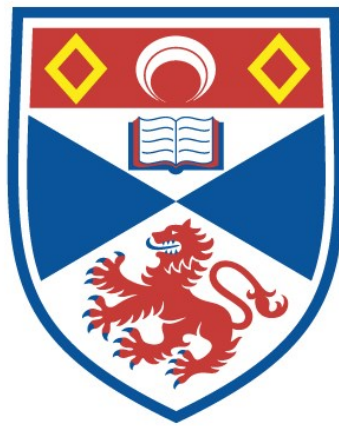


# EVENