was and was rewarded for doing so correctly. During the delay the activity of single neurons from various parts of the brains was recorded. A common finding of such studies was that there are cells in the prefrontal and parietal cortex, which are only active during the delay, their activity being linked to one specific location (Fuster, 1995). These cells were proposed to be part of a neural mechanism of WM, a mechanism that was said to maintain an active representation of relevant information in the absence of environmental cues (Goldman-Rakic, 1987, 1995).

"What" vs. "where" in the Prefrontal Cortex

Following the remarkable findings from the primate single-cell recordings, a large corpus of neuroimaging studies have attempted to reveal the neural correlates of WM in humans (see Cabeza & Nyberg, 2000, for a review). An important conclusion that emerged early in neuroimaging literature and has been subsequently validated, is the role of the prefrontal and parietal cortical regions in WM (Cohen et al., 1997; Jonides et al., 1993; Paulesu et al., 1993). It is consistent with the main outcomes from the primate literature. An early neuroanatomical model of WM also stems from the research on non-human primates and some influential theories that resulted from this research, such as the theory of the "what" and "where" visual streams in the primate brain (Mishkin & Ungerleider, 1982). The two streams were proposed to be relatively distinct perceptual systems, specialising in information about objects vs. their locations. The object ("what") and location ("where") systems were anatomically ascribed to the ventral and dorsal occipito-temporal cortices respectively. Based on studies of cytoarchitecture, i.e. the microanatomy of the cortical columns, and investigations of cortical connectivity, Goldman-Rakic and co-workers have hypothesised that the prefrontal cortex is also functionally organised according to the "what" vs. "where" informational domains, with a similar anatomical organisation to the one from posterior areas: ventral ("what") vs. dorsal ("where") (Goldman-Rakic, 1987; Wilson et al., 1993). These researchers have recorded single-cell activity in different prefrontal locations, while monkeys performed delayed response object or location WM tasks. Cells that were active during the delay in response to the identity of objects were predominantly located in the ventral PFC, whereas cells that were active during the delay in response to location were situated in the dorsal PFC. However, there have been methodological criticisms of these studies, in particular regarding the interpretation of results (Rushworth & Owen, 1998). Furthermore, other single-cell recording studies have not found a clear ventral-dorsal dissociation between cells encoding object vs. location information (Rao et al., 1997). Nevertheless, even the authors of the latter study admitted that there may be a relative, statistical predominance of domain-specific neurons in certain prefrontal areas (Miller, 2000). Therefore, the evidence from single-cell recordings for some form of functional anatomical segregation between the "what" vs. "where" WM pathways is rather persuasive.

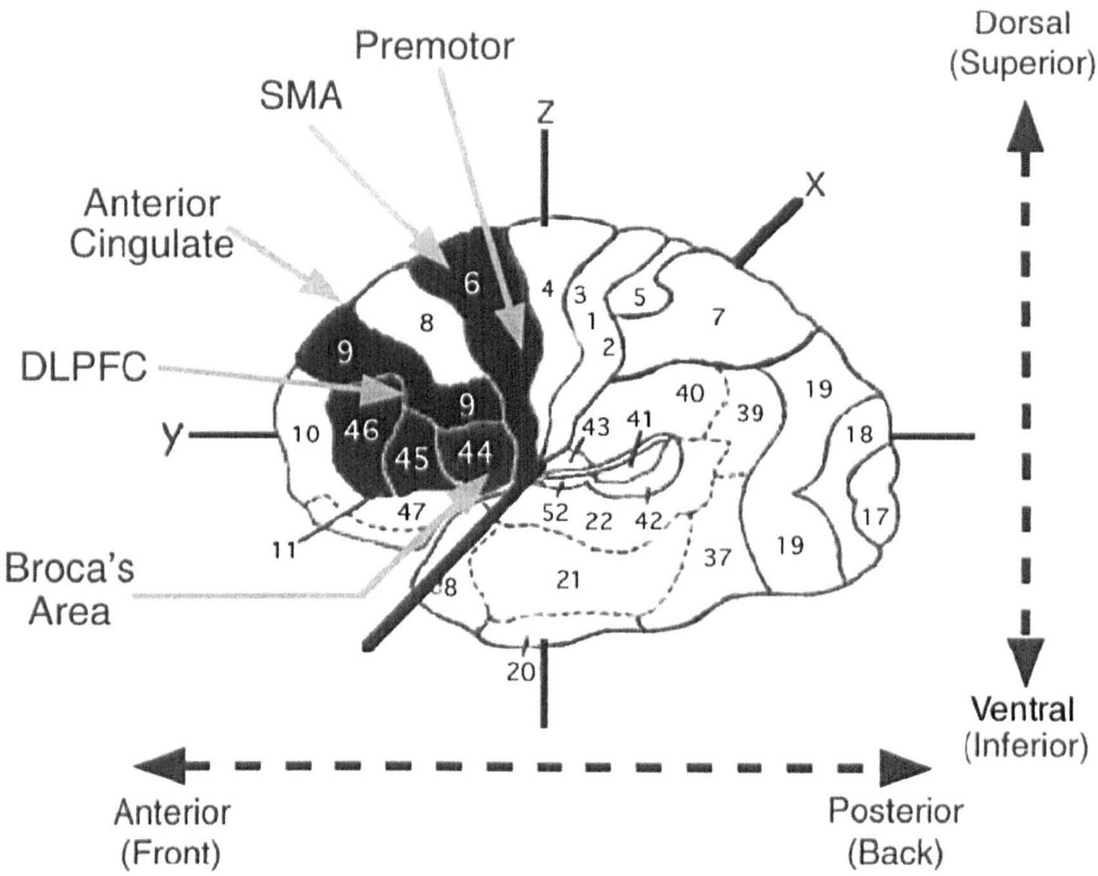


Figure 1. The anatomy of the prefrontal cortex.

Notes: DLPFC- dorso-lateral prefrontal cortex; SMA- supplementary motor area; the numbers correspond to Brodmann Areas.

However, it is not clear to what extent the model developed on the basis of non-human experimentation is applicable to WM and PFC in humans. Although a large corpus of neuroimaging studies have attempted to tackle this issue, there is still little consensus with regard to their results. Several studies using non-spatial and spatial materials in WM paradigms found that they activated the ventral and dorsal divisions of the PFC respectively (Courtney et al., 1996, 1998; McCarthy et al., 1996, see Fig. 1 for the anatomy of the PFC in humans). Nevertheless, an equally impressive number of studies found no evidence for spatial (ventral regions) vs non-spatial (dorsal regions) organisation of the human PFC (Nystrom et al., 2000; Postle & D'Esposito, 2000; Postle et al., 2000). A recent neuroimaging study that addressed this dissociation found evidence of the ventral vs. dorsal streams in posterior brain regions, but not in the PFC (Postle et al., 2000). Moreover, unlike earlier studies which often based their conclusions on separate comparisons of the conditions of interest with the baseline, some recent studies have directly statistically compared the spatial vs non-spatial conditions and failed to reveal differential patterns of activation in the PFC (Postle et al., 2000, Nystrom et al., 2000). Nevertheless, the latter investigations were justifiably criticised for not matching the spatial and non-spatial WM tasks on difficulty (Goldman-Rakic, 2000). To conclude, the validity of the functional anatomical organisation of the ventral and dorsal PFC according to the "what" vs. "where" domains needs to be further examined in humans.

Neuroanatomical correlates of the executive processes

Some authors have proposed an alternative functional distinction between the ventral and dorsal regions of PFC, which also arose from monkey lesion studies (Petrides, 1994). Instead of reflecting differences in domain specificity (i.e. "what" vs. "where"), PFC anatomy was proposed to reflect a processing difference, with the ventral region specialised predominantly in maintenance and the dorsal region in manipulation of information (Rushworth & Owen 1998). Manipulation of information in WM is often referred to as executive processing, by analogy with the Central Executive component of WM (Baddeley & Hitch, 1974). The idea of the relative segregation of executive and memory functions in the PFC has received substantial neuroimaging support (D'Esposito et al., 1995; Rowe et al., 2000; Stern et al., 2000). Furthermore, many authors have claimed that the dorsal region of the PFC (i.e. the dorso-lateral PFC, dlPFC, see Fig. 1) tends to show activation when manipulation of information, in addition to maintenance, is required. Maintenance alone often fails to activate the dlPFC. For example, in a *functional Magnetic Resonance Imaging (fMRI)* study, Rowe et al. (2000) implemented a delayed item recognition paradigm, in which the scans of the delay interval and of the response interval were separated, thanks to the temporal advantages of rapid fMRI scanning technology, referred to as *event-related fMRI*. The task presented three consecutive dots in different locations. After the delay a cursor appeared on the screen followed by a probe and there were two kinds of responses that the participants could provide depending on the probe. If the probe was a number (e.g. "2"), then participants needed to move the cursor with a joystick to the location of the second dot they saw earlier ("selection condition"). If the probe was an "X", then participants had to move the cursor to the location of "X" ("maintenance condition"). Since participants were not aware at the beginning of each trial what kind of response was to follow, they had to memorise the locations and temporal order of dots in both conditions. In only one condition the response required the selection of the correct response among three alternatives (the selection condition). When compared to a rest baseline, the scan of the delay interval (maintenance) did not reveal an increase in dlPFC activation. In contrast, such an increase was found in response to the interval when selection was performed (Rowe et al., 2000).

However, investigators who oppose the idea of a processing distinction within PFC and that of specialisation of its dorsolateral region in manipulation rather than maintenance (O'Reilly et al., 1999; in press), have argued that in paradigms such as the one by Rowe et al. (2000) the condition said to require "manipulation"(Smith & Jonides, 1998), or "selection" (Rowe et al., 2000), or "monitoring" (Stern et al., 2000) is different in several respects from the condition thought to involve solely maintenance. One important difference pointed out by O'Reilly et al. (1999) applies to several studies whose conclusions supported the presence of a dissociation between manipulation vs. maintenance in the PFC. For example, in Rowe et al.'s (2000) "selection" condition, participants are presented with a number (e.g. "2"), which stands for the serial order of a particular location. This explicitly requires the re-coding of the WM content (locations) into numeric representations, a process relying on transfer of numeric knowledge into WM from long-term memory. In contrast, Rowe et al.'s (2000) "maintenance" condition, which is the delay interval, does not explicitly ask for numeric encoding of serial order and it is conceivable that participants do not tag locations with numbers ("1,2,3") during delay and only do so during "selection" forced by the presentation of numbers. Thus, the difference between the "selection" and "maintenance" activations (dlPFC activation in the former but not the latter) could be due to the integration of different types of information (i.e. location and number) in the dlPFC.

Furthermore, O'Reilly and co-workers proposed that, in general, activation of dlPFC, seen only in complex WM tasks, could be explained by more abstract representations in the dlPFC, as compared to more detailed, feature-bound representations in other regions of the PFC (e.g. ventral or orbitofrontal areas). O'Reilly et al. (in press) developed a computational model which instantiated the differentiation between more vs. less abstract representations in the PFC, in order to simulate monkey lesion data that apparently indicate different functions within the PFC (Dias et al., 1997). These monkey studies employed a version of the Wisconsin Card Sorting Test, the ID/ED task (Roberts et al., 1988), in which stimuli of two or more categories of stimuli (referred to as *dimensions*) are presented and the criterion is switched either within stimuli of the same dimension, i.e. intra-dimensionally (ID), or between dimensions, i.e. extra-dimensionally (ED). Monkeys with lesions to the orbitofrontal PFC are more impaired when they have to suppress previously, but no longer, correct responses within dimensions, whereas monkeys with lateral PFC damage have deficits responding to a different dimension and suppressing the responses to the old correct dimension (Dias et al., 1997). Dias et al. interpreted these results as indicating a functional dissociation within the PFC: inhibition vs. attentional shifting. In O'Reilly et al.'s (in press) computational model, orbitofrontal PFC contained representations of stimuli within dimensions, while lateral PFC represented dimensions and not individual stimuli within dimensions. Although the model made no functional distinctions within PFC, lesions to the model led to a similar double-dissociative pattern as in monkeys. Importantly, although the abstract vs. detailed differentiation is binary in the model, O'Reilly et al. (in press) stress that it most likely represents a continuum from less to more abstract representations with the most abstract ones being processed in the dlPFC. Although O'Reilly and co-workers have expressed opposition to functional differentiation within PFC, in their models of WM they implemented functional differentiation between PFC and the *basal ganglia,* a group of structures in the lower part of the brain (see Fig. 2, Chapter 3). In these models basal ganglia regulate the updating of contents actively maintained in the PFC through gating dopamine pathways that project from basal ganglia into the PFC. Hence, although the model does not implement maintenance vs. execution within the PFC, it does so between PFC and basal ganglia.

Furthermore, despite O'Reilly and colleagues' compelling arguments against functional specialisation within PFC, some evidence is difficult to account for without resorting to functional specialisation. For instance, most theorists agree that active inhibition of a response tendency is a process of an executive nature (Norman & Shallice, 1986). In an elegant design, Smith & Jonides (1998) contrasted two verbal delayed item recognition tasks. The two tasks used identical stimuli and contained identical requirements. In one of the tasks half of the probes were non-targets on the current trial, but were targets on the previous trial ("recent negatives"). The other task was a standard item recognition task, in which current probes never appeared on the previous trial. The authors predicted that the task containing "recent negatives" requires increased inhibition, as compared to the standard task, because the processing of "recent negatives" demands suppressing the response from the previous trials. Moreover, if dlPFC would be associated predominantly with executive processing, higher activation in response to "recent negatives" should be found in this region. Indeed, the direct comparison between the "recent negatives" and the standard conditions revealed only one area of significant activation, the left dlPFC. An alternative explanation for this activation in dlPFC would be to suppose that WM traces last longer in the dlPFC compared to other PFC areas and that for this reason the similarity of probes on the current trial to the probes from the previous trial is detected in the dlPFC. However this is contradicted by data showing that amongst PFC areas, dlPFC does not show the most sustained activity in WM tasks (Cohen et al., 1997).

In conclusion, it may seem that the association of some frontal regions (dlPFC) with "executive" processes can often be accounted for in alternative terms, without postulating functional differentiation within the PFC. However, this is not always the case and some data regarding the executive role of dlPFC is difficult to explain without resorting to some functional specialisation assumptions. Moreover, even models that oppose functional differentiation within PFC contain functional differentiation within the WM system (PFC vs. basal ganglia). It appears that the nature of processing in WM demands a trade-off between the stability of WM representations and the flexibility of WM contents, i.e. the ability to update WM effectively (O'Reilly et al, 1999; in press). It is difficult to imagine that both processing tendencies can be implemented by a completely unitary, homogeneous system, hence the need for sub-systems dedicated preferentially, but not entirely, to either maintenance or "execution", and this has been captured in many theories of WM. The divergence between such theoretical accounts concerns more the anatomical correlates of the specialisation (ventral vs. dorsal PFC or PFC vs. basal ganglia) or the precise nature of the specialised functions, rather than the presence of functional specialisation.

The functional neuroanatomy of the phonological loop and the visuo-spatial sketchpad

A significant line of research represents the attempts to determine the neuroanatomical substrate of WM architectures proposed in the cognitive literature. A good starting point was the very popular WM model by Baddeley and colleagues, discussed above (Baddeley & Hitch, 1974, Baddeley, 1986, 2000). In a series of neuroimaging experiments employing Positron Emission Tomography (PET) and fMRI as neuroimaging technologies, a number of researchers (Jonides et al., 1993, Paulesu et al., 1993; Awh et al., 1996; Smith & Jonides, 1998) tried to map the components of the Baddeley and Hitch (1974) WM model. The initial studies used the "cognitive subtraction" method (Posner et al., 1988), based on the concept of "pure insertion" (Sternberg, 1969). The logic of this concept is based on a linear decomposition of cognitive tasks into more elementary components. Accordingly, complex cognitive tasks are made up of more elementary components, which simply add up so that the insertion of a new process does not alter the existing processes. For example, in order to determine the neuro-anatomical correlates of the phonological loop by cognitive subtraction, one needs two verbal tasks, which differ in only one process, the short-term maintenance of information. In a PET study of verbal WM, Awh et al. (1996) employed two tasks, using identical materials. The participants were presented with several letters on the screen, followed by a probe letter, which they had to classify as belonging or not to the initially presented set of letters. The only difference between the two tasks was that the WM task had a delay inserted between the set of letters and the probe. According to the cognitive subtraction logic, the subtraction of brain activation of the no-delay (control) task from the delay (WM) task should reveal the anatomical correlates of WM, without confounding it with other processes (perception, motor response), equivalent in the two tasks. The results revealed several regions in the left hemisphere that showed more activation in the delay, compared to the no-delay tasks, i.e. prefrontal (Broca's area, the premotor area and the supplementary motor area: Brodmann Areas, BAs, 44 and 6) and parietal (BA 40) regions (see Fig 1). A very similar, left-lateralised pattern of activation was revealed by Paulesu et al. (1993), who used the same imaging technique (PET), the same tasks and the same type of methodology (subtraction).

In their study, Awh et al. (1996) have also used an additional verbal WM task, in which participants were presented with letters in a sequence of trials and on each trial they had to compare the currently presented letter with the one that appeared two trials ago. The task is referred to as 2-back and is a version of n-back tasks (Kirchner, 1958; see Chapter 9 for a detailed discussion of n-back tasks). As a non-WM control, Awh et al. (1996) used the same stimuli, but asked participants to compare the letter on each trial to one target letter, learned before the task started. This kind of control task is often referred to as "0-back". The subtraction of the 0-back from the 2-back task revealed activation of the same set of left prefrontal (BA 44 and BA 6) and left-parietal (BA 40) areas. Subsequently, a large corpus of neuroimaging studies confirmed the left-lateralised character of activation in verbal WM tasks (for a review, see Cabeza & Nyberg, 2000). Moreover, left-lateralised activation of BA 44 (Broca's area) in tasks containing verbal WM requirements has been one of the most reliable findings in the neuroimaging literature.

Importantly, activation of Broca's area in verbal WM tasks is not confined to cognitive subtraction paradigms. The "pure insertion" logic of the latter has been recently questioned, despite its wide use in neuroimaging studies (Friston et al., 1996). For example, adding memory requirements to a search task may lead to a perceptual re-organisation, such that the activation left after subtracting the search task would not only reflect memory, but perceptual re-organisation as well (Smith et al., 1998). In other words, the insertion of additional processes may change the nature of the existing ones. Therefore, some investigators turned to the so-called parametric variation designs, employed earlier in neuroimaging studies of long-term memory. In a parametric study of verbal WM (Jonides et al., 1997), load was varied by incrementally changing the value of n in an n-back task, generating 4 levels of the task (0-back, 1-back, 2-back and 3-back). Significant monotonic increases in activation in response to an increasing memory load could serve as a reliable indication of role of that region in verbal WM. Such increases were found in several, predominantly left-hemispheric, brain regions. Left prefrontal and left-parietal cortices showed the highest activity among those regions.

Several neuroimaging studies aimed to differentiate between storage and rehearsal in the phonological loop (Baddeley, 1986, 2000). If such differentiation can be identified at a neuroanatomical level, then a simple prediction would be that amongst left-sided prefrontal and parietal areas active in the verbal WM task, some had to be involved predominantly in storage and others in rehearsal. In the n-back task study outlined earlier (Awh et al., 1996), in addition to the 0-back control task, there was a control in which participants were repeatedly presented with the same sequence of letters and asked to press a key when they saw a letter and then silently rehearse it until they saw the next letter. If storage and rehearsal are dissociable, the subtraction of this task from the 2-back task should only leave the activity of areas associated with storage. Indeed, the authors found only activity in the parietal area and all the left prefrontal activity (Broca's area, left premotor and supplementary motor areas) observed in the 2-back/0-back contrast was removed now by the control task containing rehearsal.

Paulesu et al. (1993) also had a second control involving rehearsal, which was contrasted with the item recognition WM task. Participants were presented with letters and they had to silently judge whether those letters rhymed with a target letter. It was assumed that rhyming judgements required sub-vocal articulatory activity, but did not contain memory (storage) requirements. As expected, the subtraction of this task from the WM task left only the left parietal activation. These results suggest that the prefrontal regions shown in the neuropsychological literature to be associated with speech generation (Broca's area, BA 44, premotor and suplementary motor areas, BA 6, see Fig.1) are the most likely anatomical substrate for the rehearsal mechanism in the phonological loop. Since Broca's area has been associated with the production of speech, the outcomes from the imaging investigations are consistent with the proposal by Baddeley and collaborators (Baddeley, 1986, 2000) that rehearsal of verbal material has the form of a re-play of the speech (articulatory) codes. On the other hand, storage seems to rely on parietal regions (BA 40), and there is considerable evidence from conduction aphasia, caused by lesions to the left parietal cortex, of impairments of storage, e.g. the inability to say words backwards, in the absence of speech production or rehearsal problems.

However, while the neuroimaging evidence discussed above does suggest that left prefrontal and parietal areas (Broca's area, the supplimentary motor and premotor areas, BA 40) are the brain regions that support verbal WM, this is not evidence that these brain areas are specifically associated with verbal WM and do not subserve spatial WM as well. This issue was addressed in neuroimaging studies of spatial WM that used similar paradigms (mainly subtraction) and equivalent tasks (item identification, n-back). Such studies do not find left-lateralised prefrontal and parietal activation (Smith et al., 1998). Moreover, some of the areas considered to be intimately associated with the phonological loop (e.g. Broca's area) are rarely found active at all in studies of spatial WM (see Cabeza & Nyberg, 2000). When verbal and spatial WM are shown to activate overlapping areas (e.g. parietal areas), the activation tends to be left-lateralised in verbal tasks and bilateral in spatial WM tasks (Smith et al., 1998).

There have been some reports of right-lateralised prefrontal and parietal activity in spatial WM tasks. For example, Jonides et al. (1993) used an item recognition paradigm similar to the one employed in a verbal WM study described above (Awh et al., 1996). As in Awh et al., there were two recognition tasks: one with a delay between the stimulus set and the probe (WM condition) and one without a delay (control task). The critical differences, compared to Awh et al.'s verbal WM study, were the stimuli and the instructions. Jonides et al. (1993) used dots instead of letters and asked their participants to determine whether the location of the probe dot is one of the locations of three dots presented earlier. The pattern of brain activation was clearly distinct from those found by Awh et al. (1996). As in the study of verbal WM, significant differences between the WM and the control task were also found in prefrontal (BA 47, BA 6) and parietal (BA 40) regions. However these activation foci were found in the right, and not the left, hemisphere. In addition right-sighted activation was found in one brain region, whose activity has not been observed in verbal WM tasks- the right anterior occipital cortex (BA 19). Predominantly right-sided activation in spatial WM tasks was also found in other studies (e.g. Reuter-Lorenz et al., 2000). Additional evidence that distinguishes spatial WM from verbal WM is provided by behavioural, electrophysiological and neuroimaging investigations of the role of visuo-spatial attention in spatial, but not verbal, WM (this evidence is discussed in detail in Chapter 8).

To summarise, WM is well described both in terms of its cognitive architecture and neuro-anatomical correlates (Baddeley, 2000; Smith & Jonides, 1998, 1999; Smith et al., 1998). Although some issues are still awaiting investigation (e.g. integration of verbal and semantic memory, rehearsal and storage in spatial WM, the presence of de-centralised attentional mechanisms), there is ample behavioural evidence for the functional segregation of WM and studies of functional neuroanatomy of WM provide additional support for this (Awh et al., 1996; Jonides et al., 1993; Paulesu et al., 1993, Smith & Jonides, 1998). In addition there are biologically-driven computational models of WM which aim to integrate behavioural, neuroimaging and biochemical data (O'Reilly et al., 1999, 2001; in press). These models also implement a distinction between maintenance and executive (gating) mechanisms.

The following chapters examine the differential involvement of the Central Executive WM component in cognitive tasks found to be differentially modulated by positive mood.

PART II. EFFECTS OF EMOTION ON ANALYTICAL AND CREATIVE TASKS: A CENTRAL EXECUTIVE ACCOUNT

There is one domain that combines features otherwise shown only in isolation in the literatures on effects of mood on cognition discussed in Chapter 1. It is the domain centred on the effects of positive mood. For instance, it has been found that positive mood facilitates insight/ creative problem-solving (Isen et al., 1987), while impairing analytical (deductive) reasoning (Oaksford et al., 1996). Importantly, the information-processing aspects of these effects have been accounted for in terms of differential modulation of the Central Executive component of WM (Oaksford et al., 1996). The neurobiological correlates of these effects have also been the object of careful scrutiny (Ashby et al., 1999). For the above reasons the differential effects of positive mood on creative and analytical tasks were taken as the starting point in the current investigations of affect-modulated WM processing.

The studies that are reported here (Chapters 6 and 7) are based on prior investigations of differential effects of positive mood on cognitive tasks. However, these studies did not manipulate mood. Instead their aim was to test one of the key assumptions that underlies the explanation of differential effects of positive mood on analytical vs. creative tasks in terms of the Central Executive, namely that creative and analytical tasks make different demands on the Central Executive. Though there are good reasons to believe that the latter is true and there are behavioural and neuro-biological data indirectly suggesting this, there has not been a direct test of the differential WM demands of analytical and creative tasks. Studies 1 and 2 presented below perform such a test, on both the behavioural and the neurophysiological levels.

Prior to reporting our studies we will discuss the evidence available to date regarding the differential effects of positive mood on insight and deductive tasks. It is important to review this evidence in order to see how the assumption tested in the studies reported later emerged from the extant literature. In Chapter 3, an outline of this evidence is provided. In addition, in Chapter 3 a biologically-plausible model of the effects of positive mood on cognition is discussed in conjunction with related biologically-driven computational accounts of WM processing. The link between the effects of positive mood and WM is further developed in Chapter 4, with an emphasis on the Central Executive component of WM, and predictions are formulated with regard to the involvement of the Central Executive in different types of tasks. In Chapters 5, 6 and 7 it is reported how these predictions were tested.

Chapter 3. Differential effects of positive mood on creative (insight) vs. analytical (reasoning) performance

3.1. Cognitive tasks facilitated by positive mood

Several groups of investigators, most notably Isen and colleagues (Greene & Noice, 1988; Estrada et al., 1994, 1997; Isen et al., 1987; Kahn & Isen, 1993), have examined the effects of induced positive and negative mood on several types of tasks, thought to tax creative processes. There are five types of tasks which are particularly relevant in the current context: it is possible that the facilitation of these tasks by positive mood can, at least in part, be explained by the interaction between positive mood and WM.

1. A series of experiments (Estrada et al., 1994, 1997) investigated expert problem-solving in organisational contexts in conditions of positive or neutral mood. Positive mood was induced, in most cases, via small, but unexpected, monetary rewards. For example, in one study, professional doctors were asked to reach a diagnosis on the basis of a number of symptoms. These problems could only be solved by non-traditional approaches to the presented set of symptoms. It was found that in conditions of positive mood participants were more likely to solve the diagnosis problems, i.e. they were more likely to adopt a novel, non-traditional approach (Estrada et al., 1997).

2. In another design, employed for testing the influence of positive mood on flexibility of choices, participants were asked to make a number of choices from the same set of items (e.g. food items). It was found that the elicitation of positive mood led to more

diverse choices, as long as the chosen items were not associated with negative outcomes (Kahn & Isen, 1993).

3. The Remote Associates Test was initially designed for testing individual differences in creativity (Mednick, 1962). In the original version, participants were presented with three unrelated words and asked to generate a word, which would be associated with each of the original three words. Isen and colleagues (Isen et al., 1987) employed the Remote Associates Test for investigating the effects of positive mood on creativity. The authors employed film clips as an experimental mood induction procedure. Participants who performed the test after watching films with a positive affective content generated significantly more valid remote associates compared to participants who saw a neutral film clip or to participants who saw no film. Participants who saw a negative film clip did not perform differently from the control groups.

4. Verbal fluency, which was briefly introduced earlier in the discussion of the resource allocation model (see Chapter 1), is a widely employed task. In neuropsychological studies verbal fluency has been shown to be a reliable measure of frontal lobe function (Benton, 1968), with left-hemispheric dominance. This lateralisation pattern was confirmed in neuroimaging studies of verbal fluency, which reveal predominant activation in the left PFC and left parietal cortex (Phelps et al., 1997). The results from the neuroimaging study of the effects of experimentally induced depressed mood on verbal fluency (Baker et al., 1997), discussed earlier in the context of the resource allocation model, showed that regional brain activity in this task can be modulated by negative affect. One of the important features of verbal fluency is that participants have to avoid repetitions of the previously generated items,

which implies that the latter have to be kept track of, but at the same time kept relatively inactive so that they do not overshadow the current response. Patients with damage to the frontal lobe, especially on the left side, tend to have deficits switching to the next response (Benton, 1968). Another interesting insight provided by studies of "frontal" patients is that they tend to approach the task differently. The analysis of the items generated by neurologically intact controls showed that they tend to apply certain strategies (e.g. say the items they see around them, focus on items from a certain category until it is exhausted, etc.). Individuals with frontal lobe damage do not seem to make much use of such strategies and their responses are much less predictable from the previous items.

What made verbal fluency attractive to investigators of creativity (Isen et al., 1987) is the requirement to suppress the preceding responses and move on to novel items. Creative thinking is also assumed to heavily rely on the ability to easily switch to new responses (Ashby et al., 1999). Further, the generated items can be characterised in terms of their semantic "distance" from each other. The more able the participant is to inhibit previous response tendencies, the greater the "distance" between different items. Moreover, if the task is performed via utilisation of strategies for generating new items, then a creative approach would be associated with rapid shifts of strategies, or semantic categories to which these are applied, or with less common strategies. Consequently, if positive mood were to facilitate creativity in the verbal fluency task, it would lead to an overall advantage in terms of the number of generated items, and also to less common responses. This is precisely what was found in studies of effects of induced positive mood on verbal fluency (Greene & Noice, 1988).

Some interesting results were obtained by Bartolic et al. (1999) who compared the effects of induced positive and negative mood on verbal and spatial fluency. This study was already mentioned earlier in the context of interhemispheric asymmetry models of emotion. The authors found better verbal fluency following positive mood induction as compared to negative induction, with the opposite effect on spatial fluency, the latter being better after negative than positive mood induction. Unfortunately, the authors do not report the effects relative to the neutral state (baseline), which makes these data difficult to consider in the present context. Furthermore, Velten statements were used for inducing mood changes and the only baseline condition in the experiment was the one with no statements, i.e. there was no control condition with affectively neutral statements preceding verbal fluency.

5. The fifth type of cognitive tasks, whose facilitation by positive mood has been documented, is insight problem-solving. The phenomenon of "insight" was first systematically investigated by members of the Gestalt school of psychology (Duncker, 1945; Maier, 1931). It refers to problem situations that seem unsolvable where the obvious approach to the problem is not productive ("impasse"- Ohlsson, 1984a,b), but where the solver finds no alternatives to the obvious approach ("fixation"). However, a proportion of people may reach the solution rather suddenly and unexpectedly (the "aha" experience). Since insight problems are ill-defined, as compared to other types of problems, and since they often require people to transpose themselves into non-trivial situations, a relationship between creativity and insight has been postulated by numerous authors (Metcalfe, 1986a,b; Ohlsson, 1984a,b). Therefore, these problems have attracted the interest of researchers of modulation of creativity by positive mood.

3.2. Positive mood and insight problems

In an influential study of the effects of mood on creativity, Isen et al. (1987) divided their participants into four groups. Three groups saw film clips (with positive, negative and neutral affective content) and one served as a no-film control. Following the film clips, participants were asked to solve one insight problem (the Candle Task, Duncker, 1945, see Fig. 4, Chapter 6, for the problem content). The authors found that in the positive mood condition significantly more participants found the solution, as compared to all other three conditions. Performance on the insight task did not distinguish between the negative-film, the neutral-film and the no-film conditions. Isen et al. (1987) concluded that positive mood facilitates insight problem-solving. This conclusion was strengthened by the results from an independent group (Greene & Noice, 1988), which also found that positive mood improved performance on the same insight problem as in Isen et al. (1987).

When one carefully considers the data on the facilitatory effects of positive mood on a variety of tasks assumed to involve creative thinking, two kinds of questions may arise. Firstly, despite ecological considerations in favour of the common creativity thread in these tasks, they are rather different in their demands, stimuli, etc. Therefore, there is need for a more elaborate theoretical framework, which would explain how these different tasks are modulated by positive mood, beyond the mere assumption that they make similar creative demands. Secondly, it has been claimed above that the effects of positive mood on cognitive processing are rather specific. This is not obvious from the similar effects of positive mood on the five tasks mentioned above. Thus, it is necessary to examine if there are tasks with which positive mood interacts

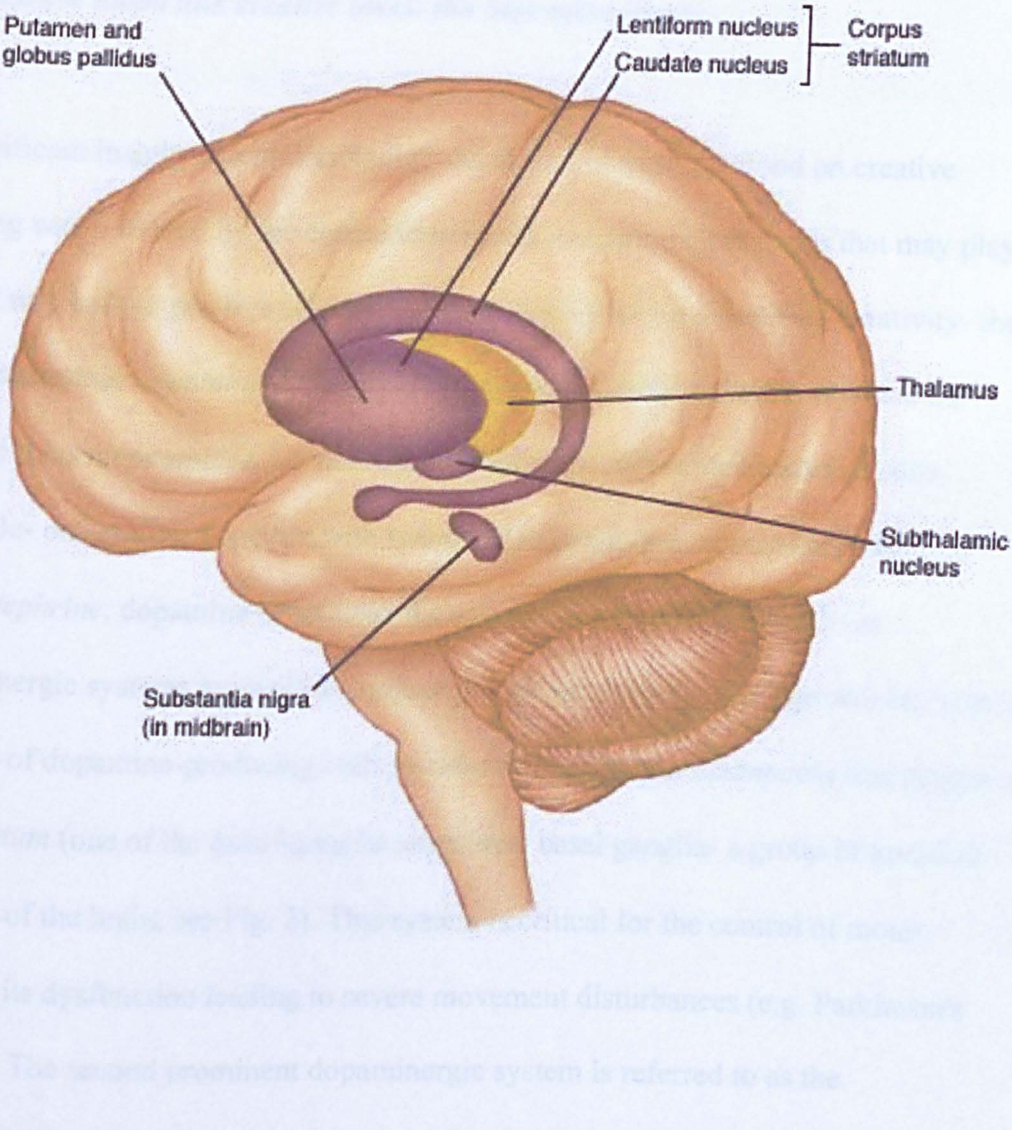


Figure 2. The macro-anatomy of the basal ganglia.

in a different way. These two issues will be covered in sections 3.3 and 3.4, respectively.

3.3. Positive mood and creative tasks: the dopamine theory

A significant insight into understanding the effects of positive mood on creative thinking was provided by the consideration of a neurobiological factor that may play a crucial role both in positive affect and in cognitive processes requiring creativity- the neurotransmitter *dopamine*. Dopamine belongs to the family of neuromodulators referred to as *monoamines*, i.e. neurochemicals made of one elementary protein molecule- one amine. Together with two other monoamines, *epinephrine* and *norepinephrine*, dopamine constitutes the subclass of *catecholamines*. Two dopaminergic systems are well-documented. The *mesostriatal* (or nigrostriatal) system consists of dopamine-producing cells in *substantia nigra pars compacta* that project to the *striatum* (one of the *basal ganglia* structures; basal ganglia- a group of nuclei at the base of the brain, see Fig. 2). This system is critical for the control of motor activity, its dysfunction leading to severe movement disturbances (e.g. Parkinson's disease). The second prominent dopaminergic system is referred to as the *mesocorticolimbic* system. It is composed of dopamine-producing cells in *the ventral tegmental area*, whose projections are somewhat more diverse than those of substantia nigra cells. Fibres from the ventral tegmental area innervate vast territories in the PFC, as well as the anterior cingulate, the amygdala, the hippocampus, the olfactory bulb and cortex, and the nucleus accumbens. The mesocorticolimbic system is intimately involved in processing reward stimuli (Wickens, 1990) and is particularly relevant in the present context. However, the two systems are interconnected, especially via the amygdala and the nucleus accumbens, and functional changes in one system are strongly reflected in the other.

As mentioned above, there is considerable evidence for the role of the mesocorticolimbic dopaminergic system in the processing of reward. For example, it has been established that the amount of dopamine released in the ventral tegmental area increases after the presentation of rewarding stimuli (Wickens, 1990). It has to be noted that reward, at least in humans, is closely associated with positive affect. Moreover, the amount of dopamine released decreases once reward becomes predictable (Schultz, 1992), which parallels the effects observed with elicitation of positive mood: gifts are more effective in inducing positive mood when they are unanticipated. Further, drugs that mimic the effects of dopamine (i.e. dopamine agonists) produce similar effects to rewarding stimuli (Beatty, 1995). Naturally produced substances associated with feelings of pleasure (i.e. the endorphins) stimulate the dopamine system, thus increasing their own effect (Harte et al., 1995). Finally, neuroleptics (dopamine antagonists) are known to flatten affect or even induce depression (Kumari et al., 1998).

In addition to its well-documented role in the processing of reward (hence, in positive affect), the mesocorticolimbic dopaminergic system has been more recently associated with the ability to switch contexts or to update cognitive representations. It was already said above that dopamine projections originating in the ventral tegmental reach the PFC. Several recent experiments with animals suggested that the updating of previously learned WM contents is disrupted by the reduction in the dopaminergic innervation of PFC (Schultz et al., 1993). On the basis of these data, the proponents of several biologically-plausible computational models of WM processing assumed that information in WM is only updated after dopaminergic input from the basal ganglia into the PFC reaches a certain threshold (O'Reilly et al., 1999; Frank et al., 2001). In other words dopaminergic projections from the basal ganglia onto PFC act as a gate for the information flow into WM. The increase in dopamine flow beyond a certain threshold opens the "gate" and WM contents can be updated.

A model that integrates the dopamine-reward and dopamine-updating functions is the dopamine theory of the influence of positive mood on cognitive processing (Ashby et al, 1999). The model proposes that positive mood is associated with increases in dopamine release in both the above-mentioned dopaminergic systems, but especially in the mesocorticolimbic system. The increases in dopaminergic input into cortical territories (e.g. PFC) facilitate certain types of cognitive processing. In concordance with the biologically-plausible models of WM by O'Reilly and co-workers (Frank et al., 2001; O'Reilly et al., 1999), the increase in dopaminergic turnover in the PFC leads to an easier updating of information WM. Ashby et al. (1999) propose a similar effect of dopamine in the anterior cingulate, with regard to the involvement of the latter in response selection. Importantly, not all increases in the amounts of dopamine are assumed to be beneficial. The relationship between the levels of dopamine and the task performance is proposed to have an inverted U-shaped function, with moderately-high levels of dopamine being the most beneficial for certain tasks. Inappropriately high levels of dopamine may lead to inopportune and maladaptive switching, as documented in schizophrenia (American Psychiatric Association, 1994). This disorder is characterised by very frequent context switching and also by abnormally high levels of dopamine. Ashby et al. (1999) discuss a number of cognitive tasks, in particular the five types of tasks presented earlier (see 3.1), and show that the facilitatory effects of positive mood on all these tasks can be explained in terms of increased dopaminergic input to the PFC and the anterior cingulate, since all five tasks critically depend on the ability to update or switch the response perspective.

In conclusion, the model provides an elegant unifying account of both normal and abnormal performance. At the same time, Ashby et al. (1999) also state that the model does not predict facilitatory effects of positive mood on processes that are subserved by brain areas that do not receive dopaminergic projections. Furthermore, the model admits that high levels of dopamine can disrupt processes that are dependent on cortical regions rich in dopaminergic projections, but it assumes that positive mood rarely leads to exacerbated levels of dopamine and that it is more likely to induce moderate increases. Yet, as it will be proposed below, even moderate levels of positive mood can make WM updating inappropriately frequent/ intense, with negative consequences for certain cognitive processes/ tasks.

3.4. Tasks disrupted by positive mood

In a series of carefully designed experiments, Oaksford et al. (1996) investigated the effects of experimentally induced positive and negative mood on analytical thinking. Interestingly, one of the main motivations for the authors was the finding by Isen and co-workers (Isen et al., 1987) of facilitation of insight problem-solving performance by induced positive mood. Oaksford and colleagues attempted to determine whether the effects of positive mood on analytical tasks would also be facilitatory. They chose to employ a well-known deductive reasoning task, Wason's Selection Task (Wason, 1966, 1968). In this task participants are presented with a conditional rule and four instances which could potentially obey or violate the rule, and asked to choose only the instances that could violate the rule. The task has several versions, which have been classified as abstract or concrete. The main difference between the two types is that the concrete type presents the logical contents of the task in a real-life situation. Performance on abstract versions has been shown to be very low (about 4% logically valid responses, Wason, 1968), as compared to performance on concrete versions (up to 90% logically valid responses, Cheng & Hollyoak, 1985). Different versions of the task are discussed in detail in Chapter 6. Oaksford et al. (1996) employed a concrete version of Wason's Selection Task. The design and mood induction procedure were very similar to the ones from Isen et al.'s (1987) study of insight problem-solving. Prior to the reasoning task, some participants were shown a film-clip and some were not. Further, there were three kinds of clips: affectively-neutral, with positive affective content and with negative affective content. Oaksford et al. (1996) found that both positive and negative mood had a disruptive effect on reasoning performance. Positive mood was also found to impair performance on a Central Executive task (the Tower of London task, Shallice, 1982). At a general level, Oaksford et al. (1996) interpreted the effects of positive mood in terms of the resource allocation framework (Ellis & Ashbrook, 1987), with resources being reallocated in the positive mood condition from the reasoning task to mood-related processing. At a more detailed level, the authors explained the outcome in terms of the depletion of the Central Executive component of WM by both positive and negative induced mood. Furthermore, in discussing the apparent contradiction between their finding of impaired reasoning performance in conditions of positive mood and the facilitatory effects of positive mood on insight tasks found by other authors (Isen et al., 1987), Oaksford et al. (1996)

proposed that this contradiction may be explainable by differential demands of the two types of tasks. Reasoning was proposed to rely on Central Executive/ WM processing, whereas insight and other creative tasks on retrieval from long-term memory. The implications of this proposal are discussed in what follows.

Chapter 4. Positive mood and the Central Executive component of WM

4.1. Mood, reasoning and the Central Executive

In order to further validate their explanation based on Central Executive processes, Oaksford et al. (1996) employed two additional manipulations. It has been argued that the demands on the Central Executive are especially high when WM is involved in two or more tasks concurrently (Shallice, 1988). Furthermore, syllogistic reasoning has been shown to rely on cortical regions reliably associated with WM (e.g. PFC). The use of random number generation as a concurrent task was shown to disrupt syllogistic reasoning (Gilhooly et al., 1993). Consequently, Oaksford et al's account that the effects of positive mood on Wason's Selection Task were caused by depletion of the Central Executive would predict a similar impairment of the reasoning performance in the presence of a concurrent task. Oaksford et al. (1996) tested this prediction in their second experiment and confirmed it. Furthermore, a detailed analysis of participants' responses in Wason's Selection task in the first and second experiments revealed similar confirmatory strategies in participants' responses when reasoning took place in the presence of positive mood or in the presence of the concurrent task.

An alternative, more direct, way of probing the induced mood-Central Executive account is to take a task known to heavily depend on the Central Executive, and test the effects of induced positive and negative mood on this task. This was precisely what Oaksford et al. (1996) did in their third experiment. They chose to use the Tower of London Task (Shallice, 1982), developed for investigating the Supervisory

Attentional System (Norman & Shallice, 1986) model of the Central Executive. It was shown that tests of verbal and spatial ability were poor predictors of the performance on the Tower of London Task, taken to indicate that the task has little relationship to the verbal and spatial slave-systems in WM (Shallice, 1982). Consequently, it was argued that the task engages primarily executive processes. Oaksford et al. (1996) found that positive affect impairs performance on this task, as it does on Wason's Selection Task. In contrast, the effects of negative mood on the Tower of London Task were not statistically distinguishable from the affectively-neutral control. Therefore, it seems reasonable to conclude that the explanation of disruptive effects of mood on reasoning in terms of the Central Executive depletion holds reliably only for positive mood.

4.2. Differential effects of positive mood: different WM demands?

The outlined evidence regarding positive mood and cognition, i.e. from studies by Isen et al. (1987) and Oaksford et al. (1996), strongly suggests a differential pattern of effects exerted by positive mood on cognitive tasks. In particular, induced positive mood appeared to facilitate performance on tasks requiring flexibility or creativity, but it seemed to hinder reasoning and other analytical performance. The facilitatory effects of positive mood on tasks involving creativity and cognitive flexibility have been explained in terms of the impact of dopaminergic circuits on the ability of rapidly and effectively update cognitive representations (e.g. the representations in WM) (Ashby et al., 1999). On the other hand, the disruptive effects of positive mood on reasoning were mimicked by the effects of a concurrent task, suggesting the relationship between the negative influence of positive mood and the Central Executive. Moreover, induced positive mood also impaired the performance on a task which has been directly related to the Central Executive component of WM, the Tower of London Task, which gives further credit to the explanation of the disruptive effects of positive mood on deductive reasoning in terms of depletion of the Central Executive resources in conditions of positive mood (Oaksford et al., 1996).

A proposal that seems to follow logically is that the two types of tasks make differential demands on WM processing. It is conceivable that the five types of tasks assumed to require creativity/cognitive flexibility, discussed in the context of facilitatory effects of positive mood, may not require rigorous strategy application and accurate memory of the intermediary processing steps. For example, the failure to remember accurately all the words that were generated in a verbal fluency task or searched in the Remote Associates test is unlikely to seriously affect performance. In contrast, analytical tasks seem to be critically dependent on the accuracy of intermediary representations in WM. Such representations can be demanding in at least two kinds of circumstances.

Firstly, there are analytical tasks that require a relatively large number of intermediary steps (e.g. some versions of the Tower of London Task, see Eysenck & Keane, 2000) and the accurate maintenance of these steps can be difficult. Secondly, there are analytical tasks that have a large and complex set of starting conditions. These conditions need to be re-activated simultaneously with the response options being examined at any stage during the task. Such simultaneous access is likely to be very demanding for WM. Wason's Selection Task can be viewed as an example of such a task. It comprises a rather complex set of initial instructions (including the conditional statement) that need to be activated with high fidelity and examined simultaneously with potential outcomes of choosing one of the four cards in the response set. Therefore, it seems likely that the control of such intermediary processing makes a significant demand on the Central Executive component of WM.

On the other hand, high accuracy in intermediary processing may be detrimental for tasks like verbal fluency, the Remote Associates or insight problems, because it may impede what is essential in these tasks, namely the ability to rapidly switch among alternative representations/responses. Hence, it is possible that in such tasks the optimal strategy is a trade-off between accuracy/detail of intermediary WM contents and rapid/frequent updating of those contents. Since these considerations are somewhat speculative, one should examine the evidence that would support the claim that creative processes are less reliant on memory for intermediary steps than are analytical processes. At least with regard to one type of creative tasks, there seems to be compelling evidence suggesting their limited reliance on the Central Executive.

4.3. Insight problem-solving and its demands on the Central Executive

Three properties of insight problem-solving are of particular importance for examining the demands insight tasks make on WM. Firstly, insight tasks are ill-defined as compared to other tasks (Eysenck & Keane, 2000). For example, some analytical tasks, such as the Tower of London are explicit with regard to the type of allowed responses. Other analytical tasks (e.g. Wason's Selection Task) implicitly provide the complete range of possible responses, which is the total number of combinations of between one and four cards. Typically insight tasks are less explicit with regard to such information. Hence, as has been argued above, it is likely that there is more information available to the problem-solver in analytical tasks and this information has to be manipulated in WM.

Secondly, people are less able to verbally report the intermediary steps during insight problem-solving (Metcalfe, 1986a,b; Metcalfe & Wiebe, 1987). Moreover, verbal reports were shown to hinder performance on insight tasks. For instance, Schooler et al. (1993) asked participants to verbalise their thoughts as they were solving analytical and insight problems. Concurrent verbalisation seemed to facilitate analytical performance, but impaired performance on insight tasks. The authors concluded that insight problem-solving engages processes that are not readily accessible to verbal report. They also compared the negative effects of verbalisation on insight with similar effects of verbalisation on other tasks and suggested that all these tasks seem to be less amenable to analytical approaches. This would be consistent with the idea that insight is less dependent on the types of processing that the Central Executive component of WM coordinates. However, the conclusions based on the effects of verbalisation on insight are open to the following criticism: they are based on the rather strong assumption that analytical approaches rely predominantly on verbal processing. Yet, influential theories of reasoning, considered to be analytical (Oaksford et al., 1996), stress its visuo-spatial character (Johnson-Laird, 1995).

Thirdly, people are not only less able to report the intermediary problem-solving steps in insight, they are also less aware of the proximity of the solution in insight tasks, as compared to other tasks. This leads to the unexpected character ("suddenness") of solution to insight tasks. In a series of ingeniously designed experiments Metcalfe and

Wiebe (1987), asked their participants to provide patterns-of-warmth feedback depending on how close they were to solving the problem. Subsequently, participants' patterns-of-warmth were found to be a good predictor of their solution times on algebra problems, but not of solution times on insight tasks. This suggests that people are less aware of the processes underlying insight even when such awareness does not need to be expressed verbally. Furthermore, these data also suggest a non-incremental, discontinuous character of insight problem-solving. Additional evidence for the non-incremental character of creative processes was provided by a psychophysiological study in which heart-rate was measured during creative and analytical problems (Jausovec & Bakrasevic, 1995). A gradual, incremental increase in heart-rate preceded the solution to analytical tasks, whereas an abrupt increase in heart-rate happened before the solution to creative tasks was found. The low level of awareness in insight processes is in sharp contrast to what characterises WM processing, in particular its Central Executive functioning. It has been proposed by numerous authors that WM and, in particular, the Central Executive and its conceptual equivalent, the Supervisory Attentional System are among the most essential mechanisms subserving awareness (or conscious awareness) (Baddeley, 1986; Norman & Shallice; 1986; Shallice, 1988).

4.4. More on positive mood and the Central Executive

The above considerations are consistent with the idea that insight processes are less dependent on the Central Executive component of WM than are analytical processes (e.g. reasoning). It also seems likely that this difference between the two kinds of tasks could explain the differential effects of positive mood on them. Positive mood may induce a fast-updating processing mode, associated with relatively loose Central

Executive functioning, which may be beneficial for certain processes (e.g. insight), but detrimental to other processes (e.g. reasoning). A series of recent studies by Phillips (2001) appear to provide further support for this presupposition. The author examined the effects of positive mood on several cognitive tasks. As in Isen et al., (1987) and Oaksford et al. (1996) positive mood was induced by means of positively-valenced film clips. The manipulation of interest in the study was the comparison between tasks that required rapid switching from one response to the next (i.e. verbal fluency) with tasks that also require such switching, but which also require continuous control over the response criteria. Phillips (2001) contrasted a traditional version of verbal fluency and uses fluency with a modified version in which participants had to alternate between the two fluency tasks.

The outcome was that positive mood led to more responses in verbal fluency and in uses fluency, but fewer responses when participants had to alternate between the tasks. Similar effects were found with the Stroop task. Positive mood speeded up responses when participants were asked to perform the Stroop task according to one criterium, but slowed down responses when participants were asked to alternate between naming criteria. Importantly, as shown by the levels of performance on the tasks with or without alternation, the observed effects of mood could not be explained in terms of task difficulty (e.g. with easier tasks being facilitated and harder task disrupted). Phillips (2001) explained the differential effect of positive mood in terms of disruption of the Central Executive. Evidently, this account rests on the assumption that the alternation of task criteria makes a higher demand on Central Executive resources, as compared to processing in accordance with individual criteria. This assumption has considerable appeal, considering the poor performance of frontal patients on tasks, such as the Wisconsin Card Sorting Test, requiring frequent shifts in the employed criteria. Importantly, the position held by Phillips (2001) makes a distinction between shifts between responses, which require relatively little Central Executive/WM capacity, and shifts in criteria, which require an accurate representation of the criteria necessary at any processing step. Furthermore, alternating tasks is in many respects similar to performing tasks concurrently. The latter, i.e. dual-task processing, has been consistently linked to the functioning of the Central Executive (Baddeley, 1986; Shallice, 1988).

4.5. Testing WM differences between insight and analytical processes

It has been concluded above that the literature on the modulation of cognitive processing by positive mood meets several important criteria. The reviewed studies examined the effects of normal mood, rather than clinical or sub-clinical manifestations of emotion, which eliminates potential cognitive confounds present in affective disorders. Further, in contrast to generalized effects of emotion discussed in Chapter 1, intriguing differential results were found with positive mood: facilitation of performance on some tasks (Isen et al., 1987; Greene & Noice, 1988) and impaired performance on other tasks (Oaksford et al., 1996). Importantly, such differential effects were also observed in tasks that were well matched psychometrically (i.e. alternated vs. non-alternated verbal fluency and Stroop tasks (Phillips, 2001). Moreover, the differential effects of positive mood on cognitive processing have been explained (Oaksford et al., 1996) in terms of a relatively well-defined and well-investigated cognitive construct, i.e. WM and its Central Executive component (Baddeley and Hitch, 1974, Baddeley, 1986, 2000). Finally, a neurobiological model proposed to account for the facilitatory effects of positive mood can accommodate the disruptive effects of positive mood on some cognitive tasks (the dopamine model, Ashby et al., 1999), in conjunction with recent biologically plausible computational models of the role of dopamine in WM (O'Reilly et al., 1999). In particular, the model by O'Reilly et al. (1999) proposes that dopamine controls the balance between the stability vs. the plasticity of WM contents. High levels of dopamine increase the likelihood of updating the WM contents. Following from the explanatory logic of Oaksford et al. (1996), positive mood may lead to levels of dopamine that induce inappropriately frequent (or extensive) updates of WM contents in detriment of their stability.

The idea that positive mood has differential effects on cognitive processes that differ in their demands on the Central Executive component of WM has considerable appeal. Nevertheless, the logical argumentation concerning the differential effects of positive mood on tasks requiring creativity and flexibility vs. tasks demanding accurate analytical processing rests largely on indirect support. There is little direct evidence for the differential WM involvement in creative vs. analytical tasks. Studies 1 and 2, reported below, represent an investigation of the WM correlates of insight and analytical (reasoning) processes. A direct comparison is performed between the Central Executive involvement in the two types of tasks both at the level of behavioural performance as well as at the level of brain electrical activity, recorded by means of Event-Related Potentials.

Chapter 5. Methodological considerations

5.1. Concurrent task methodology

The present investigation proposes to compare two types of tasks studied in the context of the effects of positive mood on cognition: insight tasks (Isen et al., 1987) and deductive reasoning tasks (Oaksford et al., 1996). This provides the obvious benefit of consistency and continuity across studies. However, given the complex character of such tasks, a problematic issue concerns the measurement of the amount of WM processing in these tasks. With regard to recordings of brain potentials, it is difficult to isolate WM processing in the temporal continuum of the tasks. For example, if brain electrical potentials are recorded during an insight and a reasoning task and differences are found between the potentials corresponding to the two types of tasks, it would be difficult to establish the extent to which such differences arose from differences in WM processing. This is related to the problem of locating WM processes in the temporal continuum of the tasks, in order to extract the most relevant differences in electrical potentials.

The use of concurrent task methodology can provide viable solutions for these concerns. With regard to behavioural phenomena, it has already been mentioned that several authors have used concurrent tasks in order to manipulate the demands on the Central Executive component of WM. Importantly, this methodology has been employed (e.g. Oaksford et al., 1996) with the reasoning task that we use, Wason's Selection task (Wason, 1968). The logic of the use of concurrent task methodology in the current investigation is the following. If the same task is used as a concurrent task to both the insight and the reasoning tasks, it will deplete Central Executive resources in both tasks. Depletion will be greatest in the task which uses considerable Central Executive processing. In other words, the task that is more reliant on the Central Executive will be more disrupted by the concurrent task.

Concurrent task methodology can also help circumvent the problem of isolating WM processes in the temporal continuum of insight or reasoning tasks. The processing of a secondary task concurrently with an insight or a reasoning task would require the Central Executive to alternate between the "primary" task (insight or reasoning) and the concurrent task. Let us suppose that the concurrent task consists of a number of discrete events (stimuli) with a short duration, which require WM updating. Since it seems reasonable to assume that the periods of highest demand on the Central Executive would be associated with the alternations between the "primary" and the "concurrent" tasks, the brain potential recordings associated with discrete events in the concurrent task would reflect the extent of the Central Executive involvement.

5.2. Event-Related Potentials and WM processing. The P300 component

Electroencephalography (EEG) is the term used for recordings of brain electrical activity from the scalp. Segments of the EEG recording associated with (time-locked to) discrete stimuli are referred to as Event-Related Potentials (ERPs). In addition to the obvious advantage of being able to capture the periods of activity associated with specific events, multiple ERPs can be averaged to increase the signal-to-noise ratio across multiple trials time-locked to the same category of stimuli. For example, in an experiment comparing two classes of words (e.g. regular past-tenses and irregular past-tenses, Lavric et al., 2001), the averaging across ERPs corresponding to different regular items would eliminate the changes in electrical signal associated with idiosyncrasies in individual items and augment the electrical response to common characteristics (the morphological status). ERPs in response to individual stimuli are referred to as ERP *epochs* or *trials*.

An important characteristic of the ERP literature is the identification of the so-called ERP waveform components, features of the ERP wave (e.g. peaks) with similar morphology (i.e. shape), latency and scalp topography (i.e. regions of the scalp, in which the component is present). Components are usually identified by a letter, indicating whether the component is a positive or a negative shift relative to the baseline, and the latency at which it usually occurs (e.g. N400- negative deflection at 400ms postsimulus onset). A widely used approach is to employ ERP components as markers of specific perceptual/cognitive processes. This is thought possible whenever an ERP component has been systematically altered by certain experimental manipulations. For example, N400 is commonly elicited by the presentation of words that are semantically aberrant in a given context.

An ERP component with relevance in the current context is P300 (i.e. positive deflection at about 300 ms post-stimulus onset). The literature on P300 is ample (see Polich & Kok, 1995, for a review and Donchin & Coles, 1988, for an extensive discussion). The explanation for this is quite simple: P300 can be found in almost any ERP response to a discrete stimulus, in both visual and auditory modalities (see Fig. 3). However, the interest in P300 has also been stimulated by the sensitivity of this component to the complexity and novelty of stimuli. The latency of the component tends to be longer and the amplitude larger for more complex relative to simpler stimuli (Polich & Donchin, 1988). An influential theory on the significance of P300 in terms of information processing proposed that P300 indexes the updating of WM contents (Donchin & Coles, 1988, but see Verleger, 1988, for an alternative view). Recent studies have supported the relationship between P300 amplitude and WM updating (Gevins & Cutillo, 1993).

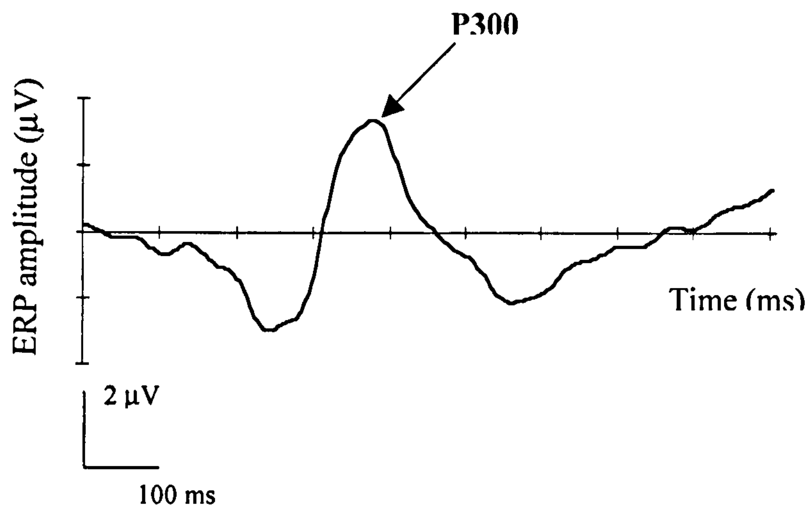


Figure 3. The P300 peak recorded in response to counting auditory stimuli (tones). This task served as a control condition in Study 2 (see Chapter 7).

More recently it has also been established that P300 is generated by several sources in the brain, with the largest contribution from the prefrontal cortex and the right parietal cortex. Importantly, the prefrontal P300 is generated earlier and is referred to as P3a, whereas the right-parietal P300 happens somewhat later and is referred to as P3b (Knight & Grabowecky, 1995). It turns out that P3a and P3b have differential sensitivity to experimental manipulations. In particular P3a is more sensitive to stimulus novelty, which is of special relevance in the context of the current investigation. It has been proposed that P3a reflects the prefrontal involvement in WM processing (Knight & Grabowecky, 1995).

In the present investigation, ERPs timelocked to the concurrent task were recorded. P300 in response to a task, which is concurrent to either an insight or an analytical task, was measured. If the analytical task requires large Central Executive resources, the interspersed concurrent task events should be more demanding and, hence, elicit a larger P300 than in the insight task, with the most prominent difference in P3a. However, it is also conceivable that larger demands on the Central Executive in the analytical task can lead to less attention being devoted to the concurrent task, hence, to a smaller P300 amplitude. In order to distinguish between these alternative explanations of a possible P300 difference between the analytical+concurrent and insight+concurrent conditions, these two conditions were compared to a control condition. In the latter P300 was measured solely in response to the task that acted as a concurrent task in the dual-task conditions. In this case, larger P300 amplitude in any of the dual-task conditions, compared to the control, would unambiguously be interpreted as greater, rather than smaller WM processing load. As mentioned earlier, the degree of interference in the insight and the analytical tasks provoked by the concurrent task, could serve as a behavioural measure of Central Executive involvement.

It has to be noted that the use of ERP waveform components is not uncontroversial. Firstly, there are certain issues related to the identification of ERP components. What appears to be a unitary waveform peak can mask temporally and spatially distinct components (Donchin & Heffley, 1976). There are several mathematical instruments used to circumvent this problem by segmenting the ERP waveform into more elementary components. Two of the most commonly used tools are Principal Component Analysis (PCA) and Independent Component Analysis (ICA). PCA has a relatively long history of being employed in ERP analysis (Donchin & Heffley, 1976); therefore it was decided to use it in the current investigation for the identification of components from the P300 family (see Chapter 7 for details on PCA applied to ERP analyses).

Another limitation of the ERP component approach is difficulty in generalising across studies. For example, it is difficult to objectively determine whether a peak observed in one study is equivalent to the peak observed in another study. There are sophisticated analytical (source-localisation models) or experimental (neuroimaging, intra-cortical recordings) tools for circumventing this problem, but their use is not always an option. Reliable source-localisation algorithms have only been available recently and require multichannel recordings. The concurrent use of ERPs and neuroimaging is still in its incipient stages, whereas intra-cortical recordings can only be used in individuals undergoing brain surgery. A relatively simple measure is to employ a control condition in order to be less dependent in the interpretation of results on previously determined functional significance of ERP components. For example, let us suppose that little is known about the significance of P300 and a P300 difference is found in response to a secondary task administered concurrently to insight vs. concurrently to analytical problems. The presence of a control condition, e.g. ERPs in response to the secondary task administered alone can clarify the ERP results, even in the absence of prior knowledge about P300. As mentioned above, one can use the ERPs in response to the concurrent task alone as a baseline with the lowest

WM/Central Executive processing load. Amongst the two conditions with concurrent processing (insight + secondary task or reasoning + secondary task), the condition that will show the largest difference from the baseline is likely to be the one with the highest demand on WM/Central Executive. Consequently, although a great deal is known about the ERP components from the P300 family, one does not have to entirely rely on the "cognitive significance" of P300. On the contrary, it is beneficial to introduce a baseline condition in the form of the ERPs recordings of the secondary task administered alone.

To reiterate, a direct comparison of the WM/Central Executive processing in insight (creative) and reasoning (analytical) tasks would be performed by introducing a secondary (concurrent) task consisting of brief stimuli to which ERPs would be timelocked. The behavioural measure of WM/Central Executive processing in the insight and analytical tasks would be the degree of disruption by the presence of the concurrent task. The modulation of ERP components from the P300 family, especially P3a, in conditions of concurrent task processing and relative to the baseline of the secondary task presented alone, would represent the electrophysiological correlate of WM/Central Executive processing. However, prior to implementing this paradigm, the creative and analytical tasks had to be identified and piloted. Such pilot work was performed in Study 1.

Chapter 6. Study 1 (Pilot)

6.1. Introduction

The study is part of an investigation whose main hypothesis is derived from the literature on differential effects of positive mood on certain cognitive processes. Positive mood was found to facilitate performance on tasks believed to require creativity and flexibility (Greene & Noice, 1988; Estrada et al., 1994, 1997; Isen et al., 1987), but disrupt performance on analytical tasks (e.g. deductive reasoning, Oaksford et al., 1996). Biologically-driven computational accounts (Ashby et al., 1999, O'Reilly et al., 1999) are compatible with the hypothesis (Oaksford et al., 1996) explaining these differential effects in terms of differential demands of creative and analytical tasks on the Central Executive component of WM. In order to ensure consistency and continuity, it was decided to employ the cognitive tasks whose differential modulation by positive mood is well documented: insight tasks (Isen et al., 1987) and reasoning tasks (Oaksford et al., 1996). In addition, the choice of insight tasks was also influenced by the presence of other behavioural and psychophysiological evidence suggesting a distinct mode of WM processing, as compared to other tasks. They may be best solved when information transferred from long-term memory is constantly and rapidly updated (see Oaksford et al., 1996 and Phillips et al., 2001, for similar proposals). Although the updating may involve the Central Executive/ WM, it does not require accurate representation of large amounts of information in WM, as in analytical tasks.

ERP methodology imposes a critical constraint on paradigms employing ERP recordings, which concerns the minimal number of averaged ERP trials per condition. Although ERP studies vary with respect to the minimal number of averaged trials, the consensus is to have at least 25-30 ERP trials per condition for each subject, free of technological or muscle artifact. Depending on whether elimination or correction of contaminated trials is the procedure utilised for filtering the artifact, it may or may not be necessary to add ERP trials to account for the filtering. In the present ERP investigation it was decided to eliminate, rather than correct, ERP trials contaminated by artifact. This means that the minimal number of acquired ERP trials has to be larger than the minimal number of trials required for averaging. Based on previous ERP studies employing the same equipment (Brunswick & Rippon, 1994), and based on other ERP studies employing artifact elimination, the number of potentially contaminated trials was estimated as approximately 25% of the acquired trials. Consequently, the minimal number of acquired ERP trials per participant per condition was set to 40. Considering that in the present investigation the concurrent task consists of discrete and brief stimuli with an inter-stimulus interval (ITI) of at least 1.5 sec (shorter ITIs may lead to excessive difficulty in the primary tasks, insight and reasoning), the total time required for the acquisition of the minimal ERP trials per condition is approximately 60 sec. The main objective of the current pilot study is to examine how closely time-to-solution in the cognitive tasks of interest can match the total time required for the ERP recording.

6.2. Method

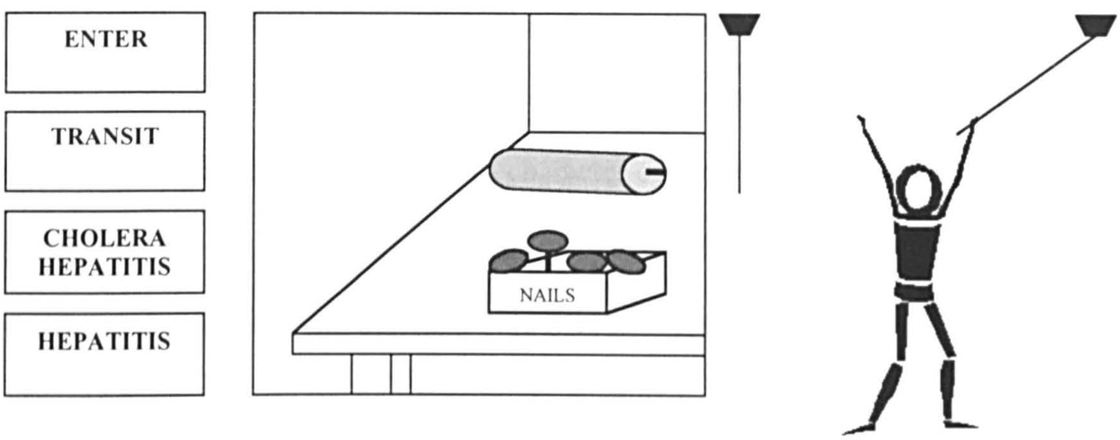
Participants

Twenty six participants (15 females and 11 males, mean age 20.1, sd 1.94, range 18-27) received course credits for taking part in the experiment.

Tasks

Insight tasks

Two well-known insight tasks were examined: the Candle problem (Duncker, 1945) and the Two Strings problem (Maier, 1931, see Fig. 4 for the problems). The Candle problem was employed by Isen et al. (1987) in their study of the effects of positive mood on creativity. As discussed earlier, it was discovered that participants were more likely to find the correct solution after positive mood was induced. There are few if any reports of solution times to the Candle problem (Isen et al. did not report solution times). In addition, there are several versions of the problem. In some versions the nails are not in a box, instead matches are in a box. Furthermore, sometimes the task is presented in a realistic set-up (with the objects being present in the room), whereas in other cases, only a description and a diagram are given to participants (e.g. Isen et al., 1987). The current investigation chose to employ the latter for practical reasons related to the ERP data acquisition. Despite the scarcity of data on solution times in the Candle problem, one assumption seems reasonable: given the ill-defined nature of insight tasks (Eysenck & Keane, 2000), one may expect considerable variability in solution times. Hence, it was decided to supplement the Candle problem with another insight task- the Two Strings problem, in order to fill the time needed for ERP acquisition in the insight condition, whenever solution times in the Candle problem would be very short.



You are an immigration official. Among the documents you have to check is a medical form. One side of this form indicates whether the passenger is entering the country or is in transit, while the other side of the form lists names of tropical diseases for which the passenger has passed the medical check-up. Your duty is to make sure that passengers who enter the country have passed the medical check-up for cholera (you have to make sure that if the form says "entering" on one side, the other side includes Cholera among the list of diseases). Four passengers are showing you their forms. Which of the forms would you have to turn over to check (as an experienced officer you would only turn over the ones that need to be turned over)?
Correct answer: the first and the last (top to bottom).

You are in a room and the only objects you have are a table, a candle and a box of nails. The table stands next to the wall. How would you attach the candle to the wall so that it does not drip onto the table below? There are no additional objects you can use and the table cannot be moved away from the wall.
Solution: empty the box of nails, attach it to the wall and put the candle in the box.

Two strings are hanging from the ceiling. While holding one of the strings, you cannot reach the second simply by holding out your hand. How would you reach the second string and hold the two strings at the same time? There are different objects in the room, but none can be used for hooking the second string.
Solution: tie any object to the first string, swing it, go and take the second, grasp the first string when it balances towards you.

Figure 4. The reasoning and insight tasks.

The reasoning task

Oaksford et al. (1996) examined the effects of positive mood on Wason's Selection task. In the original abstract version (Wason, 1968) participants are presented with a conditional rule, e.g. "If there is a vowel on one side, then there is an even number on the other" (which in formal logic corresponds to "if p, then q"). Participants are also given four cards with the following characters on them: A (p), K (non-p), 2 (q) and 7 (non-q). They are instructed that there is a character on the other side of the cards and asked to select only the cards that will allow them to check the rule when turned. The logic of deduction is bi-valent, that is, it only operates with two values of validity ("true" or "false"), with no intermediate, graded values (e.g. "true in most cases"). Therefore, assuming that the statement applies to an infinite number of cases, it can never be confirmed, because there is always a possibility of an inconsistent case and because graded validity is not acceptable. In contrast, definitive invalidation is possible; it is sufficient to find one case that violates the statement (*the falsification principle*, Popper, 1959). Consequently, according to the logic of deduction, in Wason's Selection task it is of little use to turn the cards that can only confirm the statement (i.e. the rule), namely card "2" (q). For any letter or number that is on the other side of these cards, the rule will be true. On the contrary, one should select the cards that can potentially falsify the rule: "A" (p) and "7" (non-q). If the card "A" has anything but an even number on the other side, or if card "7" will have "A" on the other side, the rule is false.

Participants show remarkably poor logical performance on the abstract version of the task, with as few as 4% of participants making the correct selections (A and 7). One account of the low performance level is that in the abstract version the formal character of the task distracts participants' attention from the relevant aspects of the tasks. Instead, they focus on surface characteristics (e.g. letters and numbers: A, 2, etc.) and, when making the response, simply match the characters from the rule, which are repeated on the cards (A and 2) (Evans & Lynch, 1973). This perspective claimed support from experiments in which the first part of the statement was modified by introducing a negation: "If there is ***not*** an A on one side..." instead of "If there is an A on one side..." which eliminates card A from the valid selections. It was observed that A was still be the most frequently selected card (Evans & Lynch, 1973). Furthermore, the matching explanation is consistent with the prediction that thematic (realistic) versions of the task, which would draw attention to the relevant aspects of the task, should lead to more valid selections. This was indeed found to be the case. A number of experiments (Cheng & Holyoak, 1985; Cosmides, 1989) employed what is referred to as "deontic" versions of Wason's Selection task, in which participants are asked to play a particular role (a deontic version of the task is also employed in the current investigation). In "deontic" versions of the task the number of valid selections is vastly greater than in the abstract version (sometimes reaching as much as 60%-90% of participants performing logically valid selections; Cheng & Holyoak, 1985).

However, the matching account of the low performance on abstract versions of Wason's Selecction task has been questioned on several grounds. Firstly, it has been shown that matching in modified abstract versions of the task was an artifact of the use of negation ("if there is not an A on the one side, etc") (Oaksford & Stenning, 1992). Secondly, in realistic versions of the task, some 30-40% of participants still make invalid selections, which would be more difficult to explain in terms of matching.

Thirdly, the matching account would have difficulties in explaining differences in performance in different thematic versions of the task. For example, deontic contexts, in which participants enforce the rule (Cheng & Holyoak, 1985), facilitate valid selections. In contrast, "descriptive" deontic versions of the task, in which participants play the role of "observers", are associated with much poorer logical performance (Cosmides, 1989), which can be almost as low as performance on abstract versions of the task.

An alternative to matching is the explanation of invalid selections in terms of participants seeking confirmatory evidence for the rule. A more recent and elaborate variant of this approach (Oaksford and Chater, 1994, 1996, 1998) proposes that people apply everyday reasoning in the selection task and that the falsification strategy from formal logic might not be optimal in realistic conditions. This perspective is consistent with developments in philosophy of science, which question the potential of falsification in scientific inquiry (Lacatos, 1970; Quine, 1959). When the validity of an assertion needs to be established in realistic conditions, validity can be seen in relative terms and probabilistic estimates of validity become critical. Consequently, in realistic circumstances, cases that can falsify are no longer by definition more informative and the optimality of confirmatory and falsificatory strategies is largely determined by the probabilities of the properties/events contained in the assertion. For example, suppose the assertion "If one is caught stealing, one is sent to jail" needs to be tested. Since both properties of "being caught stealing" and "being sent to jail" are relatively rare (there are many more people who are not caught stealing and are not sent to jail), it could be more informative to check what proportion of those who are sent to jail were caught stealing, than to establish whether any of the **many** people who are not in jail, were caught stealing.

Applied to the abstract version of Wason's Selection task, this predicts that if participants engage in realistic hypothesis testing and treat p and q as rare (the *rarity assumption*), they would be more likely to select "2" than "7", since the former is potentially more informative than the latter. This is indeed the main logical "error" participants make in this task. Oaksford and Chater (1994) further developed their *rational analysis* model, by formalizing it in terms of Bayes' theorem. Assuming that the rarity assumption stands, the model makes accurate predictions with regard to the ranking of selections and is able to account for performance from numerous studies of the abstract Wason's Selection task. Recent developments of the model addressed criticisms related to the information measure (Evans & Over, 1996); the model was also extended to handle exceptions (Oaksford & Chater, 1996; 1998).

However, the rational analysis model, developed for explaining performance on the abstract task, could not explain the predominance of logically valid selections in thematic versions of the task. Additional assumptions had to be made in order to account for the pattern of performance in thematic tasks. In consensus with other authors, Oaksford and Chater (1994) assumed that, while in the abstract selection task people **test** the rule, in some concrete (e.g. deontic) versions people **use** the rule. A good example of the latter is the particular deontic version, in which participants are asked to enforce a rule (e.g. Cheng & Holyoak, 1985, see Fig. 4). The "enforcer" role asks participants to only attend to instances of violation, thus directly encouraging falsification. Oaksford and Chater (1994) have operationalised this in terms of utilities that people assign to different instances (cards). Only instances that can potentially violate (falsify) the rule are assigned high utility and with these modifications the model can account for the superior logical performance in some of the realistic versions of Wason's Selection task. Approaches that incorporate utilities associated with different selections are referred to as *decision-theoretic* approaches, in contrast to *information-theoretic* approaches, such as Oaksford & Chater's (1994) rational analysis of the abstract selection task. The latter does not need to employ utilities, instead assuming that people seek to maximize information "for its own sake". It has to be noted that Bayesian decision-theoretic approaches were not restricted to thematic versions of Wason's task; they were also applied to the abstract task (Klauer, 1999) and generated some predictions that were inconsistent with the information-theoretic model (Oaksford & Chater, 1994). It still remains to be seen whether the empirical data support these predictions.

To summarize, in the abstract selection task people perform hypothesis testing. In contrast, some concrete (e.g. deontic) versions of Wason's Selection task facilitate logically valid performance by increasing the utility of falsification. In other words, people engage in everyday inductive reasoning in the abstract versions of the task, whereas in some deontic tasks (e.g. "enforcer" tasks) they use falsificatory strategies, the former leading to logically valid performance. In order to explain logical errors on the "enforcer" task (often as frequent as 40%), the rational analysis model assumes that realistic hypothesis testing is the "default" strategy (Oaksford et al., 1996) and that whenever concrete contexts are not sufficiently explicit (or are not well understood), people resort to the "default" of confirmation. The disruptive effects of mood on a deontic ("enforcer") version of Wason's Selection task were also explained in terms of the "default" (Oaksford et al., 1996). Positive mood was said to occupy Central Executive/WM resources, leading to the use of the less effortful, default, strategies. This explanation also accommodates the negative effects of concurrent WM processing on Wason's Selection task, which were similar to the effects of mood (Oaksford et al., 1996). Alternative accounts of the effects of positive mood (e.g. participants adopting a more permissive attitude in positive mood conditions and being less interested in violations) would have difficulties explaining the similarity between the effects of positive mood and concurrent task processing on the selection task performance.

As already mentioned, in the present investigation it was decided to employ the version of Wason's Selection task whose modulation by mood and concurrent task was examined by Oaksford et al. (1996). Since "enforcer" tasks encourage deductive approaches, they can be more readily described as analytical, as compared to the standard abstract selection task whose analytical demands are less clear (Oaksford & Chater, 1994; Oaksford et al., 1996). Not surprisingly, Oaksford et al. (1996) used an "enforcer" version of the task (Cheng & Holyoak, 1985). Cheng & Holyoak (1985) had two "enforcer" tasks. In one of them participants were given the rationale of why they should be performing the enforcement (e.g. to prevent the spread of disease); in the other no rationale was given. It was found that providing the rationale facilitated performance (90% participants with valid selections; 60% without rationale). Since the rationale task was associated with near-ceiling performance, Oaksford et al. (1996) chose the non-rationale task for subsequent testing in conditions of induced mood and concurrent task processing. Similar reasons apply to the current investigation.

Therefore it was decided to employ a non-rationale, "enforcer" role task, based on the one from Cheng & Holyoak (1985), see Fig. 4.

Apparatus

Two microphones, an amplifier and two speakers were used for the communication between the experimenter and the participants. A closed-circuit camera and a monitor were used for monitoring participants' gaze, while they read the instructions.

Procedure

Participants performed the three tasks in random order. The instructions for each task were given to participants on paper, one task at a time. As seen in Figure 4, the instruction set for each task consisted of several lines of text and a picture. For all three tasks, the text was on the top of the page and the picture on the bottom. Participants were asked to familiarise themselves with the contents of the task and tell the experimenter if they understood the requirements. In order to minimise the eye-movement artifact in the ERPs, it was decided that in the subsequent ERP study participants would not have access to task instructions during task processing and the same applied to the current (pilot) study. Participants' gaze was monitored via a camera and approximately 5 sec after their gaze reached the part of the page where the text ended, participants were asked whether they understood and remembered the instructions. If participants asked for clarification, they were provided information within the limits of the task's standard instructions set. Subsequently, participants were asked to turn over the instructions page and attempt to solve the problem. It was decided to encourage careful processing of tasks and discourage speed-accuracy trade-offs. Therefore, participants were told that the tasks are not easy and encouraged to check the solution carefully before communicating it to the experimenter. Since the duration of the ERP recordings corresponding to each condition in the subsequent study would be set to 75 sec, it was imperative to determine participants' performance within this time interval. Hence, in the present (pilot) study participants were also stopped after 75 sec of thinking about the task and asked for the solution.

Performance measures and analysis

Performance on the two insight tasks, as in previous studies on insight (Isen et al., 1987; Kaufmann & Vosburg, 1997), was assessed by the presence of the correct response. In the Two Strings task swinging the string without tying an object was accepted as a correct answer. For Wason's Selection task, all selections made by each participant were recorded. For comparisons with insight performance, it was decided to use the number of participants who provided the logically valid answer in the selection task (i.e. who chose the "Enter " and "Hepatitis" cards).

The objective was to select the insight task closest to the selection task in terms of performance levels. For this purpose non-parametric tests (χ^2) were used to compare performance on each of the insight tasks with performance on Wason's Selection task. The same statistical test was employed for comparing the performance on the two insight tasks.

6.3. Results

The level of performance on the insight tasks, as well as Wason's Selection task (see Table 1), was comparable to the level of performance observed by other authors (Isen et al., 1987; Kaufmann & Vosburg, 1997; Oaksford et al., 1996), despite the time limit and the inaccessibility of task instructions during task performance. Performance on Wason's Selection task was only slightly lower than performance reported by other authors (54% participants providing valid selections, compared to 60% in Cheng & Holyoak, 1985). On the two strings, the proportion of participants who provided the correct solution (30%) was similar to that from a previous study by Kaufmann and Vosburg (1997). The Candle problem was associated with better performance (61%) than the one reported by Isen et al. (1987) from the neutral film group (20%). However, in the study by Isen et al. (1987) the positive film group had a much higher performance (75%).

Table 1. Insight and reasoning performance.

Participants → / Task ↓	Total	Correct	Incorrect	Solution in less than 60 sec
Wason	26	14	12	2
Candle	26	16	10	5
Two-string	26	8	18	3

The Candle problem and Wason's Selection task were associated with similar performance levels (χ^2 (1)= .31, p>.5). In contrast, fewer participants reached the correct solution on the Two Strings problem, relative to both the Candle problem (χ^2

(1) = 5.33, $p<.025$) and to Wason's Selection task (χ^2 (1) = 3.27, $.05<p<.1$), see also Table 1.

As mentioned before, the minimum time for ERP acquisition was set to 60 sec. Two participants reported the selected cards in Wason's Selection task in less than 60 sec (see Table 1). The two insight tasks were associated with more solutions before 60 sec. Three participants solved the Two Strings problem and five participants reached the solution to the Candle problem in less than 60 sec.

6.4. Discussion

The results from the pilot study provide some valuable information. Firstly, the idiosyncrasies of the current paradigm, i.e. the ERP constraints (time limit and inaccessibility of task materials), did not seem to significantly affect task performance. Wason's Selection task performance was only slightly lower, compared to previous studies (54% vs. 60%, Cheng & Holyoak, 1985). This performance difference could be due to the inaccessibility of task materials during reasoning. The performance level on the Two Strings problem was also similar to the one observed earlier (Kaufmann & Vosburg, 1997). The level of performance observed in the Candle problem is approximately equidistant from Isen et al.'s (1987) neutral and positive group performance levels. It is conceivable that the emotional state of our participants fell in between Isen et al's neutral and positive states. Alternatively, variability, small sample sizes and design differences could explain these discrepancies in performance levels. For example, in Isen et al's study the presence of the neutral film apparently facilitated performance, compared to the no-film condition (20% vs. 17%).

Secondly, at least at a simplified level, it seems possible to equate tasks coming from very distinct categories (insight and reasoning) in terms of performance. For instance, performance levels on the Candle problem and on Wason's Selection task were similar and the employed statistical procedure found no reliable difference. Thirdly, insight tasks show considerably more variability in solution times.

An important decision that had to be taken after the pilot study concerned the selection of the insight task to be used in the ERP experiment. Performance was viewed as the most important criterion. Performance levels were similar on the Candle problem and Wason's Selection task, whereas the level of performance on the Two Strings problem was considerably lower than that of the other two tasks. Therefore, performance data seemed to strongly favour the Candle problem over the Two Strings problem. However, more participants reached a solution on the Candle problem in less than 60 sec. If the same were to happen in the ERP experiment, insufficient ERP epochs would be collected for such participants and their data could not be used. An alternative would be to employ the Two Strings problem and, in order to improve performance, give participants more time with this problem. Nevertheless, this would also be problematic for several reasons. Firstly, it is not clear that more time available would necessarily improve performance. In fact, studies using this task with more time available (5min) did not find a much higher performance level than the one in the current pilot study (Kaufmann & Vosburg, 1997). Secondly, more time available for the insight task would mean that there would be more ERP trials recorded for the insight than for the reasoning condition. The latter could be problematic, because it could lead to artificial ERP differences between conditions (ERP waveforms are sensitive to the amount of averaged epochs). Although one could only record the ERPs for the pre-set 75 sec and let task processing continue for the collection of performance data, this alternative is also hardly acceptable, because it could not then be claimed that the recorded ERPs reliably reflect critical stages of the task processing.

Therefore, it was decided to employ the Candle problem as the primary insight task and the Two Strings problem as the filler insight task. For participants who would solve the Candle problem in less than 60 sec in the ERP study, the Two Strings problem would be added and the insight condition resumed until the end of the minimum-length recording window (60 sec). Subsequently, in these participants, the minimal number of ERP trials for the insight condition would be reached by collapsing the ERPs from the Candle problem and the Two Strings problem. For behavioural measures (the availability of the correct solution) only the Candle problem would be considered. Although this design does not completely circumvent the problem of the correspondence between the behavioural and ERP data, it does seem the best practical solution, since even in participants who solved the Candle problem in less than 60 sec the most rapid solution was provided in 42 sec, which would allow for 65% of the minimum number of ERP trials to be collected from the primary insight task.

Chapter 7. Study 2. Differences in Working Memory involvement in analytical and creative tasks: An ERP study

7.1. Introduction

In the present study behavioural and electrophysiological evidence was used for testing the hypothesis that analytical (e.g. reasoning) tasks are more reliant on WM processing than are creative (insight) tasks. Studies of positive mood and its effects on cognitive processing constituted the primary motivation for the formulation of this hypothesis. They indicate that insight problems are better solved in conditions of positive mood (Isen et al., 1987). In contrast, analytical (e.g. deductive reasoning) performance is impaired by positive mood states (Oaksford et al., 1996). Oaksford et al. (1996) proposed that positive mood depletes the resources of the Central Executive component of WM, which would otherwise be available for reasoning performance. Indeed, in the same study reasoning was also disrupted in conditions of dual-task performance, which is commonly thought to put heavy demands on the Central Executive (Baddeley, 1986). Oaksford et al.'s Central Executive/WM account was also supported by their findings of deficits on a Central Executive task in conditions of positive mood. The juxtaposition of these findings with the facilitatory effects of positive mood on a range of tasks thought to require creative (divergent) thinking, (e.g. insight problems, remote associates test, etc), leads to the hypothesis of differential WM involvement in the two categories of tasks. However, this prediction has not been directly tested at the behavioural or neurobiological level and the present study will attempt an investigation on both levels.

In addition to the above considerations, there are independent reasons for presuming that insight tasks are less dependent upon WM processing than are analytical tasks. For example, it has been claimed that solutions to creative problems, which would be described in information-processing terms as "ill-defined" (Eysenck & Keane, 2000; Iausovec & Bakracevic, 1995) are reached in a distinct fashion, they are unpredictable, difficult to report and they are generated suddenly (non-incrementally) in the absence of strategies. This is in contrast with the "well-defined" analytical problems, which involve systematic analysis, planning and incremental resolution. These claims are supported by the following findings:

- subjective "feeling of knowing" measures and measures of the "patterns-of-warmth" ratings of an approaching solution substantially differ for "insight" and analytical problems (Metcalfe, 1986a,b; Metcalfe & Wiebe, 1987);

- the requirement to verbalise the strategies while solving insight and non-insight tasks differentially affected the two types of tasks, which appeared to show the relative inaccessibility to the subject of the stages involved in reaching the solution to the insight task (Schooler et al., 1993).

The first attempt to investigate whether the creative/analytical distinction is apparent or real at a biological level involved the use of heart rate measures, which were performed while participants were solving ill-defined (creative) and well-defined (analytical) problems (Iausovec and Bakracevic, 1995). A gradual increase in the heart-rate preceded the solution in well-defined problems and an abrupt increase signalled the resolution in ill-defined problems. This was interpreted as indicating the incremental nature of the approach to the solution in the well-defined task and the "sudden" resolution in the creative task. Furthermore, an EEG study performed by the same group (Iausovec, 1997) found more alpha power (less activation) in most scalp regions in ill-defined (creative) as compared to well-defined (analytical) problem-solving. However, these findings lacked specificity with regard to either the cognitive or neuroanatomical mechanisms differentially involved in the two types of tasks.

The aim of the current study is to employ more discriminative EEG/ERP measures to investigate such processes, in particular WM. The P300 component of the ERP has been shown to reflect cognitive processing demands and to be sensitive to WM function (Donchin & Coles, 1988), with frontal P300 components (P3a) reflecting the encoding of new stimuli in WM (Knight & Grabowecky, 1995). The comparison of P300 responses during problem-solving tasks would therefore provide a test of the experimental hypothesis. More specifically, the degree of frontality of the P3 family components, reflected by larger P300 amplitudes at frontal sites and /or by a more prominent presence of the P3a component, will be used as a psychophysiological measure of WM involvement in the reasoning and insight tasks.

Measuring cortical responses to the WM involvement in such tasks may appear difficult given the problem of temporally locating WM in the problem-solving continuum and isolating it from other processes. This can be resolved by introducing a concurrent task, which would only tax the process of interest (WM in our case) and compete with the main task for resources available to that process. We temporally superimposed a concurrent WM task (CWMT) on analytical and insight tasks. CWMT consisted of counting discrete auditory stimuli (tones), to which ERPs could be time-locked. The cortical reflection of the competition between CWMT and the main (insight or reasoning) would be the ERPs recorded during analytical and creative problem-solving and time-locked to CWMT.

Nevertheless, the interpretation of a P300 difference in amplitude could be far from straightforward in a concurrent task paradigm. A larger amplitude in response to the concurrent task can be taken to signify either less activation in the "main" task, which makes resources available to the concurrent one (A), or more activation in the "main" task, which makes processing of the concurrent task more effortful (B). In order to be able to clearly decide between the two mutually exclusive alternatives, in a control condition ERP data were collected while participants counted the tones in the absence of a problem-solving task. In this case, larger amplitude in response to tones with vs. without problem-solving would be clearly interpreted in terms of B.

The introduction of CWMT also enables the measurement of interesting behavioural data. Concurrent task methodology has been successfully applied with the reasoning task to be employed in the current study (a deontic version of Wason's Selection task, Oaksford et al., 1996). As in Oaksford et al.'s study, the present investigation will use the performance drop attributable to the introduction of the concurrent task as a behavioural measure of Central Executive/WM involvement in the reasoning task.

Furthermore, additional analyses of the reasoning performance will be performed in order to compare the pattern of responses in Wason's Selection task to well-documented response tendencies in different versions of this task. As mentioned earlier, logically valid performance selections can be made if participants falsify (select only the cards that can potentially falsify the rule). This is the predominant pattern of responses on deontic versions of the task, which encourage falsification. In contrast, abstract versions of the task, in which participants apply realistic hypothesis testing, are associated with a strong, "default" tendency to seek confirmatory evidence (select cards that can confirm the rule). If the presence of the concurrent task leads to the depletion of Central Executive resources and this in turn leads to the use of non-analytical, "default" strategies, this should be reflected in participants' tendencies to confirm and falsify. More specifically, it would be expected that Central Executive depletion would lead to a decreased tendency to falsify and an increased tendency to confirm. The present study employs analytical procedures that permit the analysis of falsificatory and confirmatory tendencies (Oaksford & Stenning, 1992; Oaksford et al., 1996; Pollard & Evans, 1987).

In addition to applying the dual-task logic to reasoning performance (Oaksford et al., 1996), the present study also applies it to the insight task: it is examined with vs. without a concurrent task. Subsequently, the reasoning task is compared to the insight task in terms of performance alteration caused by the concurrent task. The concurrent task in the present study was specifically chosen to tax the process of interest: counting randomly presented auditory stimuli requires continuous updating of WM. Relative to a concurrent task which does not specifically tax WM, the concurrent task employed in the present design increases the likelihood of competition for WM resources between the main tasks and the concurrent task.

7.2. Method

Participants

Group 1:

Twenty (13 females and 7 males, mean age 19.15, sd 1.81, range 18-25) healthy right-handed undergraduates received course credits for the participation in the study.

Group 2:

In order to investigate the disruptive effect of CWMT on the reasoning and insight tasks, data was used from 26 participants (15 females and 11 males, mean age 20.1, range 18-27, sd1.94) who had carried out the same problem-solving tasks in Study 1 (pilot) under the same conditions but in the absence of CWMT and ERP recordings.

Apparatus

The auditory stimuli for CWMT were generated by a computer. Two microphones, an amplifier and two speakers were used for the communication between the experimenter and the participants. A closed-circuit camera and a monitor were used for monitoring participants' gaze, while they read the instructions. The EEG equipment consisted of a NeuroScience Brain Imager (series III) and an elastic electrode cap (Electro-cap International Inc., Dallas, Texas).

Tasks (see Fig. 4)

Analytical

The deontic version of Wason's Selection task, with participants playing the rule enforcer role (Cheng & Holyoak, 1985), was employed as analytical task. This is a well-defined deductive reasoning task where participants have been shown to have a uniform interpretation of the problem instructions (Cheng & Holyoak, 1985; Oaksford et al., 1996).

Creative (insight)

The Candle problem (Duncker, 1945; Isen et al., 1987) was used as the primary task in this condition because it was employed in studies that served as a basis for the hypothesis to be tested here (Isen et al., 1987). The primary insight task was closely matched with the analytical task in terms of performance (see Study 1). As Study 1 indicated, time to solution in insight tasks is relatively unpredictable and can include rapid solution times. The presence of a filler insight task (the Two Strings problem, Maier, 1931) allowed for the acquisition of the minimal number of ERP epochs per subject for the insight condition, without discarding the participants who provided an early response to the Candle problem (which would bias the sample).

A maximum time of 75 sec was set for each of the 2 conditions, this having been established as the appropriate length of time for task performance and to allow the collection of an appropriate number of ERP epochs.

CWMT

Participants were asked to silently count 50 computer-generated auditory stimuli (tones: 440 Hz, 200 ms) presented at pseudorandom intervals (mean 1500 ms, range 1000-2000 ms) either alone or during their performance on the analytical and insight tasks.

Procedure

Analytical condition

Participants sat in a sound proof and electromagnetically shielded room. On the desk in front of them they had the instruction set and the diagram for the problem to be solved. After the experimenter's command participants started reading the instructions for the problem and examining the diagram. Their direction of gaze was monitored via a camera in the participants' room. Approximately 5 seconds after their gaze reached the middle of the page (where the instructions ended) participants were asked if the task instructions were clear and provided explanations upon request. Subsequently, participants were asked to turn over the instruction sheet, fixate their gaze on a cross in front of them and attempt to solve the problem while counting the tones at the same time. They were instructed to press a mouse key when they thought they had reached the solution. They were also told that the tasks were hard and encouraged to examine the solution carefully before presenting it. 75 sec after task onset, participants were stopped and asked for the solution to the problem-solving task and also for the number of tones they had heard.

Insight condition

Procedure was the same as above except that those participants who solved the primary insight problem in less than 60 seconds (corresponding to the preset minimum of 40 ERP epochs/ participant/ condition) were given the filler insight problem and stopped when the total time for both problems reached 75 sec. If the response to the primary problem was provided in more than 60 sec, the filler task was not administered.

Control ERP condition

Participants were asked to count tones with no concurrent problem.

The order of the analytical, creative and control conditions was randomised across participants.

Data acquisition and analysis

Behavioural measures

Performance on the insight task (the Candle task) was measured by the number of participants who provided the correct solution. This was contrasted with the performance of Group 2 (control group, Study 1) in a χ^2 statistic.

Reasoning performance was measured in two ways:

1. For comparing reasoning performance with insight performance, the number of participants who provided the logically valid selection (cards "ENTER" and "HEPATITIS", *p* and *non-q*) was measured and a χ^2 statistic was used for comparisons with the insight task, as well as with reasoning performance in Study 1.

2. In order to compare the confirmatory and falsificatory tendencies in the presence vs. the absence (Study 1) of the concurrent task, Pollard indices (Oaksford & Stenning, 1992, Oaksford et al., 1996; Pollard & Evans, 1987) were computed for the present data, as well as for the data from Study 1. The confirmation and falsification indices (CI and FI, respectively), reflecting the two tendencies, were computed as follows (a score of one is assigned to each card selected):

$$CI = (p + q) - (\text{not}p + \text{not}q)$$

$$FI = (p + \text{not}q) - (\text{not}p + q)$$

This would result in CI and FI values ranging from -2 to 2.

Two independent samples t-tests compared CI in the current data with CI in Study 1 and FI in the current data with FI in Study 1. The two indices are related and cannot be compared directly with each other.

Performance on the concurrent task (CWMT) was assessed by the number of errors in counting tones i.e. the difference between the reported number and the actual number of tones presented to the subject.

As explained earlier, the present study aimed to avoid speed-accuracy trade-offs. Therefore participants were encouraged to check the solution carefully before communicating it to the experimenter. In addition, the interpretation of the response time for the participants providing incorrect (or invalid) solutions would be problematic. Therefore solution time was not measured.

ERP acquisition

The 28-channel (10/20 plus 9 additional sites- see Table 2) EEG, referenced to linked earlobes and time-locked to tones, was digitised at a sampling rate of 333 Hz for 900 ms (75 ms prestimulus baseline, 0.1-40 Hz bandpass, impedance < 5kO, forehead ground).

Table 2. Additional electrode sites (relative to the 10/20 system).

Electrodes (9) not present in the 10/20 system	FCT1	FTC2	CP1	CP2	TCP1	TCP2	PO1	PO2	Oz
Equidistant from	F7 & C3	F8 & C4	Cz & P3	Cz & P4	C3 & T5	C4 & T6	Pz & O1	Pz & O2	O1 & O2

Vertical and horizontal eye movements were monitored via supra-, suborbital and canthal electrodes respectively. EEG and EOG trials containing positive or negative amplitudes exceeding 60 mV were rejected on-line, eye-movement contaminated epochs were removed off-line. The minimum number of acquired epochs per condition was preset to 40 (corresponding to 60 sec problem-solving time) and of artifact-free epochs per condition to 30. The artifact-free ERPs were averaged for 3 conditions: control, analytical, creative. ANOVA found no statistically significant difference between the number of artifact-free epochs in the 3 conditions: analytical- 36.8, insight- 37.9, control- 39.6; $F(2, 38) = 2.55$, $p = .1$.

ERP analysis

Waveform analysis

P300 amplitude was measured as (1) the largest peak amplitude within the 250-450 ms time window and as (2) the average amplitude across the same time-window. Four regions of the scalp were defined (frontal, temporal, central-parietal, occipital) and ERPs averaged across electrodes in the four regions for both hemispheres, which excluded the four midline electrodes (see Table 3).

Both time-window average and peak ERPs were subjected to a 3-stage statistical analysis (see Table 6):

Step 1. Omnibus repeated measures ANOVA

Step 2. (following significant main effects or interactions in step1) repeated measures ANOVAs for separate regions

Step 3. (following significant main effects or interactions in step 2) post-hoc t-tests within regions.

Table 3. Scalp regions in the ERP analysis (averages across electrode sites).

Region (4)	Hemisphere (2)	Electrode (24)
Frontal (FR)	FR Left	Fp1, F3, F7, FTC1
	FR Right	Fp2, F4, F8, FTC2
Central-Parietal (CP)	CP Left	C3, CP1, P3
	CP Right	C4, CP2, P4
Temporal (T)	T Left	T3, T5, TCP1
	T Right	T4, T6, TCP2
Occipital (O)	O Left	O1, PO1
	O Right	O2, PO2

Greenhouse-Geiser corrections were applied for ANOVA results and Holm's Bonferroni procedure was used to control for α-inflation in multiple t-tests. Only corrected p-values are reported.

Hemispheres were averaged within regions unless preceded by a significant interaction involving the hemisphere factor. Factor Group, corresponding to reasoning performance (valid/invalid selections) did not enter ANOVA because of a small number of participants with valid selections (5), but separate exploratory t-tests were performed to compare the two subgroups (valid/invalid selections) in all scalp regions.

Principal Components Analysis (PCA)

PCA is a type of factor analysis which has been successfully used for the temporal decomposition of the ERP waveform and its recognised advantages, relative to the visual inspection of ERPs, are its objectivity and sensitivity (Donchin & Heffley, 1976). Importantly, PCA outcomes are often consistent with visual identification of the most common ERP waveform components. Yet, it provides additional detail and robustness to the identification of waveform components. This can be particularly useful, because often what appears as a unitary feature of the ERP waveform is a concatenation of relatively distinct events (e.g. P3a and P3b). Furthermore, electrical events can sometimes cancel each other and not be visible in the ERP waveform, but they would be identified by PCA. Technically, PCA segments the ERP waveform into relatively distinct time intervals (events), by finding the most reliable patterns of covariance between time-points in the ERP recording. For example, if ERPs are sampled at 333 Hz, there is approximately one value of the ERP signal (or time-point) recorded for every 3 ms. If the first 100 points show strong covariance, the PCA treats them as representing roughly one event with the duration of 100 time-points * 3 ms = 0.3 sec. These distinct events in the ERP waveform are referred to in the PCA as principal components or *FACTORS* (PCA "factors" will appear henceforth in capital italics to avoid confusion with ANOVA factors). Furthermore, in addition to this temporal dimension, PCA also automatically provides spatial information by computing the so-called *factor loadings* corresponding to each ERP recording site (electrode). Loadings reflect the extent of the presence of different events (*FACTORS*) at different electrode sites.

Thus, for a more thorough investigation of the sub-differentiation of the P300 component, as well as for segmenting the ERP waveforms and establishing other potential components, a PCA on covariance matrices, varimax rotated, with all time-points at all electrode sites as variables, was performed for the reasoning and insight conditions. Since the control condition was only of interest for interpreting features of the waveform (P300 amplitude), it did not enter the PCA; additional levels decrease the reliability and accuracy of the PCA outcomes. Separate PCAs for the reasoning and insight conditions were used for determining the PCA *FACTOR(S)* corresponding to the P300 time window as well as for ensuring that PCA *FACTORS* had roughly the same time latencies (i.e. happened at the same time) in both conditions. The combined reasoning/insight PCA was used for obtaining *FACTOR* scores for each subject, in each condition, at each electrode site. Only the scores for the *FACTORS* which exceeded the eigenvalue of 1 and explained more than 5% of the variance (the commonly employed cut-off) were subjected to the same stepwise analysis as waveform amplitude, with an extra-step: the omnibus ANOVA was run initially with an additional factor- PCA *FACTORS*, with 6 levels (see Table 7). Subject to significant main effects or interactions involving this ANOVA factor, individual ANOVAs for each PCA *FACTOR* were performed (only three of the latter resulted in significant differences and are reported in Table 7).

7.3. Results

Behavioural data

While there was no statistically significant difference between the number of participants who solved the insight problem correctly with vs. without CWMT (Group

1 vs. Group 2), reasoning performance was significantly impaired by the presence of the concurrent task (see Table 4). This was also reflected by better insight than reasoning performance with CWMT: χ^2 (1)= 3.75, p=.05, and the lack of statistical differences between the tasks in the previous study not employing CWMT: χ^2 (1)= .31, p>.5).

Table 4. Reasoning and insight performance.

		Reasoning			Insight		
Subject groups	No subj	Correct solution	Incorrect solution	Gr1 vs. Gr2 (χ^2, df, p)	Correct solution	Incorrect solution	Gr1 vs. Gr2 (χ^2, df, p)
Group 1 (with CWMT)	20	5	15		11	9	
Group 2 (no CWMT)	26	14	12	**3.88, 1, <.05**	16	10	**.01, 1, >.9**

Participants had a stronger tendency to confirm in the presence of the concurrent task, as indicated by higher CIs in Group 1, as compared to Group 2 (Study 1; t (44) = 2.23, p<.05, see also Table 5). Furthermore, participants showed a weaker falsificatory tendency in the presence of the concurrent task, as indicated by significantly lower FIs in Group 1, relative to Group 2 (t (44) = -2.02, p=.05).

Participants' accuracy in counting tones in the 3 conditions was statistically indistinguishable (mean N errors: during reasoning: .9, during insight: .8 control. .6, F (2, 38)= 2.48, p>.1).

Table 5. Selection frequencies and the Pollard indices (Wason's Selection task).

Group 2 (Study 1; no CWMT)						Group 1(test group; with CWMT)					
Selec-tions	No subj	CI		FI		Selec-tions	No subj	CI		FI	
		mean	SD	mean	SD			mean	SD	mean	SD
p & not*q*	14	0.65	0.93	1.27	0.87	*p* & not*q*	5	1.25	0.85	0.75	0.85
p & *q*	7					*p* & *q*	10				
p	4					*p*	4				
Other	1					Other	1				

ERP data

Waveform analysis (see Table 6). Statistically significant interactions, involving condition, region and group (participants who provided correct/incorrect responses in the creative condition) were found for both peak and time window average measures of P300. In the peak ANOVA the hemisphere factor was also significant in these interactions. ANOVAs for separate regions found the main effect of condition only at frontal sites (see Fig. 5), followed by significant t-tests between the reasoning and insight as well as reasoning and control conditions in the frontal region (in both comparisons the amplitude was larger in response to counting tones during reasoning, see Fig. 6).

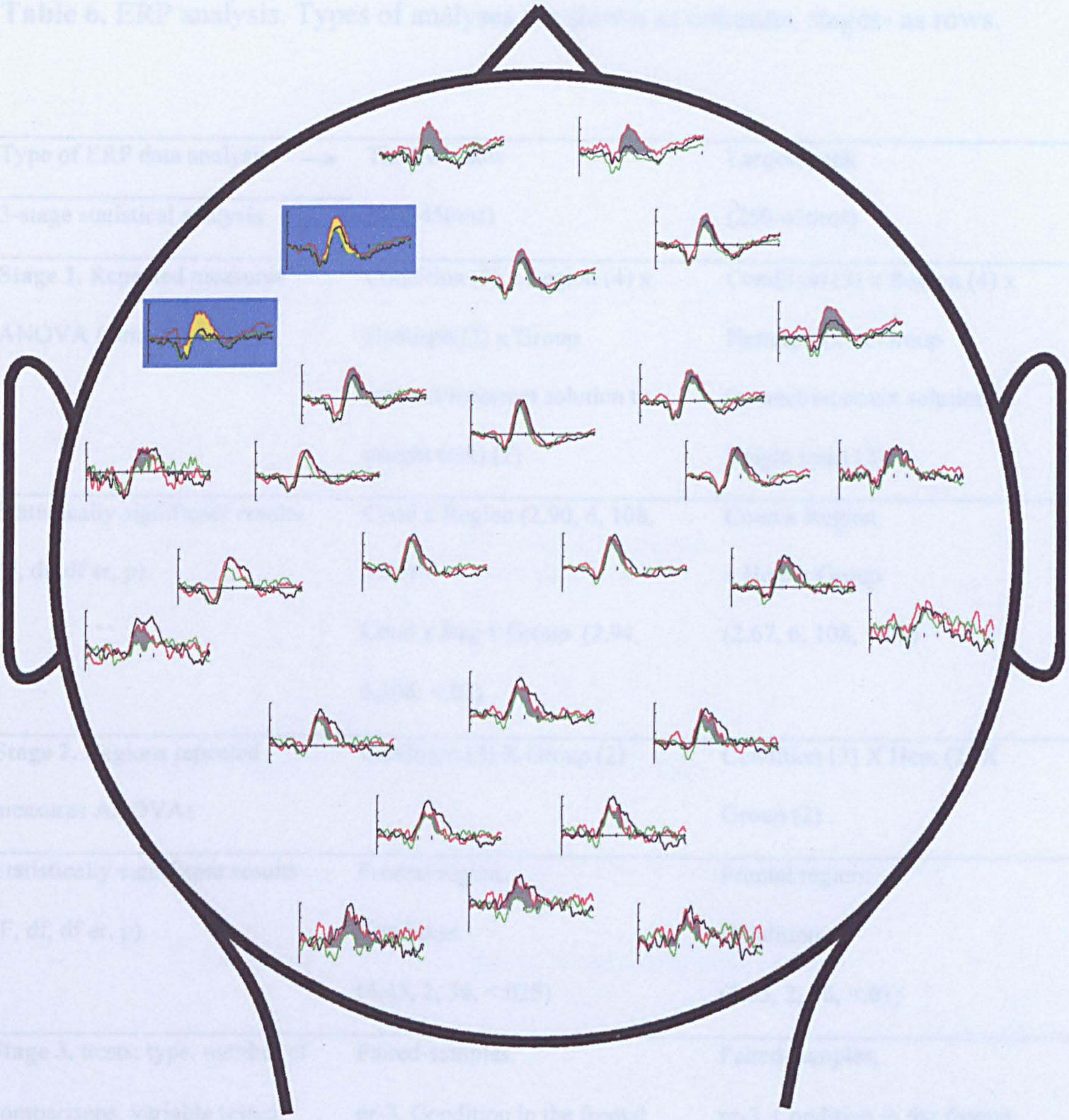


Figure 5. ERPs for the three conditions at all 28 electrode sites, averaged across participants (view from above, right on the right). Two left-frontal electrodes, displayed on a blue background (F3 and F7), showed the largest statistical difference in P300 (see also Fig. 6 for magnified waveforms at the F3 electrode).

Table 6. ERP analysis. Types of analyses are shown as columns, stages- as rows.

Type of ERP data analysis → 3-stage statistical analysis ↓	Time window (250-450ms)	Largest peak (250-450ms)
Stage 1. Repeated measures ANOVA (Omnibus)	Condition (3) x Region (4) x Hemisph (2) x Group (correct/incorrect solution to insight task) (2)	Condition (3) x Region (4) x Hemisph (2) x Group (correct/incorrect solution to insight task) (2)
Statistically significant results (F, df, df er, p).	Cond x Region (2.90, 6, 108, <.05) Cond x Reg x Group (2.94, 6,108, <.05)	Cond x Region x Hem x Group (2.67, 6, 108, <.05)
Stage 2. Regions repeated measures ANOVAs	Condition (3) X Group (2)	Condition (3) X Hem (2) X Group (2)
Statistically significant results (F, df, df er, p).	Frontal region: Condition (4.43, 2, 36, <.025)	Frontal region: Condition (5.53, 2, 36, <.01)
Stage 3. ttests: type, number of comparisons, variable tested	Paired-samples, nr-3, Condition in the frontal region	Paired-samples, nr-3, Condition in the frontal region
Statistically significant results (t, df, p).	**Frontal region:** **1. Analyt/Cre** **(2.92, 19, <.05)** **2. Analyt/Contr** **(2.22, 19, <.05 one-tailed)**	**Frontal region:** **1. Analyt/Cre** **(3.42, <.01, 19)** **2. Analyt/Contr** **(2.22, 19, <.05 one-tailed)**

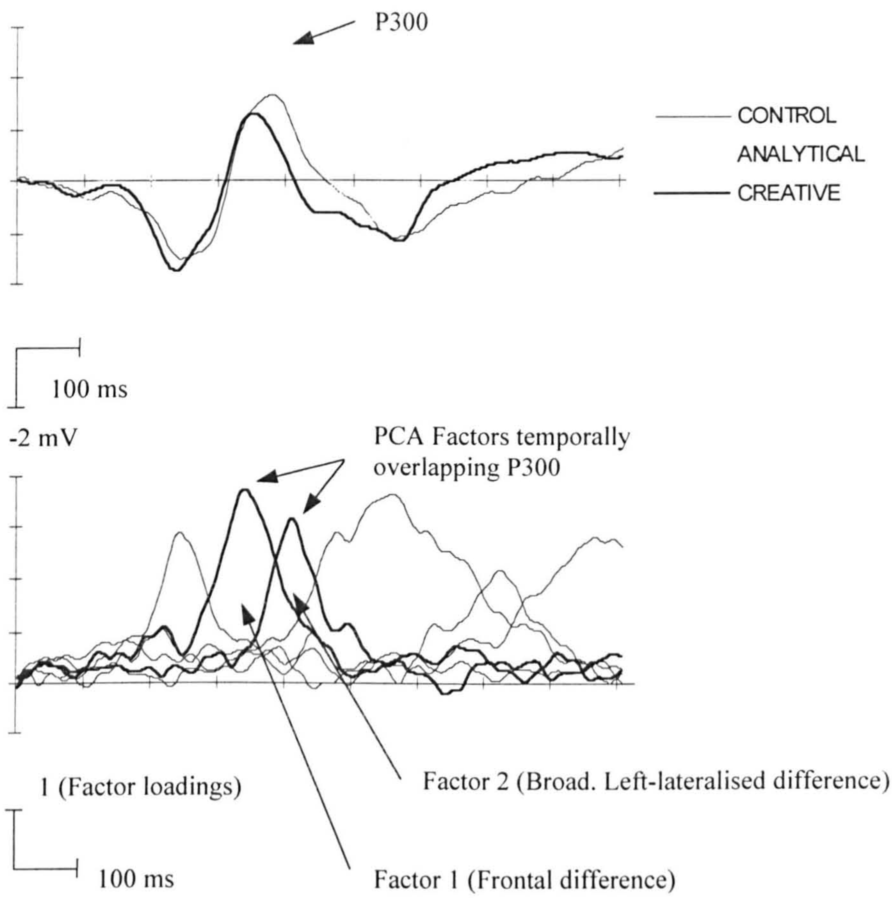


Figure 6. ***Top:*** The P300 difference shown at one of the frontal sites (F3). ***Bottom:*** Loadings of the 6 factors extracted by the PCA. The two factors that overlapped P300 and showed the difference across conditions are plotted in bold.

No significant differences were found between the insight and control conditions. The exploratory t-tests comparing participants who had valid vs. invalid selections in the reasoning task were not significant.

PCA (see Fig. 6) revealed 6 *FACTORS* in both the reasoning and insight conditions. Two *FACTORS* temporally overlapped the P300 peak (as revealed by the separate reasoning and insight PCAs). This indicates that P300 is not a unitary ERP component, but rather, it is likely to originate from at least two sources. Significant interactions (Condition X Region X Hemisphere and Region X PCA *FACTORS*) in the initial Onmibus ANOVA, were followed by comparisons of PCA *FACTORS* in the reasoning and insight (see Table 7). Only the two PCA *FACTORS* that temporally overlapped P300 showed significant main effects or interactions, followed by significant effects in ANOVAs for separate regions or t-tests. The *FACTOR* that corresponded to the earlier part of the P300 was only different in the frontal region (as revealed by ANOVA main effect of condition in that region), whereas the *FACTOR* corresponding to the second part of the P300 was different in all regions with a laterality (left) effect in frontal, central-parietal and temporal regions. In both cases the scores were higher (which reflects a more prominent presence of the *FACTOR*) in the reasoning condition than in the insight condition. A third PCA *FACTOR* showed the main effect of Group, not followed by any significant differences in the post-hoc comparisons between the two groups (correct/incorrect responders in the creative task).

Table 7. PCA results. The three PCA *FACTORS* which were associated with significant ANOVA results are shown as columns.

4-stage statistical analysis	PCA analysis		
Stage 1. Repeated measures ANOVA (Omnibus)	Condition (2) x Region (4) x Hemisph (2) x PCA factor (6) x Group (correct/incorrect solution to insight task) (2)		
Statistically significant results (F, df, df er, p).	Cond x Region x Hem (2.79, 3, 54, <.05) Region x PCA factor (10.04, 15, 270, <.001)		
Stage 2. Repeated measures ANOVA for individual PCA factors	**Factor1: 267-435ms**	**Factor2: 360-468ms**	**Factor3: 612-692ms**
	Condition (2) x Region (4) x Hemisph(2) x Group (2)	Condition (2) x Region (4) x Hemisph (2) x Group (2)	Condition (2) x Region (4) x Hemisph(2) x Group (2)
Statistically significant results (F, df, df er, p).	Cond x Region (5.41, 3, 54 <.025) Cond x Region x Group (2..94, 3, 54 <.05)	Cond (6.16, 1, 18, <.025) Cond x Region (3.12, 3, 54<.05) Cond x Region x Hem (5.22, 3, 54 <.01)	Group (8.72, 1, 18, < 01)
Stage 3. Regions repeated measures ANOVAs	Condition (2) X Group (2)	Condition (2) X Hem (2) X Group (2)	Not applicable
Statistically significant results (F, df, df er, p).	**Frontal region: Condition (6.03, 1, 18, <.025)**	Main effect of Cond in all 4 regions: FR (9.65, 1, 18, <.01), CP (8.27, 1, 18, <.01), T (8.86, 1, 18, <.01) O (6.35, 1, 18, <.025) Cond x Hem in 2 reg: CP (4.95, 1, 18, <.05), T (16.54, 1, 18, <.005)	Not applicable
Stage 4. ttests: type, number of comparisons, variable tested	Not Applicable	Paired-samples, total nr- 6, For Condition in FR, CP and T regions in both Left and Right Hem.	Independent samples , nr- 4, comparing the groups in the 4 regions
Statistically significant results (t, df, p).	Not Applicable	**Analytical/Creative Only in the Left Hem, in the regions: FR (3.87, 19,<.01,), CP (3.46, 19, <.025), T (5.62, 19, <.01)**	**None reached significance**

7.4. Discussion

This study employed a novel approach to the ERP investigation of higher-order cognitive tasks. It allowed us to objectively assess the distinctive nature of creative (insight) as opposed to analytical (reasoning) processes and to identify the source of these differences. Both behavioural and electrophysiological data indicate that the introduction of the concurrent task has more profound consequences for reasoning than insight performance. There are two main reasons for interpreting the effects of the concurrent processing on reasoning performance in terms of competition for WM resources. It is widely believed that dual-task performance makes a strong demand on WM and, in particular, on its Central Executive component (Baddeley, 1986). In addition, the concurrent task used in the present study (CWMT) was specifically chosen to involve few representations from long-term memory, but to require frequent WM updates (i.e. at each tone counted). Therefore, the present results are taken as suggesting more reliance on Central Executive/WM function of analytical (reasoning) processes, as compared to creative (insight) processes.

Behavioural differences

At the behavioural level, the differential effect of CWMT on the two types of tasks was reflected by impairments of reasoning performance in the absence of significant effects of concurrent processing on the insight task (see Table 4). There were significantly fewer participants who made valid selections in Wason's Selection task in the presence of CWMT, as compared to the processing of the selection task alone (control group, Study 1). Furthermore, while the Candle (insight) problem and

Wason's Selection task were associated with similar performance levels in the absence of CWMT (Study 1), the introduction of CWMT altered that leading to a higher performance level in the Candle problem.

A more detailed analysis of reasoning performance (the Pollard indices) clearly indicated that in the presence of CWMT participants had a much higher tendency to look for confirmatory, than falsificatory evidence (see Table 5). The Confirmation Index was significantly higher with CWMT, whereas the Falsification Index was considerably lower with CWMT. According to Oaksford et al. (1996) and the *optimal data selection* model presented earlier, confirmation is a default strategy in Wason's Selection task, not accompanied by thorough analysis of individual selections. In contrast, some deontic versions of the task (e.g. those in which participants play the "enforcer" role), encourage analytical performance, by manipulating the relative utility of individual selections. For example, the "enforcer" task, employed in the current study, encourages falsification by increasing the utility of cards that can potentially falsify and decreasing the utility of cards that can only confirm. Therefore, the fact that the depletion of the Central Executive component of WM by CWMT led to more confirmation and less falsification can be viewed as a further suggestion that participants engaged in less analytical processing in the presence of CWMT and instead resorted to a "default" strategy.

The present findings of impairments of analytical performance in conditions of CWMT are very similar to the results from Oaksford et al.'s (1996) study. Nevertheless, the current paradigm also contrasted the effects of CWMT on analytical processes with its effects on creative (insight) processes. Unlike analytical performance, insight performance did not seem to be affected considerably by the presence of the concurrent task, which is consistent with the indirect evidence reviewed earlier suggesting that insight requires less Central Executive/WM processing.

ERP differences

At the electrophysiological level, the WM difference between the reasoning and the insight tasks was reflected by the difference in P300 amplitude measured both as peak size and average amplitude (see Table 6). It was larger at frontal sites in the reasoning condition as compared to the insight condition (see Figures 5 and 6). Furthermore, P3 amplitude was also larger in the reasoning than in the control condition (in the latter participants only counted tones and had no reasoning or insight task to perform). In contrast, the P300 amplitude was the same in the insight and the control conditions. In other words, the ERPs in response to CWMT contained a larger P300 at the frontal sites when CWMT was performed concurrently with the reasoning task, as compared to CWMT alone or CWMT and the insight task. Therefore, there seems to be little doubt that the larger P300 amplitude in this case reflects competition for resources between the analytical task and CWMT. Those are most likely WM resources, as suggested by the association between P3000 and WM and by the more frontal P300 scalp distribution in the analytical condition as compared to the creative and control (see Fig. 7). Since frontal P3 family components are believed to reflect WM encoding (Knight & Grabowecky, 1995), the ERP difference appears to reflect more effortful WM updating in the CWMT when it is temporally superimposed upon reasoning.

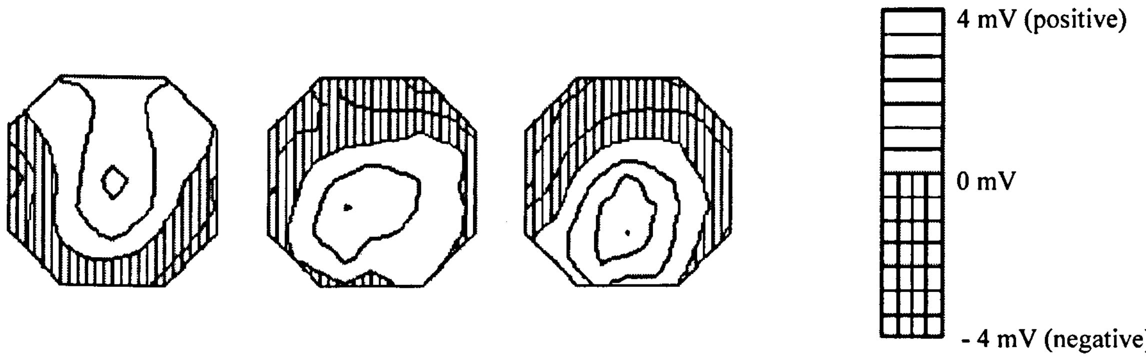


Figure 7. The scalp distribution of the P300 voltage computed as a time window amplitude average (250-450 ms). The positive and negative areas of the scalp are represented by different line patterns. The light area shows the highest P300 amplitude. From the left to the right: analytical, creative, control. The analytical condition shows a pronounced frontal scalp distribution, whereas in the other two conditions it is more posterior.

PCA

The PCA outcomes confirmed the main findings of the waveform analysis (differences were only found in the P300 temporal range and not in other PCA *FACTORS*, see Fig. 6). Furthermore, this analysis brought valuable additional information. It appears that the observed P300 difference is not uniform, but rather, it originates in at least two sources, likely to be the generators of P3a (the early, more frontal) and P3b (the late, broadly distributed). This is consistent with the literature on the cortical generators of P300 (Knight & Grabowecky, 1995). The differential condition effect (larger component scores corresponding to reasoning vs. insight) was found in both PCA factors likely to reflect P3a and P3b waveform components (see Table 7). However, the frontality of the P300 difference revealed in the ERP waveform analysis (see Fig.

7) emphasizes the role played by the neural generator of P3a in the analytical task (PCA *FACTOR* 1, see Table 7).

Going back to the predictions

The predictions in the present investigation were motivated primarily by previous findings of differential effects of positive mood on creative vs. analytical (reasoning) tasks (Isen et al., 1987, Oksford et al., 1996) and the interpretation of impairments of reasoning performance in terms of the depletion of Central Executive/WM resources in conditions of positive mood (Oaksford et al., 1996). We argued that this account lacked a direct comparison of WM involvement in creative vs. reasoning tasks. Such a comparison was performed in the present investigation at both the level of behavioural performance, as well as at the level of electrical activity originating in the cortex. As shown above, the outcome from this comparison supports the prediction that insight and analytical tasks make differential demands on Central Executive/WM processing.

A recent neuroimaging study (Houde et al., 2001) is worth mentioning in the context of the current results. The authors employed a version of theWason's task containing negations (Evans & Lynch, 1973) and geometrical figures as task materials. Participants were divided into two groups. Both groups were trained on a standard abstract version of the selection task. However, one of the groups received in addition to the standard instructions a supplementary text, containing sentences such as the following: "In this problem the source of the error lies in a habit we all have of concentrating on cards with the letter or number mentioned in the rule…". The authors termed this logical-emotional training. They interpreted the poor logical performance of their subject prior to training in terms of the matching bias (Evans & Lynch, 1973). It was found that the logic-only training failed to significantly reduce the bias. In contrast, the logical-emotional training eliminated the bias in 90% of the participants. Furthermore, the PET scans performed in both groups of participants revealed that in participants who had logical-emotional training, and not in those who had logic-only training, the post-training scans contained more frontal activation, relative to the pre-training scans (the latter contained predominantly posterior activation in the sensory areas). Although the study had methodological drawbacks (e.g. it is not clear whether the instructions in the logical-emotional indeed motivated subjects at the emotional level or they were simply better understood by the subjects), it does seem that after the logical-emotional training the subjects approached the task more analytically, as indicated by superior performance. Importantly, this condition was characterized by more frontal activation, which parallels the patter of ERP results from the current study (potentials are more frontal in the analytical task).

Limitations and critical points

Although both on the behavioural level and the level of brain electrical responses the results suggest differential WM involvement in insight as compared to reasoning (analytical) tasks, there are some limitations which complicate the interpretations of the present results.

One potential problem concerns the use of concurrent task methodology in ERP paradigms. Monsell (personal communication, 2001) argued that some activity in the main task (i.e. insight and reasoning tasks in the current paradigm) may be left undetected by the ERPs, because they are timelocked to the concurrent task (tone counting in the current paradigm). More precisely, there are at least two kinds of circumstances under which processing of the main task may be undetected by the physiological recordings time-locked to a secondary task. Firstly, the processing of the primary and the secondary task may run somewhat in parallel and additionally be uncorrelated. In this case, the physiological response to the secondary (concurrent) task may not reflect the processing of the main task. Secondly, even if the tasks are processed sequentially, there is a possibility that the processing of the main task (e.g. the insight problem) can be interleaved with processing the concurrent task, therefore avoiding competition/ interference between tasks. Both arguments appear to be valid in general. However, they do not seem to undermine the present conclusion of differential Central Executive/ WM involvement in insight and analytical tasks. It is believed that the Central Executive (or the Supervisory Attentional System) processes information in a serial manner (Baddeley, 1986; Shallice, 1988). This is consistent with the limited capacity of WM and also with the sequential character of conscious processes, for which WM serves as a workspace. Hence, even if there are some processes in the insight task happening in parallel with the concurrent task, not detected by the current method, these are likely to be automatic and not be associated with WM functioning. With regard to the second possibility, i.e. the insight and the concurrent tasks being processed in an interleaved non-conflictual manner: this would support the claim that insight processes do not require accurate maintenance of intermediary information. In contrast, inter-leaving reasoning and counting seems to affect the former, precisely because substantial amounts of intermediary information need to be kept constantly active (in WM) for successful reasoning performance.

Another, perhaps more serious, limitation of the current investigation is the possibility for the data to be explained in terms of differential involvement of different WM components in insight vs. analytical tasks, rather than one task requiring more WM resources than the other. The concurrent task employed in Study 2 (i.e. tone counting) is likely to rely on verbal processes. Therefore, it could involve one of the two WM "slave-systems", the phonological loop, more than the other, the visuo-spatial sketchpad. It is conceivable that the analytical task (Wason's Selection task) conflicted more with the concurrent task because both require phonological loop processes, whereas the insight task could rely more on the visuo-spatial sketchpad. Although this possibility is highly speculative, there is some neuroimaging evidence (Goel et al. 1997) that deductive reasoning activates regions of the brain thought to implement the phonological loop (Broca's area). This possibility could potentially question the interpretation of the results from Study 2 in terms of the analytical task making a stronger demand on the Central Executive component of WM. However, Oaksford et al. (1996) have also found that concurrent task processing impaired performance on Wason's Selection task. Importantly, the concurrent task employed by Oaksford et al. (monitoring of luggage on an X-ray machine) cannot be claimed to be closely associated with the phonological loop.

Therefore, it seems that the interpretation of both the behavioural and ERP results from Study 2 in terms of WM differences is the most plausible account. It is consistent with the results from Oaksford et al.'s (1996) investigations of the effects of concurrent task processing on reasoning performance. It is also consistent with the literature suggesting less reliance of insight on incremental processes associated with awareness of the processing stages (Metcalfe, 1986a,b; Metcalfe & Wiebe, 1987).

More importantly, it supports the explanation of differential effects of positive mood on insight (facilitation) and reasoning (suppression) in terms of distinct demands that these tasks make on the Central Executive/WM (Oaksford et al., 1996).

7.5. Effects of mood on other WM components

The two studies presented above investigated an account of the differential effects of positive mood on creative vs. analytical tasks. Its central concept concerns the Central Executive, a component of WM (Baddeley & Hitch, 1974). Since the Central Executive, or its analogue, the Supervisory Attentional System (Norman & Shallice, 1986), are viewed as mechanisms for prioritization of goals/ behaviours, significant interactions between emotion and these executive attention components of WM are predictable. It would be interesting to see whether emotions can selectively interact with the so-called "slave" components of WM, which are thought to specialize in storage. We will attempt to show that the storage components of WM contain their own attentional resources and that the latter can also be selectively modulated by emotion. A set of precise predictions will be formulated with regard to emotional states that may interact with these attentional resources. Since the literature on effects of mood on cognition contains little evidence on this, it was decided to directly manipulate mood concurrently with verbal and spatial WM tasks.

There are important considerations with regard to the type of affect to manipulate. The effects of *positive* mood on cognitive processes served as the basis for Studies 1 and 2. However, it is difficult to precisely characterize positive mood induced experimentally (e.g. by film clips) (Gross & Levenson, 1995). Moreover, it has been proposed that the neurobiological correlates of different positive affective states (e.g. appetitive vs. consummatory states) are rather different (Davidson, 1998). Although similar problems exist with the precise identification of experimentally-evoked negative emotions, certain types of negative affect (e.g. fear or disgust) are easier to predict and induce and they can be identified unambiguosly. In addition, in many mood induction procedures positive mood is often more difficult to elicit than negative mood (Davidson, personal communication, 1999). This is even more so when mood induction is concurrent (temporally superimposed) to a cognitive task. In contrast, certain forms of negative affect can be more easily induced, especially if induction is concurrent to the cognitive tasks. Consequently, it was decided to investigate the modulation of verbal and spatial sub-systems of WM by experimentally induced *negative* affect.

As mentioned above, one limitation associated with the use of complex cognitive tasks, such as the insight tasks or reasoning tasks employed in Studies 1 and 2, is the difficulty in estimating the contribution of verbal and spatial sub-mechanisms of WM. Therefore, it was decided to identify tasks whose preferential reliance on verbal or spatial WM would be well-documented.

The next chapter will introduce the evidence suggesting that WM storage components may rely at least in part on their own attentional resources and that the latter can be modulated by emotion. Finally it will investigate WM components' modulation by affect in paradigms which temporally superimpose WM processing and experimentally induced affect.

PART III. EFFECTS OF EMOTION ON VERBAL AND SPATIAL WM

Chapter 8. Attention, spatial WM and anxiety. The hypothesis

The current investigation set out to test the possibility of specific effects of affective states on verbal vs. spatial WM. Recent evidence of differences between rehearsal in verbal WM and rehearsal in spatial WM, at both the behavioural and neuroanatomical levels, can serve as a prolific ground for hypotheses regarding the effects of certain emotions. The key phenomenon here is visual attention.

8.1. Visuo-spatial attention and rehearsal in the visuo-spatial sketchpad

Behavioural evidence

The original muteness of the model by Baddeley and Hitch (1974) with regard to rehearsal in the visuo-spatial sketchpad was addressed as follows. In the same way rehearsal in the phonological loop largely relies upon articulatory (i.e. motor) codes, it was initially proposed (Baddeley, 1986) that rehearsal of visuo-spatial information may rely upon eye-movement programs. However, although there are data suggesting some role of eye-movements in spatial WM, there is also evidence that spatial WM is possible in the absence of eye-movements (Smyth, 1996). Moreover, there is also neuroimaging evidence suggesting that eye-movement programs are not the primary rehearsal mechanism in spatial WM. For example, an fMRI study that examined brain activation in response in spatial WM on one hand and in saccadic eye-movements on the other hand, found distinct regions in the frontal cortex associated with the two types of processes (Petit et al., 1998). A recent version of the idea that spatial WM may be based on motor programs (Chieffi et al., 1999) adopts a more general perspective: it is proposed that a large variety of motor codes can support short-term memory for spatial locations (e.g. eye-movements, motor programs for hand movement, etc.). The condition is that these motor codes need to be associated with movement toward a spatial location. Indeed, some evidence has indicated that, for example, spatially directed arm movements can interfere with spatial WM representations (Smyth & Pelky, 1992). Although the explanation of both verbal and spatial rehearsal in terms of similar mechanisms (motor programs) has considerable appeal, it fails to account for neuroanatomical data. Single-cell recordings in non-human primates have shown the presence in the prefrontal cortex of neurons active during the delay only, neurons active during both the delay and the movement and neurons active during the movement only (Carlson et al., 1997). Importantly, 70% of the neurons whose activity was recorded were active during the delay only. This suggests that the encoding of the sensory stimuli in WM cannot be explained solely in terms of motor codes.

An alternative account was proposed by Smyth and colleagues (Smyth & Pelky, 1992, Smyth & Scholey, 1994) and it was recently re-iterated by the proponents of the original multi-component WM model (Baddeley, 2000). The account states that rehearsal in spatial WM is based on shifts of attention from item to item. Smyth and Scholey (1994) studied performance on a traditional measure of spatial memory span, the Corsi Blocks test. Participants viewed an array of boxes on a computer screen, while a subset of these boxes was indicated one at a time. After a 12.5 sec delay the participants were required to recall the spatial sequence by touching the appropriate boxes in the order in which they were presented. The results showed that if participants were engaged in secondary tasks requiring shifts of attention during the delay, spatial memory performance was impaired, whereas secondary tasks not requiring attentional shifts did not affect spatial WM performance. A subsequent study showed that the same effect was obtained when participants were asked to maintain a fixation throughout the delay period, which rules out the interpretation in terms of a shifts of gaze (eye-movement programs) generating the interference (Smyth, 1996). Similar results, based on an interference paradigm, were also obtained by Awh et al. (1998), who gave their participants a colour classification task during the delay interval of a spatial WM task. The colour classification task came in two versions: in one, stimuli appeared in different locations on the screen and participants had to shift their attention; in the other, stimuli appeared in a fixed location. Spatial WM performance was disrupted only by the colour classification task requiring attentional shifts.

Further evidence for the role of attention in spatial WM was provided by Awh et al. (1998). The investigators reasoned that if rehearsal in spatial WM is based on attentional shifts, then stimuli presented during the delay would be processed more efficiently if they appear in the same locations as the spatial WM locations being rehearsed. This was indeed found to be the case. Participants performed a spatial WM task in which a letter (the cue) appeared in a specific location on the computer screen. In one condition participants had to memorise the location of the letter and in another condition its identity. After a delay, a probe letter was presented on the screen and participants had to decide whether it was the same location/letter as the cue. During the delay, false fonts were presented either in the same location as the cue or not, and participants made speeded keypresses to indicate their shape. As predicted by the authors, it was found that false-fonts presented in the same locations as the cue locations were processed faster. If this was due to a simple attentional effect (e.g. during delay attention is still directed to cue locations), then the facilitatory effect should have been found irrespective of the material that had to be remembered (locations or letters). Yet, the effect was only found in the memory for locations condition. Awh and collaborators (Awh et al., 1999, 2000) have also provided neuroimaging and electrophysiological evidence for the attentional basis of spatial WM rehearsal (see next section).

Neuroanatomical evidence

Recent studies indicate that storage and rehearsal in spatial WM can also be dissociated at the neuroanatomical level. Moreover, the mechanism of rehearsal in spatial WM appears to be different from rehearsal in verbal WM. Neuroimaging and psychophysiological data support the account on spatial WM proposed in the cognitive literature (e.g. Smyth and Scholey, 1994, see above), that rehearsal in spatial WM is based on attention shifts. Awh and colleagues (Awh et al., 1999) performed a neuroimaging study, based on the same logic as in their behavioural study of spatial WM (Awh et al., 1998). In the latter the authors reasoned that if rehearsal in spatial WM is based on shifts of attention, then stimuli presented during the delay in the rehearsed locations would be processed better than stimuli presented in other locations. Behavioural data confirmed that supposition. The same logic applied to neuroimaging would predict that brain visual areas corresponding to the regions of the visual field in which the rehearsed locations were presented before, should be more active than other visual areas, even if the entire visual field is equally stimulated during the delay. This was indeed what Awh et al. (1999) found in their fMRI study. Indirect evidence for the relationship between attention and spatial WM also comes from comparisons of activation patterns in studies of spatial WM and studies of spatial attention (see Awh et al., 1999), which reveal considerable overlap, especially in the right PFC.

Further evidence for the functional overlap between spatial WM and attention comes from psychophysiology. In an ERP study by Awh et al. (2000) participants were presented with "behaviourally irrelevant probes" (i.e. visual stimuli, to which they did not have to respond) during the delay period of a spatial (WM) delayed item recognition task. The stimuli appeared either in the to be remembered locations or elsewhere. In another condition (spatial attention condition), the same "behaviourally irrelevant probes" were presented in addition to targets, to which participants were cued to attend. In this condition the irrelevant probes were also presented in the same locations as the targets or elsewhere. In the spatial WM condition, the amplitude of the ERP signal in response to irrelevant probes was enhanced (P1 and N1 components) when these appeared in the same locations as the to be remembered locations. A very similar enhancement was observed in the non-memory, spatial attention condition: the amplitude of the ERPs in response to irrelevant probes was greater whenever they appeared in the location to which participants were cued to attend. Statistical analysis showed that the ERP effects of positioning the irrelevant probes were indistinguishable in the spatial WM and the attention conditions. The scalp topography of the P1 and N1 differences was also highly similar in the two conditions. These psychophysiological data indicate that the similarity between the mechanisms of spatial WM and attention can be detected as early as 100 ms after stimulus onset (the approximate timing of P1 and N1 components).

To summarise, spatial WM seems to be largely reliant on shifts of visual attention from location to location. In contrast, rehearsal in verbal WM seems to show little relation to visual attention. Concurrent visual attention tasks during verbal WM tasks have little effect on verbal WM performance. Furthermore, presenting visual stimuli in the same locations as letters in a verbal WM task does not facilitate processing of verbal stimuli, as it does to processing of locations. Finally, during the retention delay fMRI signal in visual areas was greatest in the visual areas corresponding to the rehearsed locations in spatial, but not verbal, WM tasks.

8.2. Anxiety and attention

There is one emotion believed to be intimately associated with attention- anxiety. Attentional biases in highly anxious individuals (see also Chapter 1) have been systematically investigated for some time (MacLeod & Mathews, 1988; Mogg et al., 1994; Williams et al., 1988). The theory by Mathews and colleagues (Mathews et al., 1997; Williams et al., 1988) postulated that highly anxious individuals show a facilitatory attentional bias in processing material with negative affective content. In other words, high trait-anxiety individuals are faster at detecting negative stimuli. The behaviour of low-anxiety individuals seemed initially to be the opposite of that of highly anxious individuals. Low trait anxiety participants were slower at detecting negative stimuli, as compared with stimuli with neutral content (Williams et al., 1988).

Although this was interpreted as an indication of a "protective" bias in low-anxiety individuals, a number of investigators questioned the ecological validity of these results, especially in terms of their evolutionary significance. A high threshold for potentially threatening stimuli would hardly improve one's chances for survival. Consequently, investigators attempted to diversify the test materials utilised in such experiments.

One particularly important dimension in the context of high vs. low trait anxiety was the degree to which negative stimuli were seen as threatening. It was soon found that negative stimuli that were seen as threatening by highly anxious individuals were often not seen as such by low trait-anxiety participants. Furthermore, whenever negative stimuli were perceived as threatening by low-anxiety participants, these participants showed the same attentional bias as anxious participants: they were faster at detecting targets in a set of potentially threatening stimuli (Mogg & Bradley, 1998). Whatever the implications of these results for trait-anxiety, in the current context it suffices to conclude that at equivalent levels of perceived threat the behaviour of low-anxiety individuals is similar to that of highly-anxious individuals: they show a facilitatory bias in processing threatening stimuli relative to neutral stimuli ("attention to threat").

Consequently, it can be concluded that visual attention in a state of intense anxiety (e.g. fear) is largely dedicated to processing the potential source of threat (i.e. "attention to threat"). Based on what was said earlier about attention and spatial WM, the temporal superimposition of an intense state of anxiety upon a spatial WM task is likely to result in competition for attentional resources and, hence, in impaired spatial WM performance. In contrast, verbal WM is less dependent on visual attention and therefore would be less affected by fear and the associated "attention to threat". Therefore, it is hypothesised that an intense state of anxiety would disrupt spatial, but not verbal, WM.

In the next stage, the question that arises is: what should be used as a model of intense anxiety? An option would be to administer verbal and spatial WM tasks to individuals with high trait-anxiety. Indeed, this paradigm is explored in Part IV. However, there are at least two reasons for being cautious regarding trait anxiety as a suitable model for testing the above hypothesis of selective spatial WM disruption. Firstly, some studies of trait anxiety and WM concluded that anxious individuals in fact tend to have greater impairments on verbal WM tasks (Ikeda et al., 1996; Lee, 1999). We show in part IV that high trait anxiety leads to equal spatial and verbal WM disruption, suggesting that Central Executive resources of WM are more affected than its storage ("slave") components. Yet, a possibility remains that verbal WM deficits in high-trait anxiety are at least in part caused by verbal ruminations depleting storage capacity. This would be an impediment for using trait anxiety in order to test selective attention-related effects on WM. Using anxiety (fear) evocation in healthy participants is less likely to be associated with an exacerbated tendency to ruminate. Secondly, it has already been discussed earlier (see Chapter 1) that the effects of clinical (anxiety disorders) or sub-clinical (trait anxiety) manifestation of affect can be confounded by the effects of other cognitive variables from the profile of such individuals. Hence, we have opted for employing evoked affective states in healthy participants in laboratory conditions. The following chapter will discuss two critical methodological issues: the selection of the anxiety elicitation procedure and the choice of verbal and spatial WM tasks.

Chapter 9. Methodological issues: affect induction and WM tasks

9.1. Affect induction and validation

Existing affect evocation paradigms have been criticized for employing methods of emotion evocation that require active and effortful cooperation from participants. For example, the Velten Mood Induction Procedure (Velten, 1967) requires the subject to consciously try to feel a certain emotion (e.g., sadness) or valence (e.g., negative). Even if the manipulation has an effect on the cognitive performance, it is impossible to determine whether differences in performance are associated with the resultant affective state or with the cognitive effort necessary in achieving the affective state (Buchwald et al., 1981).

Other methods of affect induction that are not dependent on effortful conscious modulation such as affectively-laden pictures, movies, or music, have also drawn criticism (Gross & Levenson, 1995; Philippot, 1993,). Several major objections have been raised. Firstly, there are usually large individual differences in the potency of such manipulations due to differential histories with the stimuli prior to viewing them in the laboratory. Secondly, affectively-laden film clips generally evoke a constellation of emotions (e.g., sadness and disgust to a film depicting famine victims). Thirdly, such procedures often fail to produce homogeneous or constant intensity affect as people tend to react very briefly to particular scenes or pictures and not others in the same film clip (Davidson et al., 1990). Finally, although the presentation of affectively-laden material does not require or depend upon effortful conscious modulation of affect, these procedures do not entirely resolve the problem of potential cognitive confounds. Affectively-charged pictures or film clips require certain amount of cognitive processing which may very well be correlated with the affective dimension of the material (e.g. there may be less in-depth processing of pictures that evoke disgust).

Another major problem arises from the fact that the affective manipulation is typically done before the cognitive task. Even if the affect manipulation was successful in achieving the desired effect, it is very difficult to objectively assess whether participants are still experiencing this effect during the cognitive task. Many of the affect induction procedures (Velten statements, films) are not amenable to concurrent use with cognitive tasks, because they are cognitively demanding. Music can be employed for concurrent affect induction. However, the presentation of music can be associated with cognitive processes that may be difficult to control for.

Therefore, to overcome limitations of existing paradigms the affect manipulation procedure employed for investigating the effects of emotion on cognitive processing needs to:

- make minimal or no explicit demands on the subject to co-operate
- involve minimal cognitive processing
- minimize individual differences in learning history
- evoke a relatively "pure" and steady level of affect
- be superimposed in time upon the cognitive task

These requirements make the threat of shock and related anxiety-evoking pseudoconditioning procedures (Chua et al., 1999; Grillon et al., 1991, 1993) particularly suitable for studies of effects of affect of cognition. This procedure minimizes individual differences in learning history, requires no explicit cooperation from the subject, has no explicit cognitive demands, evokes a relatively "pure" and steady state of anxiety, and allows for concurrent cognitive task performance and affect induction and assessment. Furthermore, psychophysiological data such as startle blink reflex (Grillon et al., 1993) and skin conductance data (Chua et al., 1999) provide evidence for the presence of anxiety induced by threat of shock. Finally, recent neuroimaging studies have provided valuable insights into the neuroanatomical substrate of anxiety induced by threat of shock (Chua et al., 1999).

In addition, a common problem of studies employing affect induction is the exclusive use of self-report measures to validate the affective manipulation. With the Velten technique, in particular, there are strong demand characteristics to answer a certain way as participants are not blind to the intended effect of the manipulation and can infer how they should answer. In general, the reliability of self-report measures has been questioned on the basis of being too subjective as they require participants to both introspect and infer how the manipulation made them feel and recall (Scherer, 1993). Also, self-report requires self-monitoring, which can make significant cognitive demands. Furthermore, self-monitoring may be more demanding in some affective states relative to others, which can be problematic in comparing different types of affect.

In the current investigation, in addition to self-report measures collected after cognitive performance, online unobtrusive and objective psychophysiological measures (Electromyography and heart-rate recordings) were taken in order to validate the presence of the target affective state (anxiety/fear).

9.2. Verbal and spatial WM tasks

Cognitive tasks typically employed in published reports of affect-cognition interactions have often involved several cognitive mechanisms such as WM, inferential thinking, long-term memory retrieval, etc. which may interact with one another in a complicated, potentially non-linear fashion and are difficult to disentangle. This problem has been discussed in Part II with regard to insight and reasoning tasks and their demands on WM. An example from the studies of effects of mood on verbal and spatial tasks are the tasks employed by Bartolic et al. (1999), i.e. verbal and figural fluency. Verbal fluency is considered to involve the Central Executive component of WM, primarily with regard to rapid switching to new items. Support for this supposition has come both from clinical studies showing that patients with WM deficits have impaired verbal fluency (Benton & Hamster, 1983), and from neuroimaging studies that found activation of brain areas associated with WM in verbal fluency tasks (Phelps et al., 1997). Nevertheless, verbal fluency also heavily relies on long-term memory. Consequently, it may sometimes be difficult to isolate the process of interest (WM in the current context). Not surprisingly, Bartolic et al. (1999) did not make any claims about the nature of the cognitive processes modulated by mood in their study and limited the conclusions to considerations of functional neuroanatomy in mood states and fluency tasks.

A related problem is that of the relatively unconstrained character of some cognitive tasks, where there is little control over the strategies that can be used (e.g. insight tasks, verbal fluency, remote associates). A further issue concerns the neuroanatomical circuitry subserving many of the tasks used in investigations of mood-cognition interactions. Often it is either largely unknown (as in the case of insight tasks), or indirectly inferred (Zarahn & Aguire, 2000), or very diverse (as in deductive reasoning, Goel et al., 1997). In addition, many cognitive tasks are likely to be sensitive to large individual differences in strategy. This problem is exacerbated by the fact that such tasks are generally not amenable to invasive non-human animal experimentation. In addition, tasks thought to have different cognitive or neurobiological profiles are difficult to match psychometrically. For example tasks thought to differentially involve the two hemispheres (e.g. Bartolic et al., 1999) are rarely psychometrically matched on perceptual, motor and performance dimensions (Davidson et al., 1990).

Therefore, in order to investigate the influence of affect on WM processing, one requires a cognitive task fulfilling the following criteria. It must: 1) not involve long-term memory processing, 2) constrain idiosyncratic strategies and have sound psychometric properties, 3) be well-matched psychometrically (applicable to two or more tasks), and 4) be well characterised in terms of functional neuroanatomy.

WM is well characterized in terms of functional neuroanatomy in both humans (Cabeza & Nyberg, 2000, Smith & Jonides, 1999) and non-human primates (Goldman-Rakic, 1989). Moreover, there are WM tasks that involve little or no long-term memory processing. Examples of such tasks are item recognition tasks and n-back tasks. In item recognition tasks (Sternberg, 1966) participants are presented with a number of items (letters, objects, etc) and, after a delay, presented with a stimulus which they either recognise or not as part of the initial set. In n-back tasks (Cohen et al., 1997; Gevins et al, 1996) stimuli are presented on the screen in trials and participants are required to match the stimulus currently presented on the screen with the stimulus presented a number of trials previously: n represents the number of trials before (e.g. in the 2-back (n=2) participants need to match the current stimulus with the stimuli presented two trials previously). In both tasks responses are binary. In the item recognition task the response is 'same' if the stimulus is part of the initial set of items and 'different' if it is not one of the initially presented set of items. In the n-back task the response is 'same' if the stimulus is the same as the one seen n trials ago and 'different' if it was not the same (stimuli to which the correct response is 'same' are referred to as targets and the ones to which the correct response is 'different' as nontargets).

As both item recognition and n-back tasks require virtually no prior knowledge and make no demand on long-term memory (for a comparison, verbal fluency tasks require lexical knowledge), they constrain idiosyncratic strategies and have sound psychometric properties (Gray, 2001). In addition, task difficulty can be controlled by altering the load parametrically (e.g., Braver et al., 1997) or by altering the number of potential responses and their similarity (e.g., letters that sound similar would make verbal versions of these tasks harder). Furthermore, distinctions within WM (verbal versus spatial versus object) can be made by virtually keeping the stimulus material identical and only modifying the instructions (Nystrom et al., 2000; Smith & Jonides, 1999). This is particularly important in the context of the current investigation of verbal and spatial WM. Finally, both item recognition and n-back WM tasks have played a critical role in functional neuroimaging studies of WM (Cabeza & Nyberg, 2000; Smith & Jonides, 1999).

In addition to fulfilling each of the previously described criteria, n-back tasks have several important additional advantages when compared to item recognition tasks. n-back tasks are continuous performance tasks in which trials are presented in blocks with a relatively constant processing load. In contrast, in item recognition tasks processing is discontinuous, with marked differences between different parts of the trial (presentation, delay, recognition). Due to their continuous character, n-back tasks can be operationalized both as a continuum (in blocks) or in discrete units (trials). For example, n-back tasks are equally suited for either relatively lengthy affective state paradigms (blocks) or shorter manipulations (single trials). Moreover, this feature of n-back tasks is especially conducive to electrophysiological and neuroimaging studies (see Part IV). In light of such considerations, the n-back tasks seem an optimal choice for a research paradigm to investigate affect-WM interactions (Gray, 1999, 2001). Furthermore the modulation of n-back (2-back) tasks by experimentally induced mood has already been investigated (Gray, 2001) and the results showed differential effects of mood on verbal and spatial WM.

Chapter 10. Study 3: Developing verbal and spatial n-back tasks. Pilot studies

10.1. Introduction

Despite their numerous advantages, there are a number of important concerns regarding n-back tasks used by other investigators (e.g., Braver et al., 1997; Cohen et al., 1997; Gevins et al., 1996; Gray, 1999, 2000). In most cases the average accuracy is above 90%, which might prove problematic in an affect manipulation study. Accuracy in easy tasks may be insensitive to experimental manipulations and one of the factors (but not the only one) contributing to this is the ceiling effect. In a binary response task, such as the n-back tasks, guessing leads to a performance of approximately 50% correct responses. The optimal performance level for a task subjected to additional manipulations (e.g. evocation of affect) is equidistant from chance (50% in n-back) and maximum performance (100%), i.e. it is 75% correct responses. Some studies using n-back tasks did approach this performance level (e.g. Nystrom et al., 2000). Unfortunately, the verbal, spatial and object n-back tasks used in this study were not well matched for performance (e.g. there were significantly fewer correct responses in the spatial task than in the verbal task).

Another aspect of previously employed n-back task which may be problematic is the ratio between "targets" (trials on which the response should be "same") and "non-targets" (trials on which the response should be "different"). Many studies to date (Cohen et al., 1997; Gevins et al., 1996; Gray, 2001; Nystrom et al., 2000) utilised a 30%/70% target/non-target ratio, i.e. an uneven number of correct "same" and "different" responses. There are reasons to presume that such distribution of responses can be problematic. If participants become aware of the uneven distribution, there is a strong bias for non-targets. In other words, responding with "different" in all trials would lead to an accuracy of 70% correct. Potentially, participants could respond with "same" only when they were very confident and have "different" as default whenever they are somewhat uncertain. Evidently, such a strategy would not be desirable for at least two reasons. Firstly, the help of the default would decrease the WM demand during the task. Secondly, such a strategy would artificially elevate the overall performance and performance on targets. Hence, if there is evidence that participants are indeed aware of the uneven distribution of targets and non-targets, then there is a potential for the default strategy and a 50/50 ratio should be used instead.

An important aspect of the use of abstract shapes and spatial location as stimuli in memory experiments is that verbal labels can be applied to the stimuli so that they can be subsequently rehearsed verbally. Some investigators who employed spatial and object n-back WM tasks (Nystrom et al., 2000) asked their participants if they had used such labelling and they reported doing so in the object n-back task. Evidently, the use of such strategies can have serious repercussions on the outcomes of experiments whose main objective is to perform verbal vs. spatial, verbal vs. non-verbal, etc comparisons. It has to be mentioned that the stimuli employed in spatial and object tasks can encourage the use of verbal strategies. For example, in spatial n-back tasks, studies often employ a limited number of locations (e.g. four or six) that are perfectly symmetric relative to the centre and show little overlap. Such locations are easy to label. In contrast if one dramatically increases the number of locations (e.g. Nystrom et al., 2000) or makes them more overlapping and less symmetric, the use of labels is more problematic. However, one has to bear in mind that increasing the number, overlap and asymmetry of locations also increases difficulty and, hence, lowers performance. For example, in Nystrom et al's (2000) neuroimaging study performance level was significantly lower in the 3-back spatial WM task than in the 3-back verbal WM task.

To reiterate, there were several concerns regarding previously used n-back tasks that had to be addressed. Accuracy levels of over 90% were considered too high in the context of concurrent mood manipulation and its effects. Furthermore, verbal and spatial n-back tasks had to be well matched for difficulty. In addition, it had to be established whether participants are aware of uneven distributions of targets and non-targets, since this may lead to the use of default strategies. Finally, in spatial n-back tasks it is imperative to reduce the use of verbal strategies by manipulating the stimulus locations so that they become less amenable to labelling. However, one has to bear in mind that the above-mentioned requirements are not independent. For example, increasing the number, overlap and asymmetry of locations also increases difficulty and, hence, lowers performance. Consequently, pilot work is needed to develop tasks that simultaneously satisfy these constraints. Four pilot studies were performed in order to address the above requirements.

10.2. Method

Participants

Twenty nine participants (17 females and 12 males, mean age 19.82, sd 1.71, range 19-24) took part in the four pilot studies, for which they received course credits. The numbers of participants who took part in each study are presented in Table 8.

Apparatus

A Pentium 100 MHz PC was used for task presentation and collection of behavioural data (accuracy and RT).

The present verbal and spatial n-back WM tasks (Gray, 1999, 2001) have identical stimuli, and are distinguished only by their instructions. As illustrated in Figure 8, stimuli are presented in trials on a computer screen (IBM compatible, 17' monitor). Each trial consists of the 500 ms presentation of a square box with several instances of the same letter inside, in upper or lower case font. The box with letters is superimposed upon a background configuration of randomly arrayed letters and it appears in six different locations. During the 2500 ms inter-trial interval the background is displayed alone. In both verbal and spatial versions of the task, participants have to decide whether the stimulus is the same ("target") or different ("non-target") from that displayed n trials ago (hence, n-back). In the present pilot studies 2-back (n=2) and 3-back (n=3) tasks were tested. Participants are also instructed to respond with their right hand as quickly and accurately as possible by pressing “s” (same) for targets and “d” (different) for non-targets.

N-back tasks

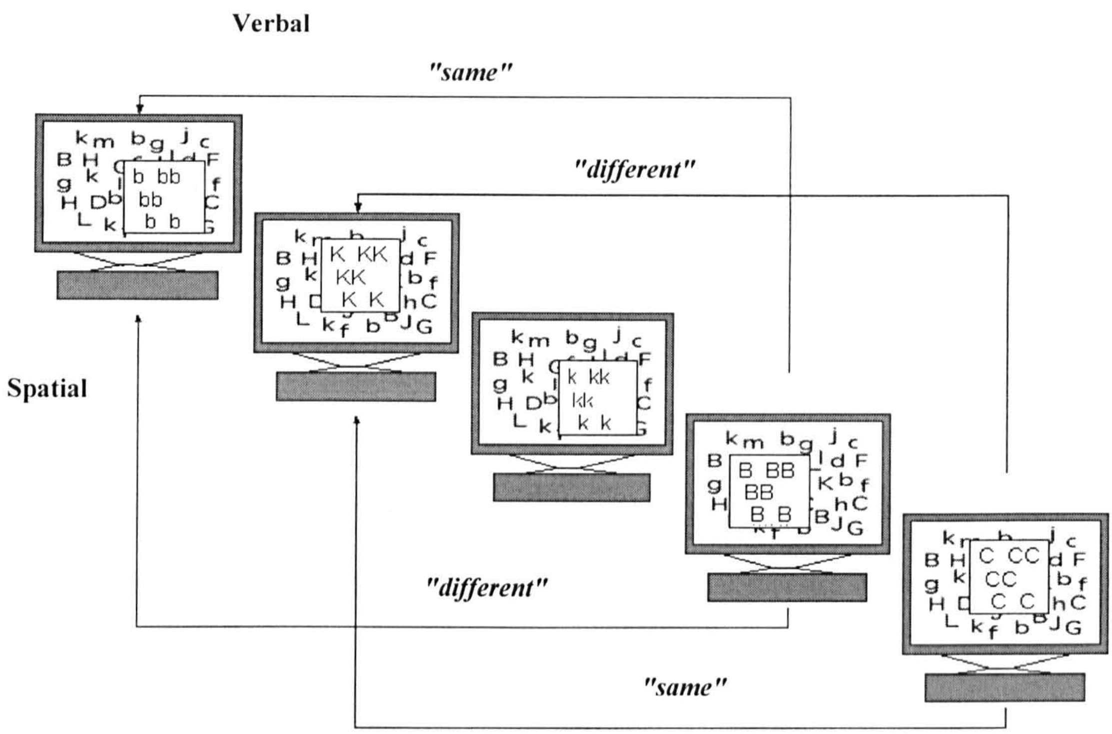


Figure 8. The verbal and spatial n-back tasks employed in the present investigation. The figure shows the 3-back version which was the end result of the four pilot studies.

In the verbal version, participants are instructed to pay attention to the identity of the letter contained in the box and ignore its location. Letters are displayed in both upper and lower-case in order to reduce the reliance on visual information and increase the reliance on phonological and articulatory codes in the verbal task. Therefore, participants are also told to ignore the case of the letter. In the spatial version, participants are instructed to attend to the location of the box and ignore the letters.

N-back trials were grouped into blocks. In the 2-back version there were 102 trials per block, which left 100 response trials (the first two trials were no-response trials, since there was nothing to compare them to); in the 3-back version there were 103 trials per block. A computer program was developed in order to generate blocks of letters/locations while simultaneously satisfying the following constraints:

- target/non-target ratio (30%/70% in pilot studies 1 and 2; 50%/50% in studies 3 and 4)
- equal probabilities of different letters and locations
- equal probabilities of upper and lowercase letters for each letter used
- the repetition of one letter/location three times in a row not more than once per block
- the repetition of one response ("same") three times in a row not more than once per block

Procedure

In all pilot studies participants performed six n-back blocks, three consecutive verbal blocks (first block/practice) and three consecutive spatial blocks (first block/practice), with the order of verbal and spatial blocks counterbalanced.

10.3. Results and discussion

Table 8. Pilot n-back results.

	Task characteristic	Sample size	Revisions	Accuracy %		SD		t test
				Verbal	Spatial	Verbal	Spatial	
Pilot 1	2-back, 30/70 targ/nontarg	7	N/A	93.7	91.4	7.1	7.7	.82 p(6)>.4
Pilot 2	2-back, 30/70 targ/nontarg	8	Shorten trial duration 3--2.5sec	88.5	89.3	7.9	8.3	-.22 p(7)>.5
Pilot 3	3-back, 50/50 targ/nontarg	8	3-back instead of 2-back; 50/50 targ/ nontarg ratio; asymmetric posit in Spatial	85.8	76.6	7.7	9.1	6.17 p(7)<.0 01
Pilot 4	3-back, 50/50 targ/nontarg	6	6 instead of 10 letters in Verbal	77.4	76.4	7.6	7.4	.31 p(5)>.5

Pilot study 1

In the first study the 2-back verbal and spatial versions of the task, developed by Gray (1999) were employed. The target/non-target ratio was 30%/70%. There were ten possible letters, all consonants, and six possible positions. The symmetry of the locations was such that if all locations were projected on the screen at the same time and a horizontal line drawn through the middle of the screen, the image on the top half would represent the mirror of the bottom half. If a vertical line were drawn through the middle of the screen, the image on the right half would represent the mirror of the left half.

The average performance on the task was over 90% correct responses in both verbal and spatial tasks (see Table 8). Performance on the verbal n-back task seemed somewhat higher, but this difference was not significant (see Table 8).

Discussion

The tasks seemed relatively well matched on performance, with a slight advantage for the verbal task. However, the level of performance indicated that the tasks were rather trivial. Easy tasks can be insensitive to affect manipulation and there is an example of such insensitivity coming from a paradigm that employed threat of shock (Chua et al., 1999). Furthermore, as argued above, if the induced affect would have a facilitatory effect on any of the tasks, it could be undetected because of a potential ceiling effect. Therefore, it was decided to increase task difficulty. As a first measure it was decided to reduce the duration of the trial in order to reduce rehearsal. It was thought that this would have a larger impact on the verbal task, thus reducing the difference between the tasks. Another measure to increase difficulty was suggested by the examination of the task materials generated for Pilot 1. A substantial proportion of trials were targets in both the verbal and the spatial tasks. Although participants are instructed to attend only to one attribute in any given block (letter or location), it is conceivable that, at least to some degree, participants would keep track of both letters and locations. In this case, the systematic correspondence of targets in the verbal task to targets in the spatial task could lead to facilitatory cross-talk (any task block could be viewed both as verbal and spatial). Therefore, it was decided to have the correspondence between what were targets and non-targets completely uninformative (50%). In other words, in half of the cases what is a target under verbal instructions would also be a target under spatial instructions, and in half of the cases it would not. Since in the task materials used in the first pilot study this was not controlled for, it was hoped that it would decrease performance to a certain extent.

In addition, the next pilot collected critical information on strategies employed by participants in the tasks. Firstly, it was important to establish whether participants were aware of the uneven distribution of targets and non-targets (30/70 ratio). If they were aware, this could lead, as discussed earlier, to default strategies and less WM processing. Secondly, it was also important to determine whether participants resorted at all to labelling in the spatial task. If the latter were the case, then the two tasks would reveal little about differences in verbal and spatial WM. Therefore, in pilot study 2, participants were asked about the distribution of "same" and "different" responses and they were also asked about the strategy they employed in the spatial task.

Pilot study 2

It seems that the two changes led to some reduction in performance, especially, as it was hoped, in the verbal task (see Table 8). However, performance fell only slightly, with an accuracy of almost 90% in both tasks. Most participants reported labelling locations (e.g. top right, bottom right, etc). All participants were aware of the numerical dominance of non-targets. Finally, most participants reported using labels sometimes in the spatial task.

Discussion

The attempts to lower performance to desirable levels (approx 75%) had only limitted effect. Hence, it was decided to resort to a more radical change replace the 2-back tasks with 3-back tasks. The literature suggests that performance in 3-back tasks is substantially lower than in 2-back tasks (Nystrom et al., 2000).

The knowledge that participants acquired about the distribution of targets and non-targets suggested that at least in certain portions of the task blocks participants could employ "default strategies". The inspection of several blocks of participants' responses confirmed that there were sequences of 4-6 consecutive trials, in which participants responded with "different", but there were no such sequences of "same" responses, indicating that participants may indeed have perceived "different" as a default. Therefore, it was decided to modify the distribution of targets and non-targets to 50/50.

It was also imperative to re-design the locations in the spatial task, so that labelling strategies would be harder to use. Locations were made asymmetric and the degree of their overlap increased, which made it more difficult to find unique labels for each location. The number of locations was kept the same as in the previous pilot studies (six). As in pilot study 2 participants were asked about strategies they used in the spatial task.

Pilot study 3

Performance fell substantially on both tasks. However the drop was much deeper in the spatial task (see Table 8), which gave rise to a significant difference between the two tasks (better accuracy in the verbal task). Only one participant (out of eight) reported using labels in the spatial task.

Discussion

The radical changes to the tasks led to significant effects on performance in the desired direction. However, performance on the verbal task was significantly higher. Hence, it was decided to selectively manipulate the verbal task. In order to reduce performance it was decided to capitalise on the well-documented phonological similarity effect described earlier in the context of evidence that supports the existence of the phonological loop. It was found that phonological similarity decreased the efficiency of the phonological loop, presumably because phonological (articulatory) codes representing similar phonemes overlap (Baddeley, 1966). Consequently, in the context of the present verbal n-back task, it was presumed that the increase in the average phonological similarity would lead to a more difficult retention of letter items. Four letters were excluded from the initial set of ten letters, so that some of the remaining six letters show significant phonological similarity (the latter was operationalized according to norms from Daugherty & Seidenberg, 1994).

Pilot study 4

Performance on the verbal task dropped considerably as a result of the manipulation of phonological similarity. Consequently, there was no significant difference in performance between the verbal and spatial tasks (see Table 8).

Discussion

Pilot 4 fulfilled the criteria concerning task difficulty: performance on both n-back tasks was close to the optimal level of 75%. Furthermore, the tasks were well-matched on performance. Also, the fact that in both the verbal and the spatial tasks there is an equal number of items (six letters and six locations) can be seen as a further advantage. Finally, two other characteristics of the tasks (the even distribution of targets and non-targets as well as the asymmetry and overlap in the spatial locations) were important gains in avoiding as much as possible the use of "default" or labelling strategies. A drawback of the above-described pilot studies concerns the small sample sizes. However, the manipulations expected to affect performance on the n-back tasks, for the most part, reached their objectives (e.g. increasing phonological similarity made the verbal n-back task more difficult). Furthermore, data the subsequent studies (see Chapters 11 and 12) confirmed the accuracy levels obtained in the final pilot study.

Chapter 11. Study 4: Effects of threat-of-shock anxiety on verbal and spatial WM

11.1. Introduction

The present study sought to test a novel, specific hypothesis of a selective effect of anxiety (fear) on spatial WM performance. We base our account on the possibility of a systematic association between certain types of affect and specific cognitive mechanisms. For example, positive mood may stimulate exploratory behaviour through rapid and non-selective WM updating, which could explain its facilitatory effects on creative tasks (Ashby et al., 1999; Isen, 1987), but disruptive effects on analytical (e.g. reasoning) tasks (Oaksford et al., 1996). Similarly, intense states of anxiety provoked by threatening circumstances (i.e. fear) are associated with an increased attention to potentially threatening stimuli, i.e. *attention to threat* (Mathews et al., 1997). Although the threshold for perceiving negative stimuli as threatening is different for individuals with high vs. low trait-anxiety, once the threshold is reached, increased visuo-spatial attention to threatening stimuli is common for both low and high anxiety groups (Mogg & Bradley, 1998). On the other hand, rehearsal in spatial WM is at least partially reliant on shifts of visuo-spatial attention, as indicated by behavioural (Awh et al., 1998; Smyth & Scholey, 1994), neuroimaging (Awh et al., 1999) and electrophysiological (Awh et al., 2000) findings discussed earlier. Moreover, WM tasks that require continuous manipulation of the information in WM, e.g. n-back tasks, may be particularly demanding with regard to such attentional resources. For example, Gevins et al. (1996) recorded brain activity during verbal and spatial n-back tasks using Event-Related Potentials (ERPs). Spatial trials showed a larger ERP deflection around 200 ms post-stimulus onset (P200), interpreted by the authors in terms of attentional processes, because P200 has previously been associated with modulation of visual attention.

Based on the above considerations, it is hypothesized that attention may represent the point of overlap between anxiety and spatial WM. If so, attentional processing associated with threat-evoked anxiety (fear) should limit visuo-spatial attentional resources during a demanding WM task and impair spatial, but not verbal, WM.

Studies that investigated the effects of experimentally induced negative mood on verbal and spatial WM are not numerous (Gray, 2001; Ikeda et al., 1996; Lee, 1999; Markham & Darke, 1991). Three of these studies employed test-anxiety (Ikeda et al., 1996; Lee, 1999; Markham & Darke, 1991), which is rather different from threat-of-shock anxiety. The mood manipulation employed by Gray (2001) may be closer in terms of the elicited affective state. Gray compared the effects of mood induced by means of affectively-laden film clips on verbal and spatial 2-back tasks (the tasks in the present study are based on Gray's tasks). The author did not attempt to induce specific affective states and conceptualised the induced emotions as “positive” and “negative”. However, the films utilised in the negative mood condition (about Halloween) were likely to induce anxiety. Although Gray (1999, 2001) reports the comparison of n-back performance in the affective states relative to each other and not to the baseline, a re-analysis comparing spatial WM performance following anxiety-inducing content vs. following neutral films (baseline), revealed impaired performance following Halloween clips, relative to baseline (Gray, personal communication, 2001). Therefore, there are indications that anxiety (or fear) can have a detrimental effect on spatial WM. However, it has to be noted that the negative mood induction also impaired verbal n-back performance in Gray's (1999, 2001) studies. The limitations of the affect evocation procedure employed by Gray (2001), as well as of other evocation techniques, have already been discussed. The present investigation used an alternative technique for the evocation of anxiety (fear), namely threat of shock. This procedure requires no explicit co-operation from participants, limits the amount of cognitive processing to the basic *attention to threat*, minimizes individual differences in learning history, and allows for concurrent cognitive task performance and affect induction and assessment. Furthermore, neuroimaging studies have provided evidence regarding the neuroanatomical correlates of anxiety evoked by threat-of-shock (Chua et al., 1999).

In addition, many of the investigations mentioned above relied exclusively on self-report measures for verifying the emotion induction, which leaves unanswered questions concerning the extent to which emotional states were in fact experienced during the cognitive tasks (Scherer, 1993). In addition to self-report, the present study utilised objective on-line psychophysiological measurement of affect. Two psychophysiological techniques were selected for this purpose. *Electromyographic (EMG) corrugator superchilii recordings* monitor spontaneous activity in facial muscles in the vicinity of the eye. The *acoustic startle eye-blink reflex EMG* measures the amplitude of the response of *orbicularis oculi* muscle in response to short bursts of white noise. The sensitivity to affective state of both corrugator and startle recordings is well-investigated (Sirota et al., 1987). Anxiety states were shown to augment the intensity of spontaneous corrugator superchilii activity and increase the amplitude of startle responses, via the activation of the sympathetic division of the autonomic nervous system (Vrana & Lang, 1990). Importantly, the objectivity of these techniques stems from the relatively automatic character of sympathetic activity.

11.2. Method

Participants

Fifty-five right-handed participants were recruited from the Introductory Psychology Subject Pool at the University of Wisconsin-Madison and through advertising with flyers and paid $25.00 US for their participation. Handedness was assessed using the Chapman & Chapman (1987) inventory. Participants with a history of neurological or psychiatric disorder or prior exposure to electric stimulation were not selected. Fifteen participants' data were discarded due to performance at the chance level (below 55% mean accuracy per WM type) or equipment malfunction. Two participants reported during the session previous experience with electric stimulation and were dropped from the analysis. Data from the remaining 38 participants (20 females and 18 males, mean age 20.63, sd 1.76, range 18-25) entered the analysis.

Apparatus

A Pentium 100 MHz PC was used for task presentation and collection of behavioural data (accuracy and RT). A modified Coulbourn stimulus isolator and a pair of silver cup electrodes were used for the generation and delivery of electric shocks. A Coulbourn S81-02 noise generator, a Coulbourn S82-24 audio-mixer amplifier and Radio Shack Optimus LV-20 headphones were used for the generation and delivery of startle probes. EMG were recorded using Sensormedics mini-electrodes, SAI Bioelectric amplifiers (SA Instrumentation Co., Caroga Lake, NY), rectified and integrated using a Coulbourn S76-01 contour and stored using a 12-bit analog-to-digital board (Analogic Corporation, Wakefield, MA).

WM tasks

Verbal and spatial 3-back WM tasks from Study 3 (Chapter 10, see Fig. 8) were employed. Their psychometric properties satisfied all the requirements set for the WM tasks earlier.

Experimental design (see Fig. 9)

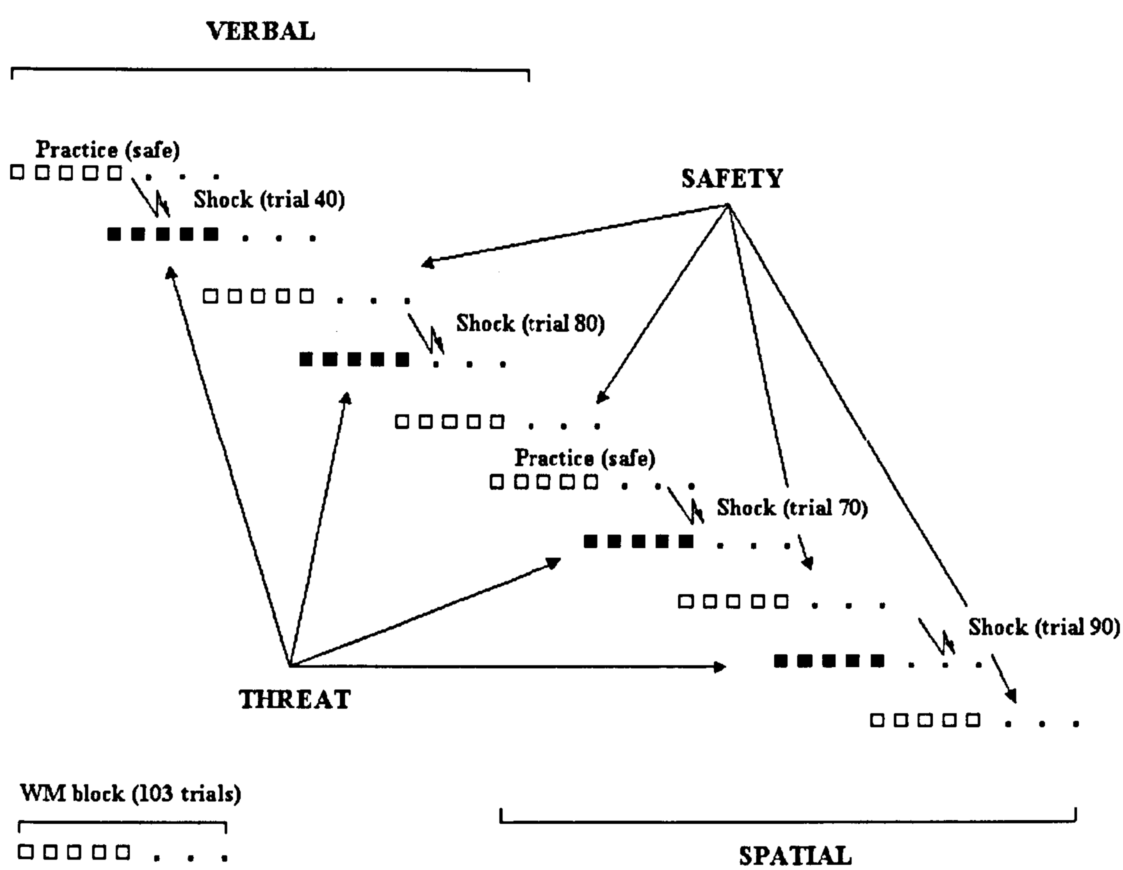


Fig. 9. Study 4. A graphic representation of the experimental design with an emphasis on the mood manipulation paradigm.

An experimental session was divided into two parts with a short break in-between. Each part corresponded to a WM type, verbal or spatial (counterbalanced across participants) and consisted of five 401.5 sec long WM blocks (103 trials each), the first representing practice and the next four the test blocks. Among test blocks half were associated with threat of shock (threat blocks) and half with safety (safety blocks). Practice blocks were also safe. Shock and safety blocks were always interleaved such that there were never two blocks of the same type in a row. The order of blocks (safety-threat-safety…or threat-safety-threat…) was counterbalanced across participants.

Threat and safety blocks were signaled by three means:

- an instruction screen with the words "Shock Block" or "Safety Block", was displayed at the beginning of each block for 90 sec (which coincided with startle probes baseline period in half of the blocks);

- two colours- olive green and dark blue matched on brightness and saturation, corresponded to either safety or threat, counterbalanced across participants;

- the experimenter entered the test room and connected (before threat) or disconnected (before safety) the shock electrodes into/from the shock box on subject's desk.

Participants were administered electric shocks once in each threat block, at different times within the block: in trials 40, 80, 70 and 90 of threat blocks 1, 2, 3 and 4, respectively.

While corrugator supercilii EMG was collected in all blocks, data on the startle eyeblink reflex was only collected in the two practice blocks and half of the test blocks (two per WM type, one per affect condition). It was decided to have half of the test blocks free of startle probes in order to control for the potential effect of probes (alone or in interaction with the affect manipulation) on performance. The order of blocks with startle probes was fixed: practice, 2nd and 3rd in each part of the session (each WM type). The combined counterbalancing across: WM type in the first block (2), affect manipulation the first block (2, safety or threat) and colour (2) resulted in 2*2*2=8 possible test schedules (e.g. Verbal- first, first block- Safety, blue = Threat), which were counterbalanced across participants (full counterbalancing was not achieved, with two schedules being slightly under-represented).

Procedure and instructions

Before performing the task participants were provided with general information on the experimental procedure. They were told that they would perform two memory tasks (one in the first part of the experiment and the other in the second part) under conditions of stress and that mild electric shocks will be used as stress elicitors. They were also instructed that between 1 and 5 unpleasant but not particularly painful shocks would be administered during the session and that each shock would be increasingly strong. Then participants were shown the equipment used in the experiment and were applied the EMG and shock electrodes. The latter and a small connector on the desk, where shock electrodes were to be plugged in (referred to as "shock box") were indicated to participants as the source of electric stimulation. In the following stage the first WM task was introduced (the verbal or the spatial 3-back) and participants performed the practice block, presented to the subject as safe; electrodes were not connected to the shock box. After practice participants were informed that they would perform a number (not specified) of task blocks of the same length as the practice and that some of them would be safe, while in some electric shocks would be likely to occur. Participants were also told that threat and safety blocks were distinguished by instruction screen content and colour of the stimuli, and that the experimenter would connect/disconnect the shock electrodes according to the block valence. During WM blocks, participants were monitored from the control room via a VHS camera and monitor. Participants had a 7 min break between the two parts of the experiment. After the last task block they filled in the self-report forms and the questionnaires. The duration of the session was approximately 2.5 hours.

Self-report

13 single-item visual-analog scales (Bond & Lader, 1974) provided participants' retrospective assessment of a variety of affective states during the experiment. Each scale, represented by a 100mm line, corresponded to one of 13 adjectives, describing the affective state: *amused, angry, anxious, aroused, ashamed, disgusted, embarrassed, excited, guilty, happy, proud, relieved, sad.* An additional 100 mm scale was given to the participants for the assessment of the strength of shock.

Electric shocks generation and delivery

A total of four shocks per subject (4 mA, 20 ms, constant current, bipolar sqr-wave, 4ms per cycle), one per WM block, were delivered to a pair of electrodes affixed superficially to the left wrist (targeting left median nerve). Within the WM trials (3000ms) shocks always occurred at 2000 ms after the trial onset.

Acoustic startle probes

Acoustic startle probes were bursts of white noise, 50 ms in duration 95 dB, and with a nearly instantaneous rise time. 16 probes (interprobe interval 18 +/- 3 sec.; 6 trials +/- 1) per block were generated in certain WM blocks (see Experimental design). The first five were delivered during the instruction screen (90 sec) and served as baseline. Within a trial (3000 ms) probes were randomly delivered at either 1500 ms or 2500 ms after the trial onset.

Startle eyeblink reflex and corrugator activity acquisition and analysis

Raw and integrated EMG from orbicularis oculi and corrugator supercilii muscle regions were collected via two pairs of mini-electrodes placed directly below the left eye (Vrana et al., 1988) and above the medial portion of the left eyebrow respectively (as suggested by Fridlund & Cacioppo, 1986). A fifth mini-electrode was placed in the centre of the forehead and used as ground. Impedances for all mini-electrode pairs were less than 20 kOhms. Raw signals were amplified 10000 times after being filtered with a1-800 Hz bandpass. The amplified raw corrugator signals were submitted to analysis. The raw signals originating over orbicularis oculi after passing through a Rockland 30 Hz highpass filter, were rectified and integrated with the time constant set at 20 ms. Both raw and integrated signals were digitized and stored at 250 Hz on a Pentium 100 MHz PC throughout the WM blocks using SnapStream software (HEM data corporation, Springfield, MI). Recording equipment was calibrated before and after each session. The units for raw and integrated EMG were microvolts (_V).

Orbicularis oculi EMG in response to acoustic startle probes was reduced to eyeblink reflex magnitude using the following procedure. Automatic peak and onset detection was performed on the integrated EMG response to each probe using an in-house software package. Each response was reviewed and approximately 40% of eyeblinks were excluded from further analysis due to excessive noise (spontaneous eyeblinks, unusually high amounts of integrated EMG during the baseline) during the 50 ms prestartle baseline or because the onset of the integrated EMG eyeblink reflex happened later than 20 ms after the startle probe. Eyeblink reflex magnitudes (in _V) were calculated by subtracting the amount of integrated EMG at reflex onset from the peak amplitude (maximum amount of integrated EMG between 20 and 120 ms following probe onset). Probes with no perceptible eyeblink reflex were assigned the amplitude of zero and included in the analysis. Finally, eyblink reflex magnitudes were z-transformed within participants and within WM blocks due to large individual differences in the distribution of this measure. Blinks that were more than 3 Standard Deviations (SD) above the mean for a given subject were excluded.

Raw EMG activity over the corrugator supercilii muscle was reduced to average power density (_V^2/Hz) within a broad EMG band ranging from 45 to 200 Hz. In order to do this, raw EMG signals were first extracted through a Hamming window, then FFT transformed. Finally power density values were z-transformed within participants.

Behavioural data collection and analysis

Dependent behavioural measures were accuracy and reaction time (RT). Accuracy was represented by the number of correct responses in every WM block and RTs for correct responses were averaged within WM blocks.

Several analytical strategies were employed. The simplest analysis was to compare threat and safety blocks without excluding any trials. However, it is conceivable that electric shocks (one in each block) might have been powerful sensory stimuli, which could partially or totally erase the current memory content. Moreover, since shocks were only administered to the left wrist, the stimulation would reach predominantly the right hemisphere and potentially lead to a selective effect on spatial WM, if one assumes right-hemispheric dominance in spatial WM. In order to control for this, at the first stage (thereafter referred to as all-4 analysis) four trials immediately following shock in threat blocks and the trials with the same order in safety blocks were excluded from the analysis: in these trials items held in memory at moment of electric stimulation were needed for responding (see Fig. 10).

Nevertheless, the first analytical strategy did not seem entirely satisfactory. To completely eliminate the confound of shock itself, a final analytical strategy was applied: separate analyses were run for the trials preceding (pre-shock) and following shock (post-shock); from the latter four trials were subtracted exactly as in the all-4 analysis.

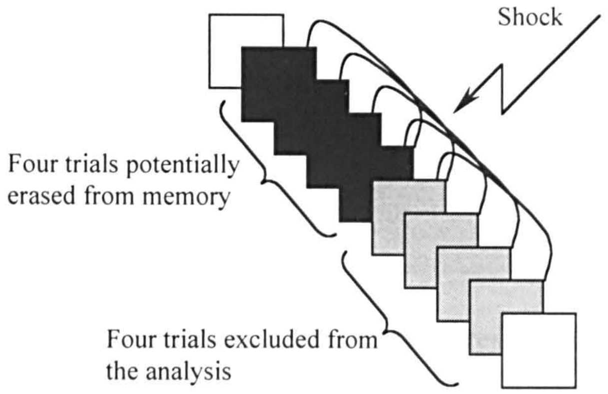


Figure 10. The all-4 analysis.

Furthermore, since shocks occurred in different trials across threat blocks (see Experimental design and Fig. 9), in order to have equal number of analysed trials per condition, the smallest number of trials were analysed as follows:

- for pre-shock it was 40 (the earliest shock occurred in trial 40);
- for post-shock it was 9 (the latest shock occurred in trial 90, four trials were dropped because of association with shock: 90+9+4=103).

All 3 analyses (all-4, pre- and post-shock) were run for both accuracy and RT. Only pre- and post-shock analyses were run for the EMG data.

Statistical analysis

Eyeblink reflex magnitudes were subjected to a 3-way ANOVA with WM (verbal / spatial), Affect (safety /threat) as within-participants factors and Gender as a between-participants factor.

Accuracy, RT, corrugator power-density and scores on the 13 self-report adjectives were subjected to 4-way ANOVAs with an additional within-participants factor: Probe (startle probe present / not present). t-tests were used as post-hoc comparisons.

Prior to running correlational analyses the following variables were computed:

accuracy decrement = accuracy (Safety) – accuracy (Threat)

anxiety measure 1 (corrugator) = corrugator power-density (Threat) - corrugator power density (Safety)

anxiety measure 2 (startle) = startle eyeblink magnitude (Threat) – startle eyeblink magnitude (Safety)

anxiety measure 3 (self-report) (for each adjective) = score (Threat) – score (Safety).

Correlational analyses were run between accuracy decrement and the three measures of anxiety. RT was not included in the correlational analysis, since the RT analyses found no significant effects or interactions involving factor Affect, confirmed by post-hoc tests.

Greenhouse-Geisser corrections were applied for violations of sphericity in ANOVAs. Holm's Bonferroni procedure was used to control for α-inflation in multiple comparisons in both post-hoc tests and correlations. Only corrected p-values are reported.

11.3. Results

Self-report (for descriptive statistics see Table 9)

ANOVA revealed significant main effects of Affect and Adjective as well as a significant Affect X Adjective interaction (see Table 10). Post-hoc tests revealed significant differences in two adjectives: "anxious" and "aroused". In both scores were higher for Threat as compared to Safety blocks.

Psychophysiological data

Startle eyeblink amplitude

A large number of participants (11) had to be dropped from the analysis due to excessive noise in the data. No reliable main effects or interactions were found for the remaining participants.

Table 9. Means and standard deviations for two self-report scales (which showed significant effects) and the corrugator power density.

	Safety		Threat	
Self-report (mm)	mean	SD	mean	SD
Anxious	0.94	1.13	2.65	1.02
Aroused	0.79	0.98	1.67	1.43
corrugator (_V2/Hz)	2878.13	2121.00	3671.64	2339.27

Corrugator power density (for descriptive statistics see Table 9)

The pre- and post- shock analyses revealed a significant main effect of Affect, followed by significant Verbal Threat vs. Verbal Safety and Spatial Threat vs. Spatial Safety t-tests (see Table 10), showing higher corrugator power-density in threat blocks as compared to safety blocks (see Fig. 11). No main effect or interaction involving WM type approached significance.

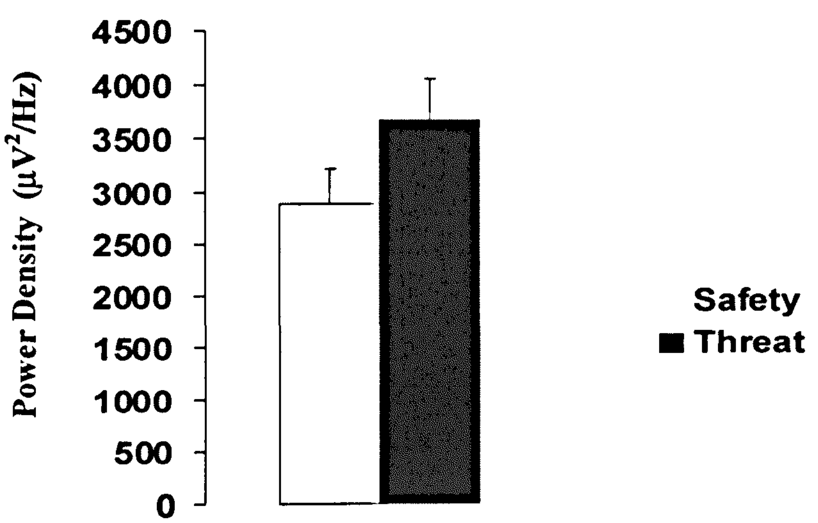


Figure 11. Corrugator power density (collapsed across WM types). Henseforth error bars in figures represent the Standard Error (SE).

Table 10. Statistically significant results.

Analysis		Statistically significant effects: ANOVA — Factors	Main effects	Interaction	t tests (corrected for multiple comparisons)
RT	All-4 trials	WM X Affect X Probe X Gender	No	WM X Affect F(1,36)=12.25,p<.002	No
	Pre-shock		WM F(1,36)=12.54, p<.002	No	Verb/Spat (Safety), t(37)=3.27, p<.003 Verb/Spat (Threat), t(37)=3.71, p<.002
	Post-shock		WM F(1,36)=6.75, p<.015	WM X Affect X Gender F(1,36)=7.66, p<.01 WM X Affect (females) F(1,36)=5.34, p<.04	No
Accuracy	All-4 trials		No	**WM X Affect** **F(1,36)=4.99, p<.032**	**Safety/Threat (WM Spat)** **t(37)=3.54, p<.001**
	Pre-shock		No	**WM X Affect** **F(1,36)=7.81, p<.008** Affect X Probe F(1,36)=3.9, p=.05	**Safety/Threat (WM Spat)** **t(37)=2.07, p<.05** No
	Post-shock		Affect F(1,36)=14.7, p<.001	Affect X Probe F(1,36)=4.8, p<.035	Safety/Threat (WM Verb) t(37)=3.75, p<.002 Safety/Threat (WM Spatial) t(37)=2.4, p<.022 Probe / No Probe (Safety) t(37)=2.36, p<.024
Corrugator power-density (z-scores)	Pre-shock		**Affect** **F(1,36)=41.77,** **p<.001**	No	**Threat/Safety (Corrug Verb)** **t(37)=5.74, p<.001** **Threat/Safety (Corrug Spat)** **t(37)= 5.04, p<.001**
	Post-shock		**Affect** **F(1,36)=41.74,** **p<.001**		**Threat/Safety (Corrug Verb)** **t(37)=6.23, p<.0001** **Threat/Safety (Corrug Spat)** **t(37)=3.84, p<.002**
Self-report (shock intensity + 13 adjectives)		Affect X Adject X Gender	**Affect,** **F(1,35)=25.11,** **p<.0001** Adjective F(12, 157)=23.66, p<.001	**Affect/Adjective** **F(12, 201)=18.07** **p<.0001**	**Threat/Safety** **Anxious, t(37)=8.7, p<.01** **Aroused, t(37)=5.23, p<.01**

Behavioural data

Accuracy (for descriptive statistics see Table 11)

No main effect of WM type was found in any of the analyses. Similar results were obtained in two analyses (all-4 and pre-shock). Both revealed a statistically significant WM X Affect interaction, followed by significant post-hoc tests that found decrements in spatial WM performance in Treat as compared to Safety (see Table 10 and Fig. 12). In the all-4 analysis the Threat verbal and Safety verbal conditions were associated with similar levels of accuracy (see table 11). In the pre-shock analysis Threat was associated with better Threat verbal accuracy relative to Safety verbal, but the t-test did not reach significance ($t(37) = -1.68$, $p>.01$).

Table 11. Means and standard deviations for accuracy and reaction time for all three analytical strategies. RTs for males and females are shown for the analysis that found sognificant interactions involving Gender (post-shock analysis).

Analysis	Behavioural measure	Verbal WM				Spatial WM			
		Safety		Threat		Safety		Threat	
		mean	SD	mean	SD	mean	SD	mean	SD
All-4	accuracy (%)	79.55	12.36	79.40	12.42	82.83	11.01	79.70	11.13
	RT (ms)	1068.74	256.92	1042.02	257.06	951.56	211.26	948.38	219.35
Pre-shock	accuracy (%)	80.65	12.82	82.68	12.48	84.99	10.61	82.25	11.26
	RT (ms)	1091.97	248.66	1083.77	269.05	972.86	198.89	961.69	240.49
Post-shock	accuracy (%)	80.56	14.88	70.76	16.22	82.31	14.26	75.73	13.39
	RT (ms)	1051.76	314.56	1016.90	315.31	947.16	239.63	929.87	229.73
	RT in females	1116.63	310.02	1030.42	341.08	926.12	202.67	960.79	225.90
	RT in males	979.68	312.24	1001.88	293.10	970.54	279.23	895.51	235.50

The pre-shock analysis also revealed a marginally significant Affect X Startle Probe interaction not followed by significant post-hoc tests (see Table 10).

The post-shock analysis did not reveal a significant WM X Affect interaction (see Table 10). It found instead a significant main effect of Affect (followed by significant t-tests for both verbal and spatial WM types, indicating lower accuracy in Threat vs. Safety) and a significant Affect X Startle Probe interaction, followed by a significant t-test showing lower accuracy with vs. without startle probes in Safety blocks.

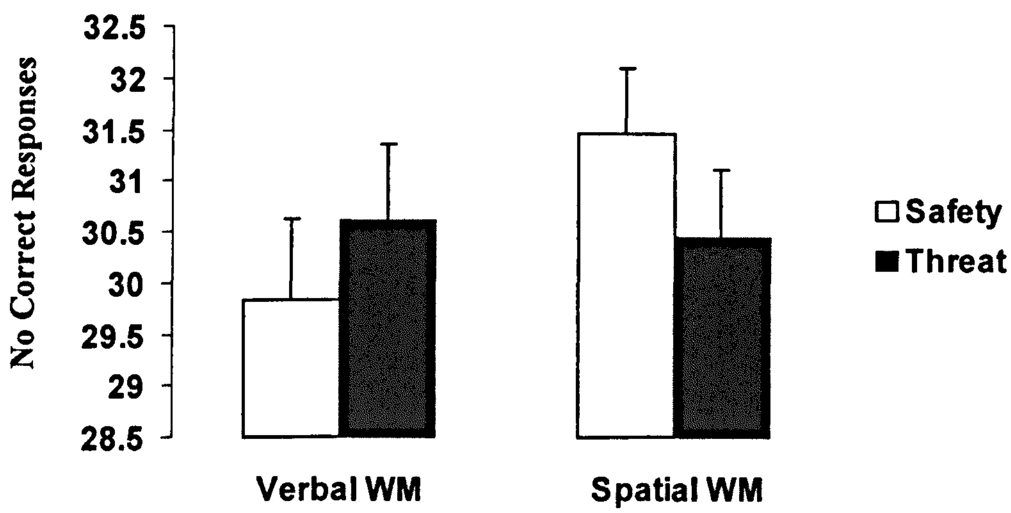


Figure 12. Pre-shock accuracy, represented as the number of correct responses out of 37 (corresponding to the first 40 trials, in a 3-back the first 3 trials of each WM block are no-response trials).

Reaction time (for descriptive statistics see Table 11)

Two of the RT analyses (pre- and post-shock) found a significant main effect of WM type, followed by significant post-hoc tests that revealed faster responses in the spatial as compared to the verbal WM task (in both Threat and Safety, see Table 10). Reaction times were somewhat shorter in Threat than Safety for both WM types, but this was more pronounced in verbal WM. This was reflected in the significant WM X Affect interaction in the all-4 analysis. However, the post-hoc tests, comparing Threat vs. Safety reaction times were not significant. A similar speed-up in the WM blocks in which shocks were administered was suggested in female participants by the WM X Affect X Gender interaction in the post-shock analysis, but it too was not followed by significant post-hoc tests.

Correlations

No correlations reached significance after the adjustment for multiple comparisons.

11.4. Discussion

One of the key objectives of the study was to induce the affective state (anxiety) concurrently, and not prior, to the WM tasks. The presence of anxiety during the memory task was confirmed both by self-report measures (adjectives "anxious" and "aroused"), and by psychophysiological techniques (see Fig. 11 and Table 9). Consistent with the extant literature (Vrana & Lang, 1990) and with our expectations, corrugator recordings revealed increased muscle activity in conditions of Threat, as compared to Safety, for both WM types. Importantly, the fact that only two out of 13 self-report adjectives ("anxious" and "aroused") showed a reliable difference between Threat and Safety seems to suggest that affect-induction was rather selective (see Table 10).

The results from the present study are highly consistent with the hypothesised selective disruption of spatial n-back WM performance in conditions of anxiety (fear). Two of the accuracy analyses, i.e. the analysis of all trials with the exception of four trials immediately following shock and the analysis of the trials that preceded shock, found that only spatial WM performance was impaired in the Threat condition, as compared to the Safety condition (see Fig. 12). In contrast, verbal WM performance remained unchanged from Safety to Threat. This was indicated by the significant WM by Affect interactions, followed by significant t-tests for spatial WM. The outcomes from the analysis of trials after shock (post-shock) did not reveal such selectivity: both verbal and spatial WM were disrupted in conditions of Threat, relative to Safety (see Table 10). It seems that differential effects were only obtained in a relatively "pure" state of anxiety and that the emotional state following the shock may have included other types of affect (e.g. anger, embarrassment, etc). In addition, the physiological effects of electrical stimulation may have been quite strong in the WM trials following shock and the exclusion of four trials may have not been sufficient to control for this factor (see below for more discussion of this issue). Although the reaction time analyses seemed to suggest that participants were somewhat faster in the spatial WM task (collapsed across Threat and Safety), none of the accuracy analyses found the main effect of WM, which indicates that the verbal and spatial n-back tasks were well matched on performance.

Participants responded somewhat faster in the Threat blocks, compared to Safety blocks (though these effects are not reliable as shown by post-hoc tests). However, this cannot be taken as an indication of speed-accuracy trade-offs. The speed-up effect of Threat was larger for verbal WM, and a speed-accuracy trade-off would predict that verbal, not spatial, WM performance should be lower in Threat blocks. The accuracy data show the opposite. Some interesting effects of startle probes were also discovered. For instance, the post-shock analysis showed that in the absence of threat the probes were associated with lower WM performance, as indicated by Affect by Probe interaction and the significant post-hoc tests.

A legitimate question to be asked is whether the spatial n-back is not more sensitive to any disruption as compared to the verbal n-back. If that would be the case, the specificity of the effect reported here could be questioned. In the post-shock analysis performance was equally impaired on the verbal and the spatial WM tasks, suggesting that the two tasks are not disproportionately susceptible to disruption.

Limitations

Despite the convergence of findings from the analyses of WM performance, the conclusion that the selective disruption of spatial WM performance is entirely attributable to the change in affective state cannot be reached. Electric shocks were employed in the study in order to standardise the state of anxiety across different participants (different expectations of the strength of shock may have lead to more variability in the level of induced anxiety). Furthermore, it was considered important to preserve a relatively steady level of anxiety in a lengthy paradigm and shocks were expected to contribute in this respect. Nevertheless, the physiological effects of electrical stimulation are complex and difficult to control even by exclusion of WM trials. Furthermore, shock as sensory stimulation could potentially account for the effect.

Another drawback of the current study is the large loss of participants from the analysis (17 out of 55 in the accuracy, RT, self-report and corrugator analyses, and 28 out of 55 in the startle analysis). The main reason for this loss was the technical sophistication of the experiment; there were four on-line control systems, which had to be integrated: the system presenting the WM task and collecting accuracy and RT data, the system generating acoustic startle probes, the system recording the EMG (corrugator and startle) and the system generating the electric shocks. There was a high risk of interference between these systems. In addition, the paradigm was long (over two hours) and tiring, and participants had to do the lengthy session with five sensors surrounding their eyes and with the shock electrodes affixed to their wrist. This may have led to lower performance levels in some participants.

Finally, another limitation of the study is the lack of significant correlations between performance spatial WM decrement and the measures of affect, which precludes one from drawing firm conclusions. Therefore, it was decided to address all these concerns in the next study.

Chapter 12. Study 5: WM and threat, but no shock. Resolving methodological issues

12.1. Introduction

We sought to test our hypothesis by employing a more rigorous paradigm, relative to the previous study. The first, most important concern that had to be addressed was the use of electric shock. Importantly, threat-of-shock does not imply the delivery of shocks. Since electric shocks can be a powerful confounding variable, the current design is limited to threat-of-shock and does not at any point contain shock delivery.

A further modification, as compared to Study 4, concerned the paradigm. In the previous study the use of startle eye-blink recordings greatly increased the duration of the session: every WM block had to be performed with and without startle probes, to control for the possible interaction of affect and probes. Furthermore, every WM block containing EMG recordings had to include a baseline period. In the present study the duration of the session was reduced by three times (from approximately 140 min to 45 min) by using a different physiological on-line measure of affective state, heart-rate recordings. The presence of threat has unequivocally been associated with increased sympathetic activity, resulting in increased heart-rate (Ax, 1953; Palomba et al., 2000). This permitted a reduction in the duration of the WM tasks. The elimination of shock delivery and the use of heart-rate also helped reduce the amount of equipment that needed to be coordinated, thus reducing the risk of data loss.

Finally, it was decided to directly test the relationship between the strength of evoked anxiety (as measured by heart-rate and self-report) and changes in WM performance using appropriate analytical techniques. It has been recently shown (Gray, 2001) that differences in participants' responsiveness to emotion induction can provide additional insight when linked to WM performance.

This resulted in a short and efficient design, which contained in one condition threat of shock, but no shock delivery.

12.2. Method

Participants

39 right-handed students with no history of neurological or psychiatric disorder were paid 10 pounds sterling for participating in the study after providing informed written consent. Two participants withdrew from the session after practice. Data from one participant were discarded because of near-chance accuracy (chance= 50%), leaving 36 participants (18 females, 18 males, mean age 20; sd= 1.76, range 18-25).

Apparatus

A Pentium 100 MHz PC was used for task presentation and collection of behavioural data (accuracy and RT). POLAR heart-rate monitor and chest strap were used for heart-rate recordings. A pair of tin sensors were used for mimicking shock electrodes.

N-back WM tasks

The study employed the same verbal and spatial 3-back WM tasks as in Study 4, with two differences. Firstly, the number of trials in verbal and spatial WM blocks was reduced from 103 to 37. Secondly, in both the Safety and Threat conditions, the verbal and spatial WM blocks were presented back-to-back.

Procedure (see Fig. 13)

Before starting the experiment, participants were told that the experiment consists of two parts: in the first part they would practice two memory tasks and in the second part stress would be induced while they would perform the memory tasks. Subsequently, participants performed Part 1. This part included three practice n-back blocks: one verbal n-back block (5 min), one spatial n-back block (5 min) and one n-back block, half of which was verbal and half spatial (4 min in total). A 3-min rest was given after Part 1.

Part 2 was preceded by another set of instructions, which informed participants that between one and three unpleasant but not particularly painful shocks would be administered during the next n-back block and that each shock would be increasingly stronger. Participants were also told that shocks were not related to task performance. Consequently participants were given the written consent form for Part 2. For participants who did not consent (two), the session was terminated. Those who provided their consent for Part 2 were shown the shock equipment (fake) used in the experiment and were affixed shock electrodes (fake). Subsequently they performed an n-back block identical to the third practice block (half-verbal and half-spatial, order counterbalanced across participants, total duration 4 min), containing two instruction screens with the words "Shock Block". This constituted the Threat condition. Importantly, shocks were not administered at any point during the experiment.

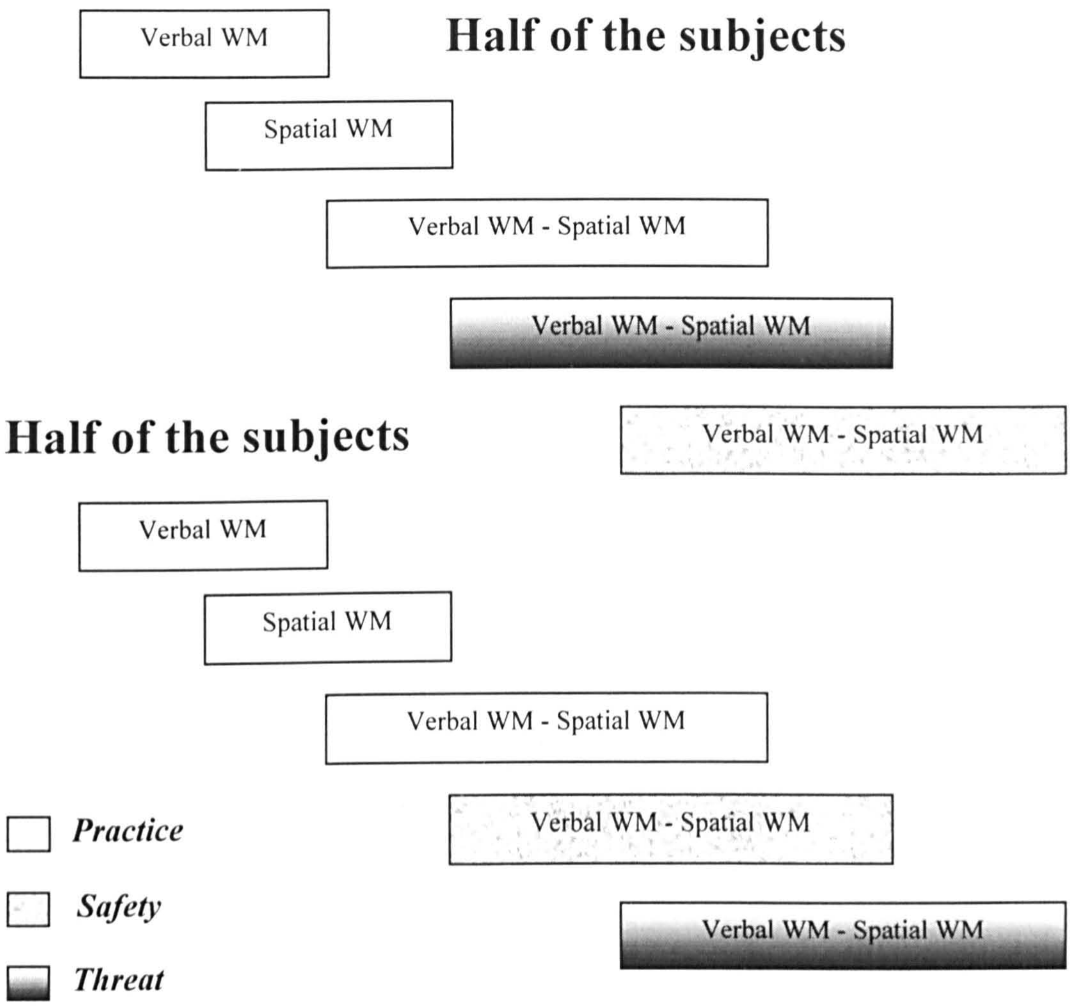


Figure 13. Study 5. Experimental design.

The Safety condition was represented by an equivalent n-back block, distinguished only by instruction screens with the words "Safety Block". Half of the participants had the Safety block at the end of Part 1, after the three practice blocks. To counterbalance for the order of Safety and Threat blocks, the other half of the participants had the Safety block after the threat block (i.e. in Part 2).

Participants were debriefed at the end of the experiment, after completing the self-report scales (see below) and the reason for the non-delivery of shock explained.

Self-report

After the experimental session, participants provided a retrospective assessment of their affective state during Threat and Safety, by making a vertical mark on each of five 100mm-long lines, i.e. *visual analog scales* (Bond & Lader, 1974) corresponding to the adjectives *anxious, excited, scared, sad, aroused.*

Heart-rate

The absolute number of heartbeats per condition was derived on-line from the electrocardiogram and subsequently reduced to the mean heart-rate (beats per minute).

Statistical analysis

Heart-rate and self-report

Participants' heart-rate was submitted to an ANOVA with Affect (safety/threat) and Task (verbal n-back/spatial n-back) as repeated measure variables and Gender as a between-participants variable.

A similar ANOVA was performed for self-report: Adjective (scores on the five visual-analog scales) X Affect X Gender.

Accuracy and RT

As an initial step, accuracy and RT were subjected to a generalized ANOVA/ regression with Task and Affect as repeated measures, Gender as a between-participants variable and HeartRateDifference (HRDif) as a continuous independent variable. HRDif was computed as the difference between heart-rates during Threat and Safety. To further investigate the relationship between n-back performance and the intensity of threat-evoked affect, similar generalized ANOVAs were performed with differences in self-report scores replacing HRDif as continuous independent variable, e.g. FearDifference (FearDif) = difference between self-reported fear (visual analog scale, adjective *scared*) in Threat as compared to Safety. Only adjectives that showed significant Threat vs. Safety differences in the self-report analysis were entered as continuous independent variables.

Post-hoc analysis and corrections

T-tests and correlations were employed as post-hoc analyses. T-tests were performed subject to significant ANOVA interactions involving repeated measure variables (e.g. Task, Affect). If independent continuous variables (e.g. HRDif) showed significant ANOVA interactions, correlations (Pearson's *r*) were computed between these and Performance Decrement (PDcr= Accuracy-in-Safety minus Accuracy-in-Threat). Such correlations would clarify the relationship between heart-rate (or self-report measures), affective state and WM performance. For example, a significant positive correlation between HRDif and PDcr would mean that the higher the heart-rate in Threat as compared to Safety, the lower the performance in Threat relative to Safety.

Greenhouse-Geisser corrections were applied for violations of sphericity in ANOVAs. Holm's procedure was used to control for α-inflation in multiple t-tests and correlations. Only corrected *p*-values are reported.

12.3. Results

Self-report (for descriptive statistics see Table 12)

Scores on several visual analog scales differentiated Threat from Safety. The ANOVA significant main effect of Affect ($F(1,34)=172.13$, $p<.0001$) and Adjective X Affect interaction ($F(4,136)=32.24$, $p<.001$) were followed by significant post-hoc t-tests comparing Threat vs. Safety for adjectives *scared* ($t(35)=10.64$, $p<.001$), *anxious* (t(35)=10.23, p<.001), *excited* (t(35)=5.94, p<.001), and *aroused* (t(35)=2.95, p<.05) (see Figure 14).

Table 12. Means and standard deviations for scores on visual-analog scales.

		Safety WM blocks		Threat WM blocks	
		mean	SD	mean	SD
Self-report (mm)	Anxious	26.03	23.50	72.11	21.39
	Excited	21.36	22.18	50.75	29.55
	Scared	15.69	20.81	62.83	27.53
	Sad	9.30	13.74	10.13	15.45
	Aroused	10.44	19.57	17.30	23.78

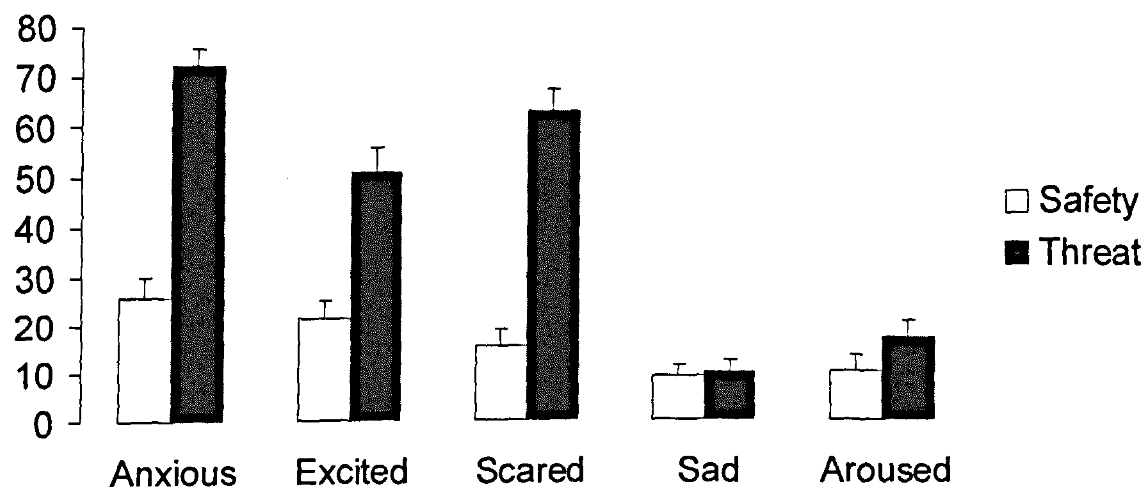


Figure 14. Scores on visual analog scales (collapsed across WM types).

Heart-rate (for descriptive statistics see Table 13)

The analysis of heart-rate found significant main effects of Affect (F(1,34)=8.46, p<.01) with higher heart-rate in Threat than Safety (see Figure 15), and Task

($F(1,34)=9.24$, $p<.01$) with higher heart-rate in Verbal n-back than in Spatial n-back. However, not all participants showed increases in heart-rate under threat of shock. For this reason, in some analyses of the effect of anxiety on WM performance, we focused only on the 24 who did show increases, i.e., those for whom there was objective evidence of a successful emotion induction.

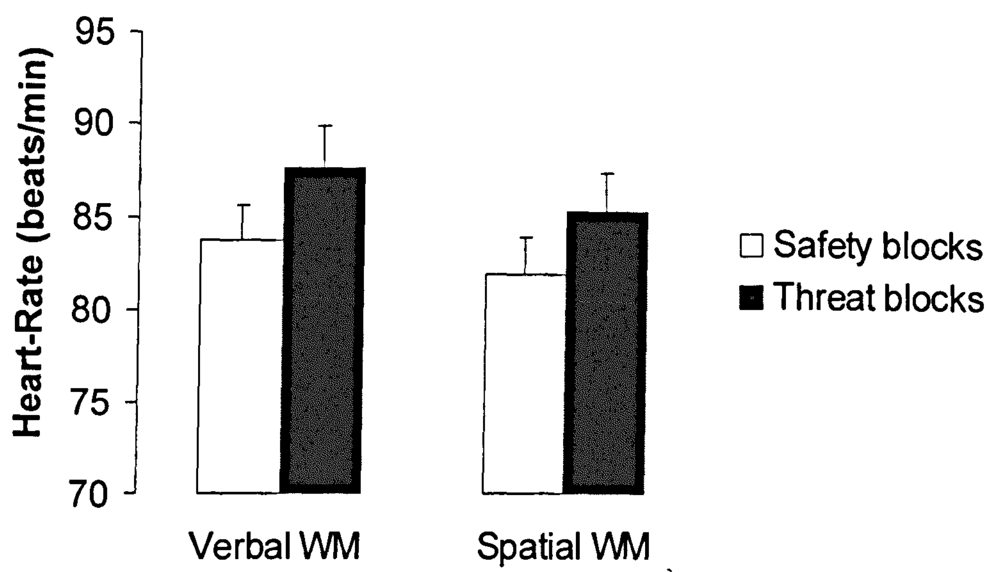


Figure 15. Heart rate in the verbal and spatial WM tasks in safety and threat.

Table 13. Means and standard deviations for heart-rate, accuracy and reaction time.

	Verbal WM				Spatial WM			
	Safety		Threat		Safety		Threat	
	mean	SD	mean	SD	mean	SD	mean	SD
Heart-rate (b/min)	83.80	11.06	87.69	13.60	81.97	11.85	85.33	12.64
Accuracy 1 (%)	78.22	12.25	74.01	17.41	80.46	9.19	73.65	13.61
Accuracy 2 (%)	77.81	11.38	76.90	15.71	81.03	8.50	72.77	13.59
RT (ms)	1063.5	302.1	1063.64	313.22	990.15	275.32	1036.44	324.29

Accuracy (for descriptive statistics see Table 13)

Our key prediction was an interaction of Affect (threat vs. safety) with Task (verbal vs. spatial) on WM performance. As expected, there were substantial individual differences in participants' responsiveness to the emotion induction. We therefore sought to control for and capitalize on these differences in the strength of the induction when assessing the key interaction of interest (Gray, 2001). Firstly, across all participants, we statistically controlled for individual differences based on physiological (HRDif) and self-report (FearDif) measures. Secondly, we focused only on participants with objective evidence for a successful emotion induction: the increase in their heart-rate in Threat as compared to Safety (HRDif).

In the first analysis of WM performance, we included measures of individual differences in the strength of the emotion induction as a continuous variable. The test of the 3-way Affect X Task X Strength-of-induction interaction affords a natural test of the hypothesis. It imposes the additional constraint that the interaction of interest be strongest for those participants experiencing the strongest emotional state. Testing this 3-way interaction by ANOVA revealed a significant Task X Affect X HRDif interaction ($F(1,33)=4.49$, $p<.05$). Similarly, the Task X Affect X FearDif interaction approached significance ($F(1,33)=3.86$, $p=.058$). The pattern of selective spatial n-back disruption was fully confirmed by post-hoc t-tests. Among t-tests comparing Threat and Safety blocks for both n-back types as well as verbal and spatial n-back blocks for both Affect types, only one was significant: Spatial Safety vs Spatial Threat ($t(35)=3.16$, $p<.05$). Moreover, there was a significant positive correlation of PDcrSpatial with HRDif ($r(36)=.44$, $p<.01$). The correlation of PDcrSpatial with

FearDif was also positive, but it did not reach significance (r(36)=.21, p=.22). The same correlations of PdcrVerbal were non-significant (r(36)=-.09, p>.6 and r(36)=-.1, p>.5 respectively). These interactions and correlations suggest that the more anxiety the participants reported and the higher their heart-rate in the Threat condition, the more impaired was their spatial, but not verbal, n-back performance.

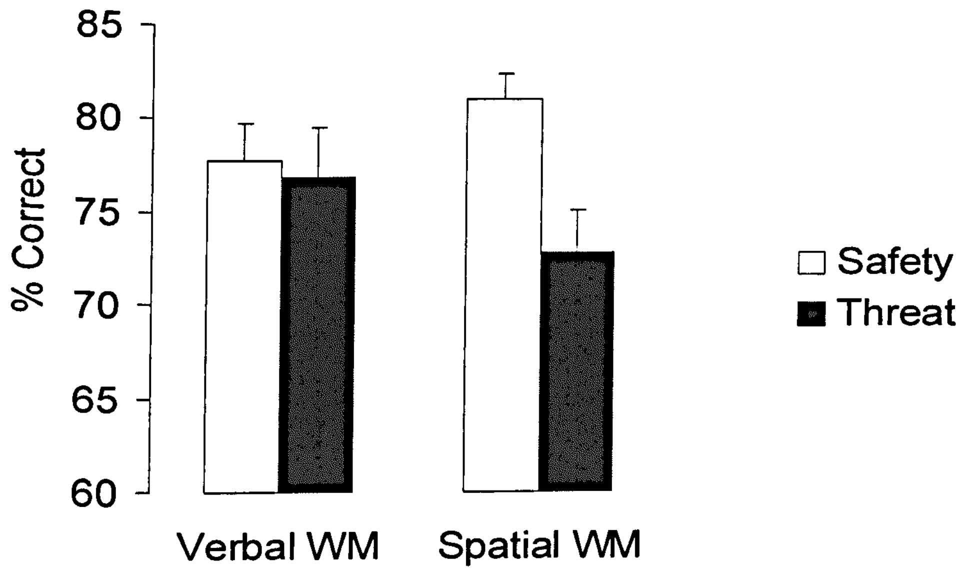


Figure 16. Accuracy in participants who showed increased heart-rate in Threat compared to Safety WM blocks.

In the second analysis, we focused only on the 24 participants with increased heart-rate during Threat than Safety. Testing the key 2-way interaction by ANOVA revealed a significant Task X Affect interaction (F(1,23)=3.95, p=.05) (see Figure 16). In post-hoc t-tests, the effect of Affect was significant for the spatial task (t(23) = 3.04, p<.007) but not the verbal task (t(23) = 0.56, p=.5).

Reaction time (for descriptive statistics see Table 13)

Participants tended to respond slower in Threat as compared to Safety in spatial, but not verbal, n-back tasks (see Figure 17). However, ANOVA interactions involving Task and Affect did not reach significance.

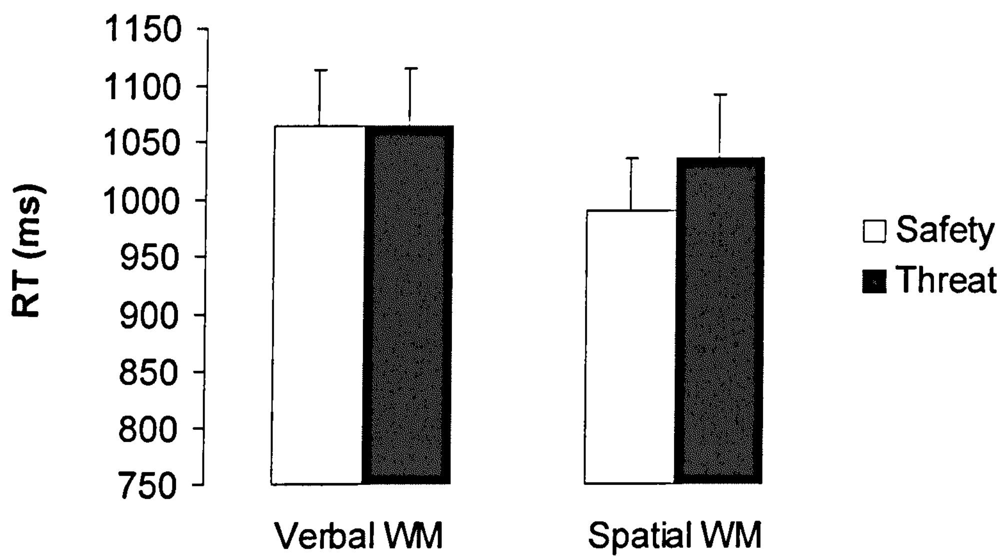


Figure 17. Reaction time in verbal and spatial WM tasks in safety and threat (data from all subjects).

12.4. Discussion

The results clearly indicate a differential effect of threat-evoked anxiety on spatial vs. verbal WM. Performance on spatial, but not verbal, n-back was significantly impaired when participants had higher heart rate and reported being more fearful in conditions of Threat as compared to Safety, which emphasizes the specificity of the effect (see Figure 16). Importantly, similar results were obtained when self-report (adjective scared) or physiological (heart-rate) measures of the difference in anxiety were used as independent continuous variables. Note that accuracy analyses found no significant main effect of Task type, and post-hoc tests revealed no significant differences between verbal and spatial n-back tasks in Safety. This indicates that the verbal and spatial n-back tasks were well matched on difficulty.

The RT findings did not find reliable differences between Threat and Safety (see Figure 17), but they indicated that there was no speed-accuracy trade off in the spatial WM task, i.e. the poorer accuracy during threat was not caused by the tendency to respond faster. The current study used objective, on-line measurement of the induced affect. Participants' heart-rate was higher during Threat as compared to Safety blocks, for both verbal and spatial n-back tasks, as revealed by ANOVA and post-hoc tests (see Figure 15). In conjunction with the self-reported differences on adjectives *scared, anxious, excited* and *aroused* (see Figure 14), it suggests that anxiety was successfully evoked by threat-of-shock for both verbal and spatial tasks, which rules out the potential interpretation of the observed spatial n-back accuracy decrement in terms of selective inhibition of anxiety during the verbal task. Higher heart-rate associated with verbal as compared to spatial n-back in both Affect conditions, indicated by the significant main effect of Task, could be explained by more muscular activity during rehearsal in the verbal task (participants were not discouraged from overtly rehearsing letters).

The current results not only confirm our previous findings (Study 4), but they resolve important methodological issues. Current outcomes rule out the interpretation of the previously observed selective disruption of spatial WM in terms of the effects of electric stimulation, because the current paradigm did not employ shock delivery. The systematic relationship between the increase in heart-rate and self-reported fear and the decrement in spatial n-back performance, revealed by ANOVAs with continuous independent variables and by correlations, is an important novel result, since it provides further validation to the selective character of threat-anxiety effects on spatial WM.

12.5. Conclusions and further questions

Visual attention and executive attention

Study 5 provided further support to the general proposal that specific types of affect are closely associated with certain cognitive mechanisms. Since the latter mechanisms can also be critical for cognitive functioning, this will predictably lead to conflicting demands. The specific case investigated in Studies 3 and 4 was that of the hypothesised overlap between intense anxiety (fear) and spatial WM. Visual attention has been proposed as the focus of overlap. The literature shows that in both normal and sub-clinical populations, the presence of threat leads to an increased (visual) attention to potentially threatening stimuli. At the same time, rehearsal of locations in spatial WM (and, possibly, in the recently postulated episodic WM buffer, Baddeley, 2000) is largely reliant on shifts of visual attention. In contrast, rehearsal in verbal WM seems to be predominantly based on the re-play of sub-vocal motor codes (which are also used during speech). Hence, in the current investigation, it was presumed that the processing of demanding spatial and verbal WM tasks (spatial 3-back task) in a threatening environment would lead to a selective impairment of spatial WM performance. This prediction was fully confirmed.

Nevertheless, there are some important issues, which remain unclear. One of them is the applicability of the term of "attention", used to interpret the present outcomes. In the literature, there are at least two uses of this term. One, more traditional, refers to the ability to filter out the sensory information from the environment, by preferentially processing input from some sensory channels (Duncan, 1980). Since attention in this sense is closely associated with perception, it is also modality-specific (e.g. visual attention), although evidence suggests that information from different modalities can be integrated at early processing stages (e.g. fear conditioning in the amygdala, LeDoux, 1996).

The second, broader use of the term "attention" or "executive attention" or "attentional selection" is used to characterise systems like the Central Executive (Baddeley & Hitch, 1974) or the Supervisory Attentional System (Norman & Shallice, 1986). Such systems are thought to serve as on-line super-ordinate decision-making instances, receiving information about the needs of the organism, as well information about the means for satisfying those needs. The term "attention" in this context refers to the limited on-line capacity of such systems.

The literature on attention to threat in anxiety and studies of attentional shifts in spatial WM refer to the first use of the term "attention". Consequently, our investigation also refers to this use, as indicated earlier by the expressions "visual attention" or "visuo-spatial attention". However, there may be intimate links between visuo-spatial and "executive" attention. Both involve prioritisation of information, be it sensory information or goals and motor programs. In other words, visuo-spatial attention can also be seen as an executive-attentional system. Not surprisingly, the brain regions associated with the two constructs also largely overlap (e.g. the dlPFC, the anterior cingulate cortex). It is not clear yet precisely how visuo-spatial attention is related to "executive attention" or "executive control". If the two are relatively distinct, this would mean that spatial WM has its own pool of executive-attentional resources, represented by visuo-spatial attention. This would further be consistent with the proposal by some authors that executive attention is not completely centralised (as the Central Executive is) and is at least in part distributed. In relation to our results, this could imply that components of WM, e.g. verbal and spatial WM, rely on relatively segregated executive/attentional resources, of which some are affected by threat-induced anxiety (fear) and some are not.

Alternatively, it is possible that executive/attentional resources are strictly centralised, as is Baddeley and colleagues' Central Executive (Baddeley, 1986; Baddeley & Hitch, 1974), with an asymmetry in the involvement of executive-attentional resources in verbal vs. spatial WM, the former (the phonological loop) being less reliant on such resources. Indeed, it has already been mentioned that rehearsal in spatial WM has been difficult to conceptualise within the original WM model. At least in part, the difficulty seems to arise from the properties of the sensory input that is fed into verbal and spatial WM. Auditory information is serial and can only be integrated over time. Speech is also represented as auditory codes, hence, it is also serial. In contrast, visual information is processed largely in parallel, with some, but possibly less stringent, need for temporal integration. Therefore, it conceivable that verbal WM, which is closely associated with auditory perception and speech, is better equipped for retaining serial order than spatial (and visual/object) WM. This is an advantage in most WM tasks, because the latter (some item recognition tasks and especially n-back tasks) require memory for serial order. This argument predicts that spatial and visual/object WM tasks should be more difficult than verbal WM tasks when the tasks require memory for serial order. There is evidence in support of this prediction. Nystrom et al. (2000) have directly compared n-back visual/object WM tasks with verbal WM tasks, as well as spatial WM tasks with verbal WM tasks. When the value of n was the same for the compared tasks (e.g. 2-back spatial vs. 2-back verbal task), the spatial and the visual/object tasks were associated with considerably lower performance than the verbal n-back task. Furthermore, in order to match the tasks on difficulty the authors switched to a 3-back in the verbal task, which was then compared to a 2-back visual/object WM task. Our pilot work with n-back tasks contains similar suggestions. Pilot 3 found that the change from a 2-back to a 3-back affected spatial WM performance more than it affected verbal WM performance and additional modifications of the verbal n-back task were needed for equating the performance levels (Pilot 4).

The above considerations together with the results from Studies 3 and 4 can be seen as indicating an asymmetry in the reliance of verbal and spatial WM on executive/attentional resources. At a close examination, however, it could still be argued that there may be different kinds of attentional mechanisms involved in the two WM components. Therefore, the present results regarding the selective effects of anxiety (fear) on spatial WM, explained in terms of overlap in visual attention, cannot be readily used for broader generalisations. It is possible that the effects of anxiety on visual attention would not generalise to the broader construct of executive attention. In order to examine this, one would need to investigate the effects of anxiety states, which are not circumscribed to a specific threatening stimulus, e.g. test-anxiety.

Test anxiety and trait anxiety

The use of test-anxiety may also help answer another important question, regarding the affect used in Studies 3 and 4. It is unclear whether the effect of intense, circumscribed threat can be generalised to anxiety states, which are less acute and which are not associated with a specific threatening stimulus or event. The studies that directly compared the effects of test-anxiety on verbal and spatial WM performance seemed to find that, in contrast to our findings of selective spatial WM disruption by threat-of-shock anxiety, test-anxiety impairs predominantly verbal WM performance (Ikeda et al., 1996; Lee, 1999). There is a theory that could reconcile these divergences.

The model by Heller and colleagues (Heller & Nitschke, 1998; Heller et al., 1995) makes a distinction between *anxious apprehension* (i.e. worry) and *anxious arousal* (i.e. panic). The two types of anxiety, though not mutually exclusive, are proposed to engage different cognitive processes (e.g. *anxious apprehension* is associated with verbal ruminations), different physiological characteristics (e.g. *anxious arousal* is associated with physiological hyper-arousal and somatic tension), and involve distinct patterns of brain activity, i.e. greater left-frontal activity in *anxious apprehension* and greater right-parietal activity in *anxious arousal*. It seems that test-anxiety would more closely match *anxious apprehension*, whereas threat-of-shock anxiety elicited in the current study would be an instance of *anxious arousal*, as confirmed by our physiological recordings. If anxiety types, described in the terms of the Heller and colleagues, have differential effects on WM, this could explain the differences in the effects of threat-of-shock anxiety on WM (predominantly spatial deficits) vs. test-anxiety on WM (predominantly verbal deficits). Threat-of-shock (anxious arousal) may have more impact on the Central Executive, whereas test-anxiety (anxious apprehension) may affect more the phonological loop. However Eysenck and Calvo (1992) and other authors (Darke, 1988) stressed that test-anxiety has a strong effect on both the Central Executive and the phonological loop, based on studies of verbal tasks thought to involve both of these WM components. Furthermore, Eysenck and Calvo's *processing efficiency* theory of trait- and test-anxiety proposes that the effects on the Central Executive are particularly strong. It is difficult to reach a conclusion based on these considerations. Therefore, it would appear useful to examine the effects of trait- and test-anxiety on the same verbal and spatial WM tasks that showed differential sensitivity to threat-of-shock anxiety (fear). This was one of the objectives of the investigations described in Part IV.

Anxiety, WM and interhemispheric asymmetries

So far, we have not discussed the potential neuroanatomical correlates of the effect observed in Studies 3 and 4. It would be tempting to hypothesize (Bartolic et al., 1999; Gray, 2001) that the functional anatomy underlying this effect is interpretable in terms of prefrontal (Davidson, 1992) or parietal (Heller & Nitschke, 1998) interhemispheric asymmetries, with more left-hemispheric activity associated with approach emotions and more right-hemispheric activity associated with withdrawal emotions. Indeed, evidence from recordings of brain electrical activity have associated *anxious arousal* with greater right-parietal activity (Heller & Nitschke, 1998) and some neuroimaging studies found greater right-prefrontal cortex (PFC) activity in anxious arousal (Rauch et al., 1997). Furthermore, there is substantial evidence that attention is right-lateralised in the prefrontal and parietal areas (see Cabeza & Nyberg, 2000, for a review) and that there is some tendency of right-lateralisation in spatial WM tasks in roughly the same cortical regions (Awh et al., 1999; Reuter-Lorenz et al., 2000; Smith et al., 1998).

However, other neuroimaging evidence suggests that caution is needed in drawing such conclusions. A recent study of threat-of shock anxiety found not right-, but left-lateralised activation in the (orbitofrontal) PFC (Chua et al., 1999). It could be objected, though, that the model of prefrontal asymmetry in emotion (Davidson, 1992, 1995) refers to the dorso-lateral (dl) and not orbitofrontal territories in the PFC. Davidson and colleagues have argued that in order to reveal asymmetric activity of brain hemispheres, direct statistical comparisons of homologous areas in the two hemispheres are needed and such comparisons should not be limited to the brain areas where main effects where found (Davidson & Irwin, 1999). Since these requirements were not fulfilled by Chua et al.'s (1999) study, it could be argued that their study failed to detect the asymmetry in the dlPFC.

On the other hand, it is not clear whether the PFC division, central to Davidson's model (dlPFC) shows asymmetry in WM tasks. Although for some PFC regions (Broca's area, suplimentary motor areas) such asymmetry is relatively well-established (see Chapter 1), these areas lie outside the dorso-lateral (dl) part of PFC (see Fig. 1, Chapter 1). The activation of dlPFC in WM tasks was sometimes lateralised and sometimes bilateral (see Cabeza & Nyberg, 2000, for a review). Importantly, direct left-right comparisons, as suggested by Davidson and co-workers (Davidson & Irwin, 1999) were almost never performed. This is especially so with regard to n-back tasks. The second study described in Part IV will address this issue, by performing direct left hemisphere-right hemisphere comparisons of dlPFC activity in the 3-back tasks investigated in Part III.

PART IV. THREAT AND SPATIAL WM: THE GENERALITY OF THE EFFECT AND ITS NEUROANATOMICAL CORRELATES

Chapter 13. Study 6: Test-anxiety, trait anxiety and performance on verbal and spatial 3-back WM tasks

13.1. Introduction

The model of the influence of anxiety on cognitive performance proposed by Eysenck and Calvo (1992, see also Chapter 1) is probably the most elaborated account of the effects of trait- and test-anxiety on tasks involving WM processing. It was built on earlier theoretical contributions concerning the impact of anxiety on cognitive processing. The model incorporates a key proposal by Liebert and Morris (1967) that anxiety impairs cognitive performance, because anxiety-related ideation (i.e. worry) interferes with attention to task-relevant information. Furthermore, the model by Eysenck and Calvo also incorporates the valuable suggestion by Humphreys and Revelle (1984), see also Revelle (1987), that anxiety is more likely to impair tasks which have increased short-term memory demands.

One of the original aspects of Eysenk and Calvo's framework is represented by their attempts to include in the model dynamic aspects of the control of resources allocated to the cognitive task. For example, although anxious rumination (worry) depletes the resources allocated to cognitive processing, a motivational mechanism triggers the allocation of additional resources to the cognitive task, so that the absolute amount of resources given to the cognitive task is restored. A likely consequence is that, although there is effectively the same amount of resources available for the task in the presence vs. the absence of test-anxiety, the total resources used during the task, including resources occupied by worry, are larger in conditions of test-anxiety. Hence, efficiency of processing is lower in anxiety. In order to emphasise the distinction between effectiveness and efficiency in test-anxiety Eysenck and Calvo termed their framework the *processing efficiency* theory (Eysenck & Calvo, 1992). The processing efficiency aspect of the model makes several interesting predictions.

Firstly, it predicts that only difficult tasks will be impaired in conditions of test-anxiety and tasks of moderate difficulty will not be affected. In tasks of low to moderate difficulty the system (e.g. WM) should have enough capacity to compensate for the resource depletion caused by anxiety. There is substantial evidence showing that test-anxiety affects primarily high-difficulty tasks (Eysenck & Calvo, 1992). Secondly, processing efficiency predicts that the effects of anxiety should be most evident when the level of difficulty in a particular task is increased, or a concurrent task is inserted. Both predictions are well supported by data (Calvo & Alamo, 1987; Eysenck, 1989).

As mentioned above, the applicability of the model by Eysenck and Calvo to WM processing largely stems from the ideas of Humphreys and Revelle (1984), i.e. anxiety primarily affects short-term memory processes, and of Liebert and Morris (1967), i.e. worry interferes with attention to the task. However, Eysenck and Calvo went on further to examine the effects of test-anxiety on components of WM (Baddeley, 1986; Baddeley & Hitch, 1974). The authors of the processing efficiency theory reviewed a significant corpus of studies that employed tasks taxing WM and concluded that test-anxiety disrupts the Central Executive and, to some extent, the phonological loop component of WM. Tasks thought to require executive processes show a larger performance drop in conditions of trait/test-anxiety than tasks that do not make large executive demands (e.g. digit span) (Darke, 1988).

However, most of the studies which served as empirical ground for the processing efficiency theory employed verbal tasks, which invariably depended on the phonological loop. In contrast the executive/attentional dimension was varied: verbal tasks with executive demands were more affected than verbal tasks requiring storage only. Consequently, the model may underestimate the influence of test-anxiety on the phonological loop. The few studies that directly compared the effects of test-anxiety on tasks that do vs. do not rely on the phonological loop, i.e. verbal and spatial WM processes, found that the verbal tasks were more disrupted (Ikeda et al., 1996; Lee, 1999; Markham & Darke, 1991). Although these authors did not rule out the effects of trait/test-anxiety on executive processes in WM, they stress the verbal character of anxious ruminations. For example, Markham & Darke (1991) concluded that "anxiety acts as a secondary task, interfering with those verbal tasks that make heavy demands on working memory" (p. 107). This is somewhat inconsistent with the processing efficiency theory assumption that central, modality-independent executive resources are the most affected by trait/test-anxiety. Nevertheless, it must be noted that the verbal and spatial WM tasks employed by these authors (Ikeda et al., 1996; Lee, 1999; Markham & Darke, 1991) suffered from some limitations. Firstly, the tasks were complex (e.g. verbal reasoning), consisting of many cognitive processes, and it is not clear how well they isolated WM functioning. Secondly, the tasks were not matched for stimulus material and difficulty.

The present study employs the verbal and spatial 3-back WM tasks, developed in Study 3 (pilot work) and used in conditions of threat-of-shock in Studies 4 and 5. It aims to measure performance on these tasks in conditions of high vs. low trait-anxiety, in order to test two main sets of predictions. Firstly, trait-anxiety is not circumscribed to specific stimuli, and, hence, would not be expected to trigger an orienting response and engage visuo-spatial attention. It has an impact on attention at the level of behavioural priorities, i.e. at the executive level. Therefore, if the attentional resources used by spatial WM are of central and executive nature, it would be expected that trait-anxiety would selectively impair spatial WM performance, just as threat-of-shock did in Studies 4 and 5. Conversely, equal disruption of verbal and spatial WM, or more verbal WM disruption in trait-anxiety, would suggest that visual-spatial attention and executive attention rely on largely distinct mechanisms and that stimulus-bound anxiety (fear) can be distinguished from fuzzier anxiety states, such as test-anxiety.

Secondly, if, as the processing efficiency framework suggests, trait-anxiety has a greater impact on the Central Executive than on the phonological loop, then verbal and spatial n-back performance should be equally affected. Conversely, if test-anxiety makes substantial storage demands on the phonological loop, and it acts as a secondary verbal task (Markhman & Darke, 1991), then verbal n-back WM performance should be more affected.

In order to ensure significant manifestations of test-anxiety one can pre-select the participants of a study based on their proneness to test-anxiety. A measure of such proneness is the background level of anxiety, operationalised as trait-anxiety. It has been well established that trait-anxiety is a good predictor of test-anxiety and for this reason the contribution of the two is difficult to disentangle (Eysenck & Calvo, 1992). Trait anxiety is a more reliable measure than state-anxiety, since the former reflects a stable characteristic of the personality and its measures are less affected by circumstantial variability. For instance, in the current study participants filled in the trait-anxiety scales twice (at selection and at test), the two being distanced in time by several months. In contrast, state-anxiety scales are only filled in once, at test. Therefore, trait-anxiety measures were viewed as more reliable predictors of test-anxiety relative to state-anxiety measures. Hence, in the present study, participants with a wide range of trait-anxiety scores were pre-selected and subsequently divided in two groups in accordance with their trait-anxiety scores. The two groups were also compared in their levels of pre- and post-test state-anxiety measures. Finally, the main experimental manipulation was to compare the low and high trait-anxiety groups in terms of verbal and spatial n-back WM performance.

13.2. Method

Participants

Potential participants were selected from a pool of 3479 students, who completed personality questionnaires at the University of Wisconsin-Madison (USA). The selection criteria were the scores on the BIS/BAS scales (Behavioral Inhibition and Behavioral Activation Scales, Carver & White, 1994). After screening of 3479 individuals, participants with high BIS (upper 30%) and low BAS (lower 30%) scores and those with the reversed profile were invited to participate in an EEG experiment and 66 of them agreed to do so, receiving course credits for their participation.

The BIS/BAS personality scales were specifically designed to measure two fundamental personality dimensions, proposed by Gray (1982): *anxiety* and *impulsivity*. Gray (1982, 1994) further proposed that the two personality dimensions reflect the functioning of two relatively distinct neurological systems. BIS/BAS scores show high correlations with other measures of trait-anxiety, e.g. STAI (the State-Trait-Anxiety-Inventory, Spielberger, 1983). In the current sample the correlation between STAI-trait and BIS (Behavioral Inhibition Scale) was 0.70, $p<.0001$ and the correlation between STAI-trait and BAS (Behavioral Activation Scale) was -0.72, $p<.0001$.

Eight participants had to be discarded from the analysis for the following reasons. Three participants' data showed that they did not understand the requirements of the n-back tasks. Five participants performed at chance (accuracy below 55% in either the verbal or the spatial n-back task). The remaining 58 participants (29 females, 29 males), mean age 19.85, sd 1.96, range 19-26) entered the analysis.

Apparatus

A Pentium 100 MHz PC was used for task presentation and collection of behavioural data (accuracy and RT).

Procedure

Verbal and spatial 3-back WM tasks (see Part II, Studies 3, 4 and 5) were administered in the second half of an EEG experiment. Participants performed one practice and two test blocks for each task (verbal and spatial). The order of the verbal and spatial tasks was counterbalanced across participants. All WM blocks (practice and test, verbal and spatial) contained the same number of trials: 79, leaving 76 responses per WM block (in the 3-back the first 3 trials are no-response trials).

Trait and test-anxiety measures

Two measures of anxiety were employed. Firstly, the BIS/BAS scales were administered several months before the study and potentials participants were pre-selected into the following two groups:

- highBIS/lowBAS (upper 30% on the BIS scale and lower 30% on the BAS scale)
- lowBIS/highBAS (lower 30% on the BIS scale and upper 30% on the BAS scale)

Only individuals from the pre-selected two groups were proposed to participate in the study. Immediately prior to the experimental session, participants' scores on the BIS/BAS scales were collected for the second time. Individuals whose original BIS/BAS profile was confirmed (43 out 58 participants) were selected in the two study groups: highBIS/lowBAS (22 participants) and lowBIS/highBAS (21 participants). The two groups were compared on WM performance measures (accuracy and RT). In addition, correlations between WM performance and BIS/BAS scores were computed.

The State-Trait-Anxiety-Inventory (STAI; Spielberger, 1983) was used as the second measure of anxiety. Participants were screened for trait anxiety several months before the experiment, as well as immediately prior to the start of the experiment. The 58-participant sample was divided by median split in accordance with trait anxiety scores (highSTAI-trait and lowSTAI-trait).

State-anxiety was measured by administering STAI-state before the beginning of the experimental session (pre-test anxiety) and immediately after the session (post-test anxiety).

WM performance

As in the previous studies, WM performance was measured as the absolute number of correct responses (accuracy) and the average reaction time (RT) for correct responses.

Data analysis

State-anxiety

Independent samples *t*-tests were used to compare the highBIS/lowBAS and lowBIS/highBAS groups, as well as the highSTAI-trait and lowSTAI-trait, in both measures of STAI-state anxiety (pre- and post-test STAI-state scores).

WM perfromance

Two ANOVAs were run as follows (with both accuracy and RT data):

1. WM verbal vs. spatial (within subjects factor) X GROUP highBIS/lowBAS vs lowBIS/highBAS (between subjects factor) X GENDER (between subjects factor).

2. WM verbal vs. spatial (within subjects factor) X GROUP highSTAI-trait and lowSTAI-trait (between subjects factor) X GENDER (between subjects factor).

Correlations (Pearson's *r*) were computed between measures of anxiety (the STAI-trait, STAI-state and BIS scales) and WM performance measures (accuracy and RT). The pre- and post-test STAI-state scores were averaged together prior to computing the correlations.

Holm's Bonferroni procedure was used to control for α–inflation in multiple *t*-tests and correlations. Unless noted otherwise, only corrected *p*-values are reported.

13.3. Results

Test-anxiety (see Table 14 and Fig. 18)

The *t*-tests comparing pre-test and post-test STAI-state scores were all highly significant, with more state-anxiety reported by the high-trait anxiety group:

- highBIS/lowBAS vs. lowBIS/highBAS: pre-test $t(41) = 4.39$, $p<.001$; post-test $t(41) = 2.73$, $p<.01$;

- highSTAI-trait vs. lowSTAI-trait: pre-test $t(56) = 4.98$, $p<.001$; post-test $t(56) = 3.47$, $p<.001$.

Table 14. Means and standard deviations for test-anxiety (STAI-state), accuracy and reaction time.

			Groups			
			BIS/BAS		STAI	
			low anxiety	high anxiety	low anxiety	high anxiety
Accuracy (%)	Verbal WM	Mean	83.17	78.76	81.20	76.26
		SD	8.75	12.00	10.54	11.28
	Spatial WM	Mean	84.55	77.00	80.99	75.93
		SD	8.54	11.57	10.70	10.50
RT (ms)	Verbal WM	Mean	1069.45	1022.31	1120.94	1069.45
		SD	167.55	211.79	205.84	167.55
	Spatial WM	Mean	973.73	935.23	1031.81	973.73
		SD	188.73	212.38	229.71	188.73
STAI-state	STAI Pre	Mean	39.91	51.97	40.47	51.95
		SD	9.00	9.03	9.83	7.57
	STAI Post	Mean	41.67	50.24	42.05	51.41
		SD	10.71	9.86	11.18	9.22

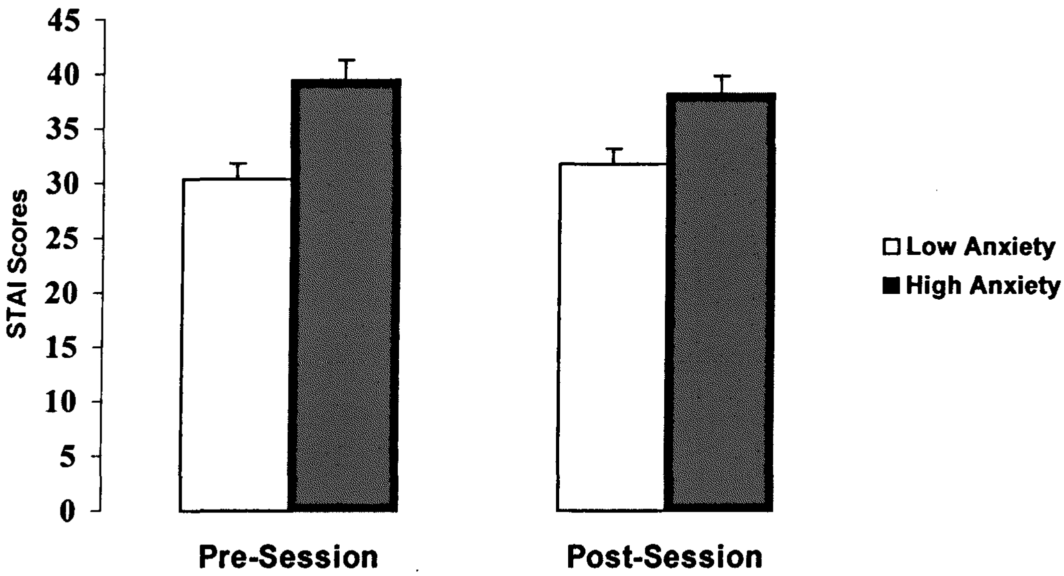


Figure 18. Test-anxiety scores comparing the groups preselected according to the trait-anxiety profile.

WM performance

Accuracy (see Table 14 and Fig. 19)

Both accuracy ANOVAs revealed a significant main effect of GROUP, with better WM accuracy in the low trait-anxiety group:

1. highBIS/lowBAS and lowBIS/highBAS as levels in factor GROUP: F (1,39) = 4.60, p<.04.

2. highSTAI-trait and lowSTAI-trait as levels in factor GROUP: F (1,54) = 5.11, p<.03.

No other main effects or interactions approached significance.

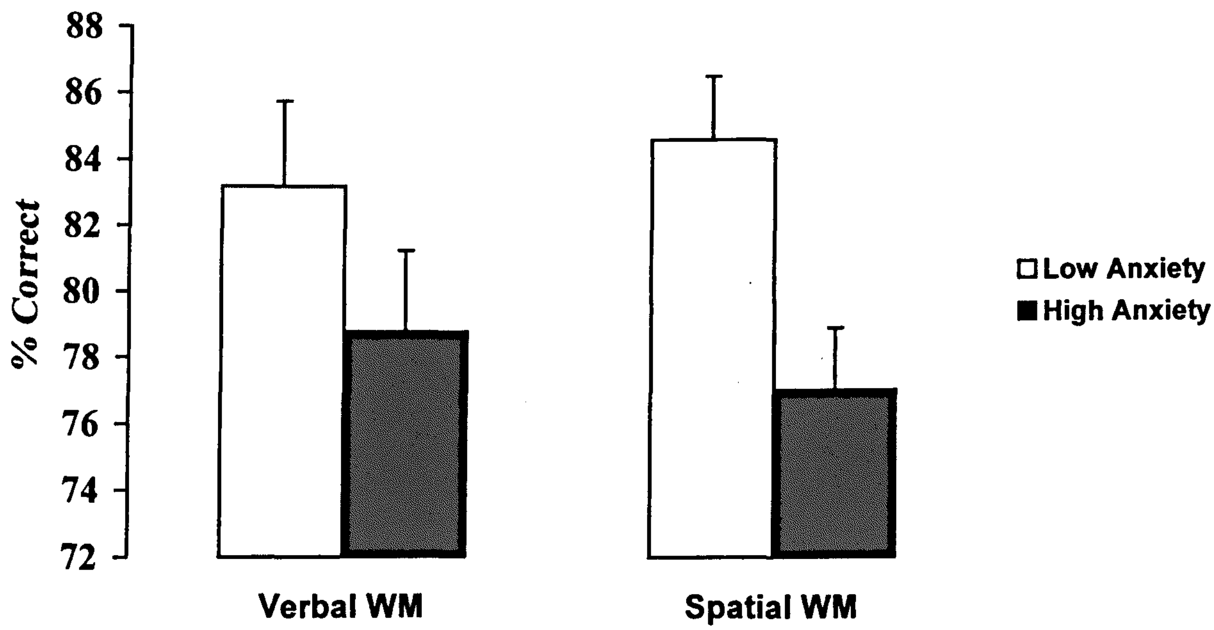


Figure 19. Accuracy in high- vs low-trait anxiety participants (BIS/BAS selection).

RT (see Table 14 and Fig. 20)

Similar results were obtained in the RT analysis.

The ANOVA with highBIS/lowBAS and lowBIS/highBAS as levels in factor GROUP found a marginally non-significant main effect of GROUP ($F(1,39) = 3.31$, $p<.075$), with faster responses in the low-anxiety group. It also revealed a significant main effect of WM, with shorter RTs in the spatial WM task: $F(1,39) = 8.01$, $p<.01$.

The RT ANOVA with highSTAI-trait and lowSTAI-trait as levels in factor GROUP also found a significant main effect of GROUP ($F(1,54) = 5.24$, $p<.03$), with faster responses in the low-anxiety group. In addition, this ANOVA revealed a significant main effect of WM, with shorter RTs in the spatial WM task: $F(1,54) = 12.91$, $p<.005$.

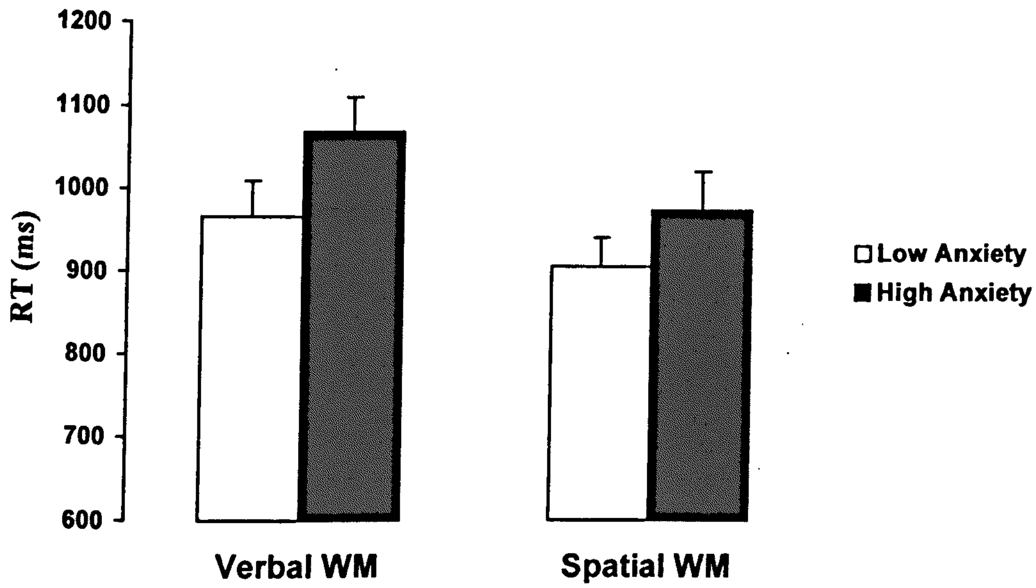


Figure 20. Reaction time in high- vs. low-trait anxiety participants (BIS/BAS selection).

Correlations

Two correlations were significant before the control for α–inflation was applied:

RT (verbal WM) X BIS scores: $r(58) = .30$, $p<.025$

RT (spatial WM) X BIS scores: $r(58) = .28$, $p<.04$

These correlations failed to reach significance when control for α–inflation in multiple correlations was applied.

13.4. Discussion

The results revealed important differences between the two groups of participants, in both test-anxiety and WM performance. As expected, the low-trait anxiety group reported significantly lower levels of test-anxiety, as compared to the high trait-anxiety group, both prior and following the experimental session (as shown by differences in state STAI scores, see also Table 14 and Fig. 18).

Both measures of WM performance, accuracy and reaction time, revealed a better WM performance of the low trait-anxiety group, as compared to the high trait-anxiety group, as indicated by the main effect of GROUP in both analyses. The verbal and spatial n-back tasks were equally impaired, as revealed by the lack of interactions in the ANOVAs (see also Table 14 and Figures 19 and 20).

Importantly, virtually the same results were obtained for the groups selected according to two measures of trait-anxiety (the BIS/BAS scales and the STAI-trait scale), which emphasises the reliability of the outcomes. Some additional support for the relationship between anxiety and WM performance was provided by the pattern of BIS X RT correlations, which were significant when not controlled for multiple tests.

With regard to the two lines of predictions discussed in the introduction, the findings appear to suggest the following. An important result is that test-anxiety does not mimic threat-evoked anxiety in its effects on WM, in particular the selectivity of the latter. Unlike threat-of shock anxiety, test-anxiety seems to be equally detrimental for verbal and spatial WM processing. This is inconsistent with previous reports of predominant verbal WM deficits in conditions of test-anxiety (Ikeda et al., 1996; Lee; 1999; Markham & Darke, 1991). However, as mentioned above, the verbal and spatial tasks used in these studies contained complex demands in addition to WM and it is not clear how well verbal and spatial tasks were matched for stimulus material and difficulty. The present study employed verbal and spatial task using identical stimuli and only differing in their instructions. They are well matched on difficulty, as indicated by equivalent levels of accuracy in Pilot 4 (Study 2), as well as Studies 3, 4 and the current study. Therefore, with regard to the first line of predictions, the present results suggest that visuo-spatial attention affected by threat-of-shock and attention (most probably of an executive nature) depleted by test-anxiety are supported by largely distinct mechanisms. Although this may have important implications (e.g. that arousal and the orienting response are not characteristic for all anxiety states), further investigations would have to elucidate this matter.

The difference between the effects of threat-evoked and test-anxiety also provides some support for the distinction made by Heller and colleagues (Heller & Nitschke, 1998; Heller et al., 1995) between anxious apprehension and anxious arousal. However, the distinction that the current data support is not that anxious apprehension, associated with worry, disrupts predominantly the phonological loop, while anxious arousal depletes executive/attentional resources. Rather, it appears that anxious apprehension and arousal both appear to affect attentional mechanisms, but that these attentional mechanisms are relatively distinct. This conclusion is relevant in the context of the second line of predictions (see Introduction). The finding of trait- and test-anxiety being associated with a generalised, unspecific WM disruption is consistent with one of the central claims of Eysenck and Calvo's (1992) processing efficiency theory that trait- and test- anxiety affect primarily the Central Executive component of WM (Baddeley, 1986; Baddeley and Hitch, 1974), and, to a lesser extent, the slave WM systems. Consequently, there is little support in the current data that anxiety acts as a "secondary" WM task (Markham & Darke, 1991) and has a prominent effect on the phonological loop.

Nevertheless, one must also consider an alternative interpretation of the present results. If, as discussed ealier, visuo-spatial attention and executive attention are equivalent, then one would have predicted selective disruption of spatial n-back performance (as with threat-induced anxiety). Although this was not observed in the current study, there is a possibility that there was such an effect, but that it was masked by the effect of a worry-component of trait anxiety, which had a selective effect on verbal n-back performance. In other words, it is conceivable that what appears as a non-specific effect of trait anxiety on n-back performance could be a sum of two specific effects, triggered by distincy elements of trait anxiety.

The problem with this account is that it lacks a basis for predicting a selective effect of trait-anxiety on visuo-spatial attention. The current paradigm did not contain any suggestions to any threatening stimuli or events. One could further assume that highly anxious participants operate in a high-vigilance mode that would be demanding on visual attention. However, this would predict faster reaction times in high-anxiety participants, quite the opposite of what was found.

In conclusion, the present results, considered together with the outcomes from Studies 4 and 5, suggest that different types of anxiety all influence WM processing at the level of attentional resources. However, it also appears that attentional mechanisms are fractionated. Furthermore, specific anxiety states appear to be associated with specific attentional mechanisms.

Chapter 14. Study 7: Neuroanatomical correlates of verbal and spatial 3-back WM tasks

14.1. Introduction

Models of prefrontal asymmetry in emotion

There have been attempts to explain the differential effects of mood on verbal and spatial WM performance in terms of neuroanatomical overlap between brain regions involved in WM and affective processing (Gray, 2001). The particular neuroanatomical model of emotion that appealed to Gray was the most influential model of inter-hemispheric asymmetry in emotion by Davidson and colleagues (Davidson, 1995, 1998; Sobotka et al, 1992). The model is based on the dichotomy between emotions that trigger approach behaviours and emotions that cause withdrawal behaviours (Davidson, 1992). With respect to the emotions involved, this dichotomy does not completely overlap with the conceptualisation of emotions as positive vs. negative. For example, while fear, a negative emotion, would be seen as a withdrawal emotion, anger, also a negative emotion, has both approach and withdrawal aspects. Similarly, positive emotions are not necessarily approach emotions. For instance, states of satiation, which can be qualified as positive, do not necessarily stimulate approach behaviours. In addition to the distinction between approach and withdrawal emotions (or affective states), the model by Davidson and colleagues was also largely inspired by a substantial corpus of psychophysiological (EEG) studies which found asymmetric frontal activity associated with affective states, traits and disorders (Davidson, 1995; Davidson et al., 1990; Henriques &

Davidson, 1997; Sobotka et al., 1992). These studies consistently showed that approach states are associated with less left frontal than right frontal power in the EEG alpha band (8-13 Hz), with the withdrawal states showing the opposite pattern. Since power in the EEG alpha band is inversely related to neuronal activity, these EEG results suggest that approach affect is associated with more left frontal than right frontal neuronal activity, whereas withdrawal affect, conversely, is associated with more right frontal than left frontal activity (Davidson, 1995). Importantly, frontal inter-hemispheric activity associated with the two types of affect, is conceptualised in relative terms. The model does not predict, for instance, that approach emotion is associated with left frontal activation exclusively, or that left frontal region is the principal brain region involved in the generation and maintenance of approach-related emotion.

The EEG studies above did not employ source-localisation procedures. Furthermore, unlike ERPs, EEG does not contain information about specific waveform deflections, whose anatomical origins are sometimes known (i.e. ERP waveform components). Hence, EEG studies could only provide very coarse approximations of the anatomical coordinates of the recorded neuronal activity, recorded from the scalp. However, further neuropsychological evidence and especially neuroimaging studies have provided more precise indications on the anatomy of the observed EEG asymmetries. Data from patients with damage of the dorsolateral PFC (dlPFC) showed that individuals with left PFC damage were more likely to subsequently develop depression, compared to individuals with damage to the right dlPFC (Morris et al., 1996).

There were also neuroimaging studies which revealed patterns of dlPFC activation consistent with the predictions of the model by Davidson and colleagues. For instance, an fMRI study by Sutton et al. (1997) found asymmetric PFC activation in response to affectively-laden pictures, in the direction predicted by the model. Another neuroimaging study which pooled data from several types of anxiety disorders (Rauch et al., 1997) also revealed asymmetric, right-lateralised, dlPFC activity associated with anxiety (phobia). However, many neuroimaging studies failed to discover asymmetric PFC activation associated with emotional states that can be qualified as approach or withdrawal-related. A meta-analysis of neuroimaging data from a large number of studies, performed in relation to inter-hemispheric frontal asymmetries in emotion (Lawrence & Murphy et al., 2001) found only limited support for Davidson and co-workers' model: positive, but not negative, emotional states were associated with asymmetric frontal activity in this meta-analysis. Furthermore, a neuroimaging study of threat-of-shock anxiety (the procedure we used in Studies 4 and 5) found lateralised activity in one PFC region, but in the opposite direction to the one predicted by Davidson and co-workers (Chua et al., 1999). Chua et al. found left-lateralised, and not right-lateralised PFC activation predicted by the model, though it has to be noted that the PFC region from this study is not part of the dlPFC. In a review of the neuroimaging literature of emotion, Davidson and Irwin (1999) provided a methodological reason for the failure of neuroimaging studies to discover dlPFC asymmetries. The authors argued that direct statistical comparisons between hemispheres are needed and few if any studies have performed them. Furthermore, it was also proposed that reliable asymmetries can be present even in the absence of the main effect in a particular brain region (in this case, dlPFC). Consequently, statistical tests of Emotion by Hemisphere, or Emotion by Brain Region by Hemisphere need to be run even in the absence of the main effect of Emotion. The latter is very rarely done. Furthermore, Davidson and Irwin argued that neuroimaging studies that fulfil these requirements (e.g. Sutton et al., 1997) do find dlPFC asymmetry associated with approach vs. withdrawal emotion.

Gray (2001) employed 2-back verbal and spatial WM tasks, observed to reliably activate the PFC (as mentioned earlier, Gray's tasks served as a basis for our 3-back WM tasks). The investigator induced positive and negative mood by means of film clips and found that spatial WM was more disrupted by positive mood than by negative mood, whereas verbal WM performance was more disrupted by negative mood than by positive mood. Gray explained the results in terms of the dlPFC asymmetry model by Davidson and colleagues, taken in conjunction with the evidence of asymmetric activation of the PFC in WM tasks. Evidence of some PFC asymmetries associated with verbal vs. spatial WM processing indeed exists, as discussed in Chapter 1. However, reliable lateralisation has only been found in areas situated outside dlPFC (e.g. Broca's area, BA 44, in verbal WM, Cabeza & Nyberg, 2000; Smith et al., 1998). Furthermore, as it will be shown below, imaging studies employing n-back tasks tend to find bilateral activation in verbal and spatial versions of the task (Cabeza & Nyberg, 2000; Smith & Jonides, 1999).

The present study applies fMRI to investigate dlPFC activation in the verbal and spatial 3-back tasks from Studies 4, 5 and 6. The study uses the region of interest (ROI) methodology, i.e. it limits the scope of the investigation to one ROI, the dlPFC (BA 9 and 46), bilaterally. More specifically, the aim of the current study is to determine whether the 3-back verbal and spatial WM tasks used in our studies activate dlPFC asymmetrically, i.e. more left than right dlPFC activation in the verbal 3-back task and/or more right than left activation in the spatial 3-back task. The clarification of this issue will provide some factual ground for determining whether asymmetric dlPFC activation can explain the differential effect of threat-of-shock anxiety (fear) on verbal vs. spatial 3-back tasks.

N-back tasks in other neuroimaging studies

Early neuroimaging studies that employed n-back verbal and spatial tasks (Awh et al., 1996) reported left-lateralised activity in the PFC in response to a 2-back letter task (in Broca's area, BA 44, as well as the premotor and suplimentary motor areas, BA 6, see Fig. 1, Chapter 1), but the comparison with an equivalent (i.e. 2-back spatial task) was not made in the same subjects. Instead, the conclusions about lateralisation in verbal and spatial WM were based on comparisons of item-recognition tasks (e.g. Smith et al., 1996). In order to address this limitation, two subsequent neuroimaging (fMRI) studies directly compared verbal and spatial n-back tasks. D'Esposito et al. (1998) used 2-back verbal and spatial tasks, very similar to the ones employed by Awh et al. (1996). The regions where activation was found were almost the same as in Awh et al. (1996), but no reliable laterality was found either in the verbal, or in the spatial task. Similarly, other neuroimaging studies using verbal or spatial n-back tasks separately and employing either PET or fMRI as imaging technologies, also did not find reliable lateralisation in verbal and spatial n-back tasks (e.g. Nystrom et al., 2000, see Cabeza & Nyberg, 2000, for a review). Moreover, some studies even found lateralisation in the opposite direction from the one initially found by Smith and colleagues (Cohen et al., 1997). This led Smith and Jonides to conclude in a recent review that n-back tasks do not show reliable asymmetry, presumably because they involve extensive manipulation of information, in addition to storage (Smith & Jonides, 1999).

However, although D'Esposito et al. (1998) performed direct statistical comparisons between the tasks, by means of subtraction (see Chapter 1), homologous regions in the two hemispheres were not compared directly. A recent study by Nystrom et al. (2000) addressed this issue, by administering n-back verbal and spatial tasks to the same group of participants and directly testing for the main effect as well as the interactions involving the hemisphere factor. The study failed to reveal left-more-than-right activation in any PFC region (including dlPFC) associated with the verbal n-back task or right-more-than-left PFC activation in response to the spatial n-back task. However, the study has been justifiably criticised (Goldman-Rakic, 2000) for failing to match the n-back tasks on difficulty (the verbal task was considerably easier, as indicated by significant verbal vs. spatial WM accuracy differences, Nystrom et al., 2000). Furthermore, the argument first raised by Davidson and Irwin (1999) in relation to neuroimaging studies of emotion, is applicable to Nystrom et al.'s (2000) study, as well as to other neuroimaging studies of WM: these studies only tested laterality in the regions that showed the main effect of WM tasks, and not in other regions as well.

In the present study I chose to directly compare 3-back verbal and spatial WM tasks, which were matched for difficulty. Furthermore, the study proposes to test for effects or interactions involving the hemisphere factor in the a-priori selected ROI (dlPFC), irrespective of the main effect of task.

Methodological considerations

General fMRI methodology

fMRI exposes the brain to a high-strength variable magnetic field and records the electromagnetic response of hydrogen ions to the field variations (Ogawa et al., 1992). The response of hydrogen ions is dependent on their concentration. Therefore, different types of tissue will respond differently structural MRI (anatomical images, insensitive to neural activity) is sensitive to such differences. Furthermore, differential responses would be expected from the same type of tissue, depending on its oxygenation level. Hence, the signal to which functional MRI (fMRI) is sensitive is referred to as Blood Oxygenation Level Dependent (BOLD) signal (Ogawa et al., 1992, 1998). In other words, fMRI reveals the parts of the brain where metabolism is more intense by detecting BOLD changes, because it is well-established that metabolic changes are directly related to the level of oxygen in blood. The further assumption that fMRI also makes is that neurons that are more engaged in a particular psychological process are also more metabolically active. There seems to be a relative consensus with regard to the latter assumption.

The combination of field strength of the magnets used in scanners and the sensitivity of the employed detectors result in the formidable spatial resolution of fMRI, with some of the recent studies claiming to have imaged ocular dominance columns in the visual cortex (Duong et al., 2001). However, the temporal resolution of the technique is rather coarse (of the order of seconds at best) and seems to be mainly constrained by the nature of the recorded process: changes in the BOLD signal follow electrochemical activity in neurons, but they are very slow compared to the latter (electrical responses can last milliseconds, while the BOLD response starts with a delay of several seconds and lasts approximately 16 seconds). Although progress in both understanding the BOLD signal and analytical techniques substantially improved the temporal resolution of fMRI, it is still not better than a second (for a comparison, the resolution of electrophysiological techniques, such as EEG, is thousands of times higher). However, as already mentioned, the spatial resolution of fMRI is superior to that of any other brain-mapping technology. Therefore, in the present study it was decided to employ fMRI in order to probe an anatomical hypothesis: the asymmetry of dlPFC activation in verbal and spatial WM tasks. The current study utilised well-understood and frequently used methods, such as the Echo-Planar Imaging (EPI), the block-design and the method of cognitive subtraction.

Block-designs and event-related designs in fMRI

There are two main types of paradigms employed in cognitive fMRI. Block-designs denote paradigms in which the events (stimuli) are blocked by condition. In contrast, in event-related designs events (stimuli) from different conditions can be intermixed, because the change in the BOLD signal associated with each event is recorded. For example, in an experiment that records the brain activity associated with nouns vs. verbs, the block design would present all the nouns followed by all the verbs (or vice-versa). The same experiment could present the items in a random order, if it chose to employ an event-related design. The latter seems to be more advantageous than the block-design. Blocking of items can lead to strong priming effects (see the well-known example of English past-tense, Seidenberg & Hoeffner, 1998) and habituation.

It would also limit the analysis to only comparisons between the existing groups of items. Event-related designs naturally avoid all these problems items can be intermixed, randomised; items can also be grouped in different ways after the recording is made (since the response to individual items is preserved). However, because of the slowness of the BOLD response, block designs are considerably more reliable in detecting BOLD signal changes and, hence, have considerably more statistical power. Therefore, not surprisingly, whenever priming and habituation are not a concern, the block design is preferred for its simplicity and power. It is still the most widely-used fMRI design. The nature of n-back tasks does not demand event-related designs. Since these tasks require participants to make comparisons across trials, the sequence of trials cannot be interrupted frequently. Hence, there is no need to scan each n-back trial separately. Evidently, it would be interesting to be able to have several scans during the same WM trial (start, middle, end) in order to distinguish between different processes. However, with the current level of fMRI technology a 3-sec trial would be difficult to scan in this way. Moreover, this goes beyond the theoretical question asked in the current study. Consequently, the present study employed a block-design with separate blocks for the verbal and the spatial WM conditions.

N-back baseline

An important issue in neuroimaging paradigms is the isolation of the process of interest. Using the earlier example of the study comparing nouns and verbs, one would not need additional conditions to reveal the difference between nouns and verbs: brain scans associated with nouns would be directly compared to those associated with verbs. However, that would only permit conclusions with regard to the difference in brain activation, it will reveal little about brain activity in response to the processing of nouns or verbs separately. The individual scans in response to nouns and verbs would contain activity attributable to perception and covert/overt motor responses, and it would be very difficult to isolate the activity associated with the process of interest (e.g. semantic processing).

There are two methods used in neuroimaging to circumvent this problem. The simplest method is the *cognitive subtraction* method (Posner et al., 1988) based on the concept of *pure insertion* (Sternberg, 1969, see Chapter 1 for a discussion). Cognitive subtraction paradigms have one or more baseline tasks (conditions), supposed to be similar to the main task (condition) in all respects but one: the process of interest. Therefore, the subtraction of baseline tasks from the main task should remove all activity but the one associated with the process of interest. However, as discussed earlier, the pure insertion assumption has been justifiably criticised and neuroimaging data were provided that questioned cognitive subtraction. The alternative to cognitive subtraction is parametric variation: varying the parameter of interest in a task at several levels, with no distinction between task and baseline. There have been parametric fMRI designs of the n-back task, which used 1-back, 2-back and 3-back tasks (Cohen et al., 1997). Though methodologically sound, such designs can also be associated with problems. For example, in parametric n-back studies a potential problem is the switching between multiple conditions (1-back verbal, 1-back spatial, 2-back verbal, 2-back spatial, etc). Furthermore, the results from parametric and cognitive subtraction paradigms of n-back tasks were very similar. Therefore, it was decided to employ a cognitive subtraction paradigm in the present study.

A further issue is the choice of the n-back baseline. Many neuroimaging studies of n-back tasks employed the 0-back baseline (comparing the item on each trial to a single item presented before the run). While the use of such baseline significantly increases the chance of finding difference in activation, it is conceivable that the item presented before the run is stored in long-term memory. Consequently, the difference between a 0-back and a 3-back may be a qualitative, rather than a quantitative one. Hence, the current study employed 1-back verbal and spatial tasks as baseline tasks for the 3-back tasks. In the 1-back task the item on each trial is compared to the item on the previous trial. The 1-back is closer in its processing demands to the 3-back than the 0-back is. However, the 3-back requires keeping track of more trials at any particular time (at least 3 trials), as compared to the 1-back (at least 1 trial), which can be seen as a difference in the WM load.

14.2. Method

Participants

Ten right-handed (Chapman & Chapman, 1987) individuals (5 females, 5 males, mean age 23.3, sd 1.67, range 22-28), free from psychological or neurological histories, were recruited, in accord with guidelines established by the Institutional Review Board at the University of Wisconsin-Madison Medical School (Madison, USA), and paid $70 for their participation.

Apparatus

A Pentium 100 MHz PC was used for task presentation and collection of behavioural data (accuracy and RT). Stimuli were presented through fiber optic goggles (Avotec, Jensen Beach, FL) suspended from the head-coil. MRI data were acquired on a General Electric (Waukesha, WI) EchoSpeed 1.5 Tesla scanner equipped with high-speed, whole-body gradients and a standard clinical whole-head transmit-receive quadrature birdcage headcoil.

WM tasks

The 3-back tasks developed in Study 3 and employed in Studies 4, 5 and 6 (see Fig. 8, Chapter 10), were also used in the present study. The task was performed in blocks of 34 trials. As in the previous studies, responses were made with the dominant hand. The only difference, compared to the previous studies was the use of control n-back (1-back) tasks, verbal and spatial.

Design

The study involved two sessions. During the first session, participants underwent a simulated experiment using a mock MRI scanner in order to adapt to the MR environment and practice the tasks. Additionally, a dental impression was acquired for the motion-attenuating bite-bar used in the second session. During the second session, participants performed the same tasks in the actual MRI scanner whilst fMRI data were acquired. Data were acquired in two scans, corresponding to the two WM tasks.

Order of presentation was counterbalanced across participants. Both scans were preceded by 4-minute practice blocks during which no functional data were acquired.

The functional scans consisted of seven blocks: four *1*-back blocks, which served as the control task, interleaved with three *3*-back blocks. The beginning of blocks was signaled by a brief cue (4.5 s). Each functional scan was 843 s in duration.

Imaging Parameters

A T2* weighted gradient-echo echo-planar (EPI) pulse sequence (TE/TR = 50/3000 ms, FOV = 24 x 24 cm, a = 90°, matrix = 64 x 64, 23 slices, slice thickness = 7 mm, interslice gap = 1 mm, 276 images per slice, scan time = 14 min 03 sec), customized to employ a Shinnar-LeRoux slice-selective pulse to yield sharper slice-select boundaries, minimizing slice cross-talk, was used to acquire functional data.

Data Processing

Functional image data were reconstructed off-line. Except where otherwise noted, all subsequent processing was performed using the MCW AFNI software suite (Cox, 1996). To minimize the effects of motion, time-series data were realigned to the first image of each scan using an iterative weighted least squares algorithm (Cox & Jesmanowicz, 1999). The resulting volume-registered time series were visually inspected in cine loops for signs of gross head movement using STIMULATE (Cox & Jesmanowicz, 1999). Analyzed functional image data were also examined for signs of the so-called "rim" artifact (Strupp, 1996). A three-parameter (mean, linear trend, and amplitude; 273 degrees of freedom) linear least-squares fit between the MR signal time-series and a hemodynamically-delayed box-car reference function was then computed for each voxel to identify paradigm-correlated MR signal changes (Bandettini et al., 1993), yielding two statistical parametric maps (SPMs), corresponding to the Verbal and Spatial WM tasks, per participant. An isotropic spatial Gaussian filter of 7-mm FWHM (~ 2x the in-plane resolution) was applied prior to statistical analyses (Friston et al., 1997).

Based upon Monte Carlo simulations performed in the same laboratory on "null" datasets (i.e., data with no structured signal changes and noise characteristics similar to those observed in "real" scans), acquired using the same scanner and identical acquisition parameters, a conservative nominal α threshold of $p \leq 10^{-6}$ (t (266) ≥ 3.95) was adopted for thresholding single-participant SPMs. SPMs were placed into normalized stereotactic space (Cox & Hyde, 1997) through a combination of manual land-marking and piecewise linear transformation. Prior to normalization, SPMs were nearest-neighbor interpolated to 1-mm isotropic voxels. Groupwise SPMs were created by squaring and summing the SPMs across participants to create Verbal and SpatiaL WM χ^2 SPMs (Hotteling, 1931). The χ^2 maps were thresholded by requiring individual voxels to exceed $\chi^2 = 35.5$, $p = .0001$, *and* show significant activation ($t \geq 3.95$) at the single-participant level in five or more participants. This is an inferentially transparent and efficient means of reducing unreliable noise sources without specifying a cluster threshold or setting the α threshold to some very high level, two alternative methods that inflate the likelihood of Type II errors. The voxel-wise threshold was thus formally set at $p \leq 1 \times 10^{-15}$ (χ^2 (10) ≥ 93.6).

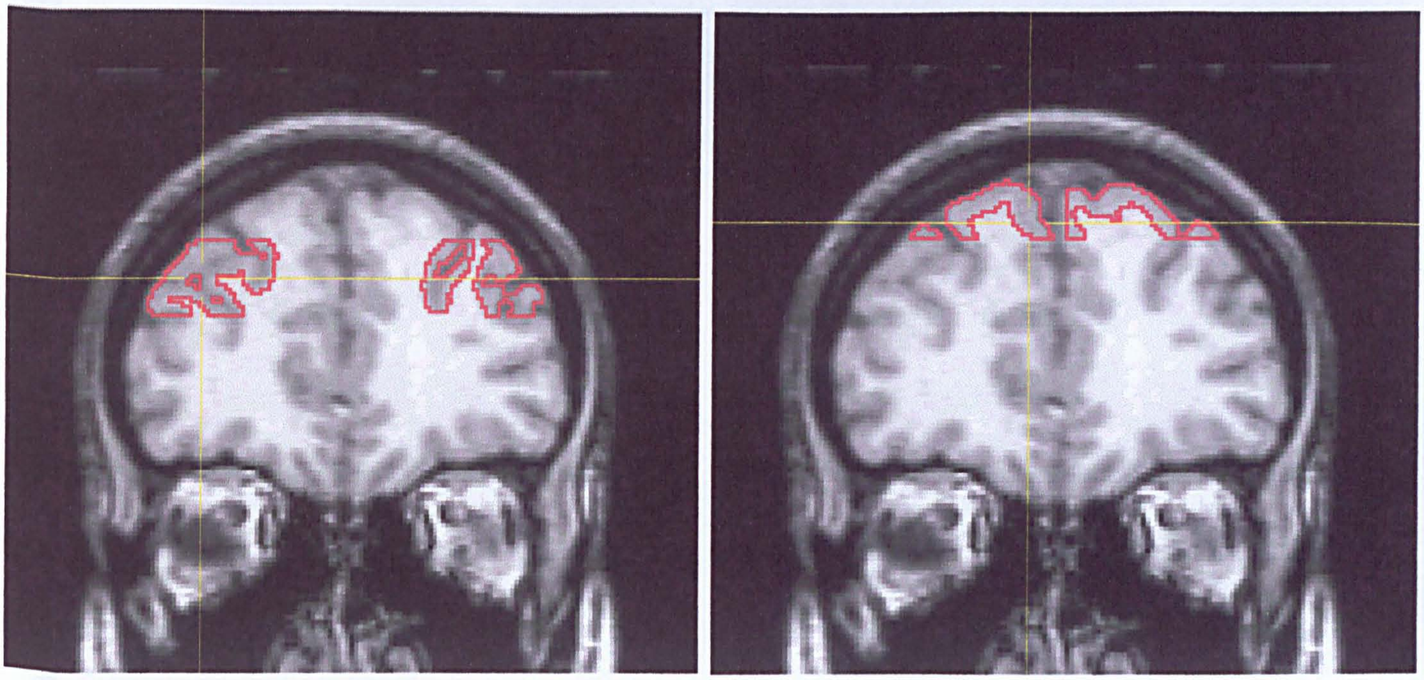


Figure 21. The segmented Regions of Interest (ROIs), circumscribed to two areas of dlPFC: BA 46 and BA 9. Free-hand drawn ROIs are shown here superimposed on coronal (right on the left) slices of a structural MRI scan.

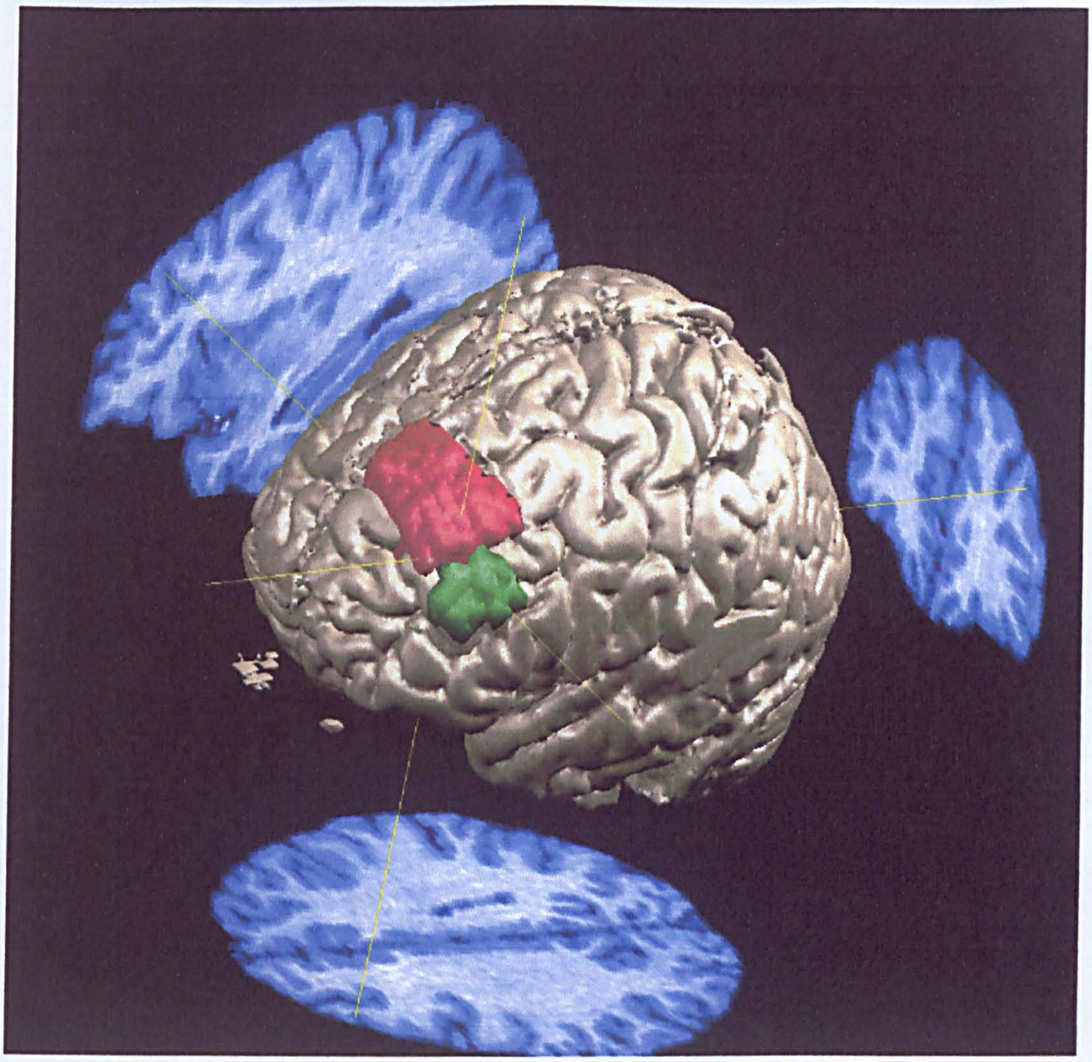


Figure 22. The segmented BA 46 (green) and BA 9 (red) ROIs in 3-dimensional reconstruction.

ROI Analyses

Separate ROIs were constructed for two cytoarchitectonic areas in the dorsal PFC, Brodmann's areas (BAs) 46 and 9, using the probabilistic map of Rajkowska & Goldman-Rakic (1995) digitized to the nearest 1 mm (see Fig. 21). In order to avoid including neighboring regions, we excluded the region 15 mm to either side of the midline for BA 46 and 10 mm to either side of the midline in the posterior (Y axis ≤ 38) portion of BA 9. ROIs were always drawn displayed on the right side of the monitor. Once drawn freehand, the ROIs were segmented using SPAM (http://psyphz.psych.wisc.edu/~oakes/spam/spam_frames.htm) and a T2* histogram-based approach that excluded non-gray matter tissue (see Fig. 22). Data were extracted separately from the single-participant Verbal and Spatial WM SPMs for each ROI in each hemisphere from thresholded ($t \geq 3.95$) and unthresholded ($t > 0$) activation SPMs to permit independent inferences to be drawn about inter-hemispheric asymmetries, if any, characterizing voxels reliably associated with WM performance and voxels that do *not* exhibit a reliable main effect of the WM versus control contrast but *do* exhibit a reliable Task X Hemisphere effect in association with task performance. That is, some voxels may show a significant effect of Hemisphere or Hemisphere X Task in the *absence* of a reliable main effect (Davidson & Irwin, 1999).

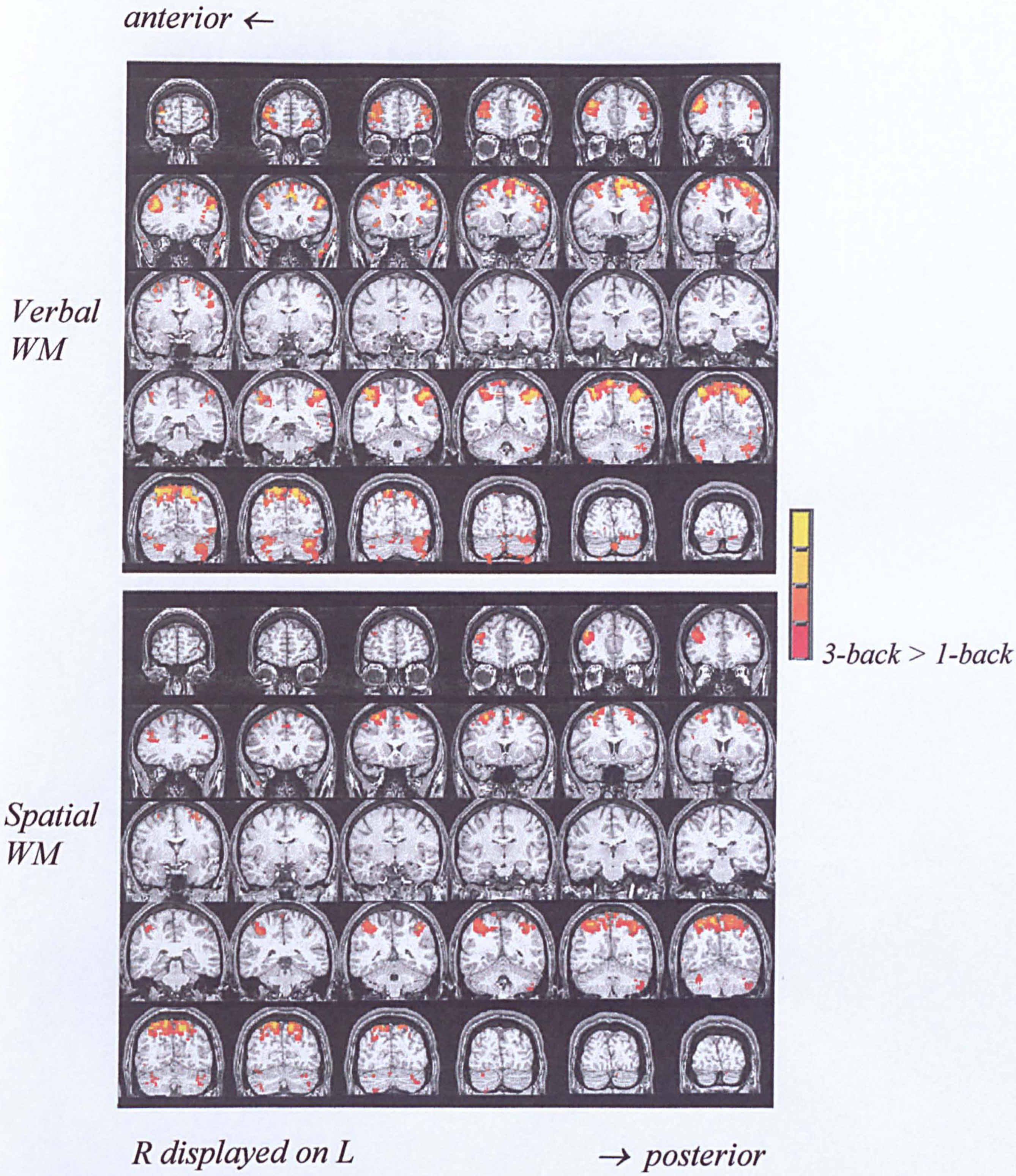


Figure 23. Coronal slices (front to back starting on the top left slice, right displayed on the left) showing the difference between the 3-back and 1-back tasks. Only voxels that showed differences in five or more subjects were included.

14.3. Results

Behavioural data

Regular electronic equipment (e.g. computers) cannot function in the scanner environment, because of the very high magnetic field. Therefore, in order to collect response data (e.g. buttonpresses) in the scanner, specialised equipment is needed. In the present study a new fibre-optic device was used to collect responses. Due to improper prior testing, the device did not have sufficient protection from the scanner field and the behavioural data were corrupted.

Groupwise SPMs

The activation associated with the Verbal and Spatial WM tasks is typical of this sort of experiment (see Fig. 23). Moreover, the pattern of activation is roughly similar across tasks: the superior and middle frontal gyri, intraparietal sulcus, and the cerebellum. Generally, the Verbal WM homologues of Spatial WM-related clusters of activation are more extensive and higher in magnitude.

ROI Analyses

Analyses were conducted as Hemisphere (Left, Right) X Region (BA 46, BA 9) x 2 (Verbal WM, Spatial WM) ANOVAs for repeated measures using the Greenhouse-Geisser correction for violation of sphericity when necessary. Hence, all tests were conducted on 1 and 9 degrees of freedom.

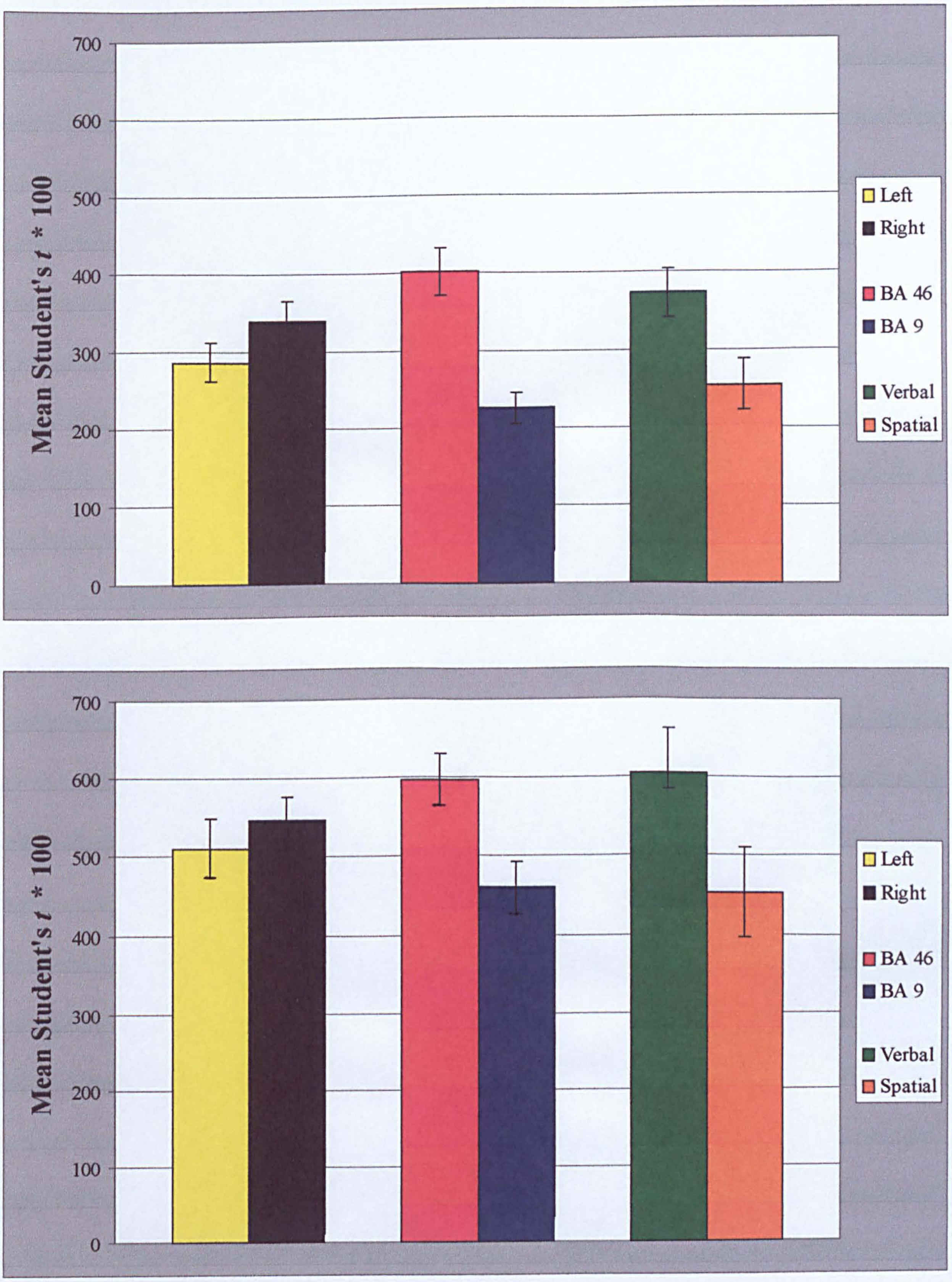


Figure 24. The main effects in the unthresholded (top) and thresholded (bottom) analyses of fMRI data. No interactions approached significance.

Thresholded SPMs

As displayed in Figure 24, significant effects of Region ($F = 20.6$, $p =.001$) and Task ($F = 5.9$, $p = .038$) were found. No other main effects or interactions were revealed.

Unthresholded SPMs

In addition to the effects of Region ($F = 57.5$, $p < .001$) and Task ($F = 6.713$, $p = .029$), a reliable effect of Hemisphere ($F = 5.6$, $p = .043$) was found (see Fig. 24). No other main effects or interactions were revealed.

14.4. Discussion

The present study aimed to test the hypothesis (Gray, 2001) that asymmetric inter-hemispheric activation of dorso-lateral prefrontal cortex (dlPFC) in 3-back verbal and spatial WM tasks, in conjunction with prefrontal asymmetries in emotion, can account for the differential effect of threat-anxiety (fear), observed in Studies 4 and 5. More precisely, if it is true that:

A) spatial 3-back performance relies predominantly on right dlPFC activation, while verbal n-back performance relies primarily on left dlPFC activation

and that

(B) threat-anxiety activates the right dlPFC more than the left dlPFC,

one could predict a selective spatial n-back by threat-anxiety interaction (as observed behaviourally in Studies 4 and 5). The objective of the present study was to test one of the two constituents of this hypothesis (i.e. A). For A to be true, a significant Task (spatial vs verbal) X Hemisphere, or Task X Hemisphere X Region needs to be revealed. No such effects were observed. Although the present outcomes do not rule out potential WM asymmetries in PFC areas outside the dorso-lateral region (e.g. Broca's area), the model of prefrontal inter-hemispheric asymmetry in approach vs. withdrawal emotions was specifically formulated with regard to the dlPFC (Davidson, 1998). Therefore, the results do not corroborate the neuroanatomical explanation of selective disruptive effects of threat-anxiety on spatial 3-back performance in terms of prefrontal asymmetry in emotion (Davidson, 1992, 1995, 1998). Importantly, the study performed statistical tests of interhemispheric differences irrespectively of the presence of main effects, as required by Davidson and Irwin (1999).

One limitation of the present study is inherent to fMRI technology. The activation data from verbal and spatial WM tasks represents an average of the neural events during WM trials. It is conceivable that neural events of short duration (e.g. 10-50 ms) can be asymmetric, but that such asymmetries would remain undetected due to low temporal resolution of fMRI. To address this concern, modern multichannel EEG or MEG recordings combined with source-localisation algorithms, are needed.

GENERAL DISCUSSION

Summary of individual studies

The general theme of the investigations presented here is the influence of emotion on Working Memory. The effects of positive mood on the Central executive component of WM served as context for the studies reported in Part II. The impact of negative affect (anxiety/fear) on the verbal and spatial WM mechanisms were investigated in Parts III and IV. Affect was directly manipulated in Part III via affect evocation procedures and indirectly manipulated in Part IV through pre-selection of participants with specific emotional profiles. The seven studies described in the thesis employed three types of cognitive tasks, thought to have differential WM demands, namely analytical (reasoning) tasks (Studies 1 and 2), creative (insight) problems (Studies 1 and 2) and continuous performance (n-back) WM tasks (Studies 3-7). All three types of tasks were piloted (in Studies 1 and 3) in order to ensure adequate levels of performance prior to testing experimental hypotheses. A number of experimental paradigms were utilised, most notably concurrent task methodology (Study 2) and experimental affect evocation (Studies 4 and 5). Several types of data were collected: behavioural (Studies 1-6), physiological (ERPs- Study 2, EMG- Study 4, heart-rate- Study 5), clinical (anxiety questionnaires, Study 6) and neuroimaging (fMRI, Study 7).

Part II (Studies 1 and 2) directly tested one of the key assumptions in the explanation of differential effects of positive mood on analytical (reasoning) vs. creative (insight) performance (Isen et al., 1987, Oaksford et al., 1996), namely that the two types of tasks make differential demands on the Central Executive component of WM

(Oaksford et al., 1996). Study 2 employed a concurrent task paradigm, previously used with reasoning tasks (Gilhooly et al., 1993; Oaksford et al., 1996). The concurrent WM task was temporally superimposed not only upon reasoning, but also upon insight processing, and the degree of interference with the two types of tasks compared. The presence of the concurrent WM task had a significant negative impact on reasoning performance, consistent with previous research (Oaksford et al., 1996), but did not seem to affect insight performance. Electrophysiological (ERP) recordings, taken in response to the concurrent task, showed an increase in the amplitude of an ERP waveform component closely associated with WM processing, P300. The increase was only observed when the concurrent task was temporally superimposed upon reasoning. The superimposition of the concurrent task upon an insight problem resulted in the same P300 amplitude as in response to the concurrent task administered alone. Furthermore, the ERP results do not rely solely on the ERP waveform analysis. A more objective and sensitive analytical tool, Principal Component Analysis, confirmed and further extended the conclusions regarding P300.

To conclude, there is good agreement between behavioural and ERP data, both suggesting differential Central Executive/WM involvement in reasoning and insight processes. This finding strengthens the interpretation of previously observed differential effects of positive mood on creative and analytical performance in terms of WM processing. Biologically plausible computational models of WM (O'Reilly et al., 1999) suggest that updating is critical for normal WM functioning. Such updating is thought to be controlled via dopamine projections from the basal ganglia into the prefrontal cortex. The same projections were proposed to mediate the beneficial effect of positive mood on tasks requiring creativity and flexibility (Ashby et al., 1999). It seems likely that the rapid and relatively unselective updating induced in conditions of positive mood can indeed be facilitatory for creative tasks. However, such updating may be detrimental for tasks requiring careful analysis and maintenance of intermediary information (e.g. reasoning tasks). It also appears likely that the larger amplitude of the P300 ERP waveform component in the analytical condition reflects the trade-off between re-organisation of WM in response to the concurrent task and the need to maintain detailed intermediary representations in the reasoning task. Since such a trade-off would be less costly in the insight task, the P300 amplitude in response to the concurrent task during insight problem-solving was the same as during the concurrent task performed alone.

In Part II it was difficult to control for the possible confound of differential involvement of WM slave-systems (Baddeley and Hitch, 1974), i.e. the phonological loop and the phonological sketchpad, in the reasoning and the insight tasks. Part III (Studies 3, 4 and 5) was specifically dedicated to testing potential differences between these two WM components in their sensitivity to affect. Verbal and spatial n-back tasks were developed and rigorously piloted in order to obtain tasks that would only differ in the type of information to be held in WM. Furthermore, unlike Part II which only provided indirect evidence with regard to the effects of mood on WM, Part III employed experimental mood induction. Based on the well-documented phenomenon of *attention to threat* in anxiety (Mathews et al., 1997), as well as the role of visuo-spatial attention in spatial WM, it was hypothesised that spatial WM would be selectively disrupted by anxiety (fear) induced by threat-of shock, whereas verbal WM would be less affected in conditions of threat-evoked anxiety. Two experiments confirmed this prediction, both with and without delivery of electric shocks. Three physiological techniques (startle eye-blink, corrugator and heart-rate recordings), validated the presence of self-reported anxiety (fear) under conditions of threat-of-shock. The analyses also showed a direct relationship between the physiological and self-report measures of anxiety (fear) and the decrement in spatial, not verbal, WM performance. These data provide support for the proposal that threat-induced anxiety and spatial WM, when concomitant, compete for visual attention resources. Though indirectly, it also corroborates the view that spatial WM, more precisely its rehearsal mechanism is based on attention and that verbal and spatial storage components of WM do not use identical pools of attentional resources.

In Part IV (Studies 6 and 7) it was attempted to clarify two important issues regarding the effect observed in Part II.

Firstly, it was interesting to see if the effect of anxiety elicited by threat-of-shock would generalize to forms of anxiety that are less stimulus (or event) bound, e.g. trait and test anxiety. Verbal and spatial n-back performance was compared across two groups of participants, selected on the basis of high vs. low trait anxiety scores in questionnaires. Participants were grouped (selected) twice, according to scores on two of the most well-known measures of trait-anxiety (the Behavioral Inhibition and Behavioral Activation Scales, Carver and White, 1994 and the Spielberger State-Trait-Anxiety-Inventory, Spielberger, 1983). In both selections trait anxiety successfully predicted state-anxiety differences between groups measured before and after the experimental session. Furthermore, trait anxiety was associated with impairments in both verbal and spatial WM performance. Therefore, trait/test anxiety does not mirror in its effects on WM the selectivity of threat-of-shock anxiety (fear). These results contradict some suggestions in the literature that verbal WM performance may be more impaired than spatial WM performance by trait and test anxiety. They also support one of the central claims of Eysenck and Calvo's (1992) processing efficiency theory, namely that trait and test anxiety affect the Central Executive component of WM more than the verbal and spatial storage components.

The second question asked in Part IV, refers to the neuroanatomical correlates of the effect observed in Part II, selective spatial WM deficits in conditions of threat. One of the most influential models of functional neuroanatomy of emotion is the model of prefrontal asymmetry (Davidson, 1992, 1995, 1998). The model proposes that the dorso-lateral division of the prefrontal cortex (dlPFC) shows left vs. right activation asymmetry corresponding to approach vs. withdrawal affective states, respectively. In conjunction with putative dlPFC asymmetries in WM tasks, Davidson's model was used to explain differential effects of positive and negative mood on verbal and spatial 2-back WM tasks (Gray, 2001). However, although WM tasks indeed show asymmetric PFC activation, this has only been documented for PFC areas outside its dorso-lateral (dlPFC) division, e.g. Broca's area, premotor and suplimentary motor areas. Therefore, Study 7 employed neuroimaging (fMRI) in order to determine whether the 3-back WM tasks used in Studies 3-6 are associated with asymmetric dlPFC activation. No evidence of reliable asymmetry in dlPFC activation in verbal and spatial 3-back tasks was found. This result casts doubt on the potential interpretation of the anatomical correlates of the effect observed in Part II in terms of Davidson's prefrontal asymmetry model (e.g. Gray, 2001). It is concluded that alternative neuroanatomical models have to be developed in order to account for the observed behavioural effect.

General conclusions

In addition to the interpretation of individual studies, the present investigations resulted in two conclusions of a more general nature.

Firstly, an examination of the effects of positive affect on insight and reasoning tasks in conjunction with the effects of negative affect (fear and anxiety) on verbal and spatial Working Memory suggests that various forms of emotion influence cognitive processing at a motivational level. Emotion seems to prioritise among cognitive mechanisms and such priorities are most likely evolutionarily-driven. For example, positive mood of the sort elicited by several groups of researchers (Estrada et al., 1997; Isen et al., 1987; Oaksford et al., 1996) appears to both facilitate exploratory behaviour and relax attentional constraints, thus contributing to rapid and relatively unselective updating of WM contents. Therefore, the tasks that fit this strategic pattern (e.g. insight tasks) are facilitated and, conversely, tasks whose requirements conflict with this pattern (reasoning) are disrupted. Similarly, emotions elicited by the presence of an explicit threat, i.e. anxiety and fear, are likely to automatically trigger visuo-spatial attentional mechanisms, in order to localise the threatening stimuli. It does not appear that all forms of anxiety lead to this activation of visual attention. For example, test anxiety did not seem to selectively interact with spatial WM. This suggests that the cognitive correlates of emotions broadly falling within the same category, e.g. fear and test-anxiety, may be rather different and that particular emotions may serve rather specific functions in the environment. These functions may determine the cognitive mechanisms with which individual emotions are associated, e.g. fear and visual attention.

The second conclusion is that the distinction between slave- or storage-systems and executive/attentional systems may not hold very well. In the classical multi-component model of WM (Baddeley & Hitch, 1974), there is a clear distinction between the attentional component, the Central Executive, not "equipped" with storage capacity, and the "slave" systems that perform storage of verbal and visuo-spatial information but have no role to play in selecting or prioritizing information (i.e. attentional capacity). If, as it appears, spatial WM (the visuo-spatial sketchpad) is intrinsically associated with shifts of attention, the above distinction seems to lose substance, because a fundamental process in one of the storage WM components, i.e. rehearsal in spatial WM, is based on a process that is intrinsically associated with the selection/prioritization of visual input: visual attention. Furthermore, there could be other implications of this.

One possibility is that attentional resources are centralised, but that there is some asymmetry in the relation between the Central Executive and the "slave" systems. In other words, visual attention could be part of the Central Executive and verbal and spatial WM could have differential links to the Central Executive, with spatial WM being more closely associated with Central Executive processes. A more radical possibility proposed by some theorists (Shah & Miyake, 1996) is that in contrast to classical theories of centralised attentional/executive function (Central Executive, Baddeley, 1986, Supervisory Attentional System, Norman & Shallice, 1986), the systems which perform the prioritisation of behaviours, appear to be fractionated. We favour a middle-perspective based on comparisons of the effects of different kinds of anxiety, i.e. fear vs. trait/test anxiety, on WM sub-systems. For instance, the similar effects of trait-anxiety on verbal and spatial WM support the presence of a centralised attentional/executive mechanism. On the other hand, the selective effects of threat-anxiety suggest the de-centralised character of some attentional systems. Visual attention seems to have critical importance for some WM components, but not for others. This idea has recently been proposed in the cognitive behavioural (Smyth, 1996) and cognitive neuroimaging (Awh et al., 1999) literatures and our results support it.

The general conclusions are still somewhat speculative and more evidence is needed for choosing the viable accounts. It seems that experimentation involving manipulations of affect can be rather fruitful, due to the specificity of some of the emotion-cognition interactions. In contrast to traditional views on the effects of emotion on cognitive processing, e.g. the resource allocation model, it is increasingly clear that the modulation of cognitive processing by emotion can be selective. It is hoped that the present studies can serve as an indication of this.

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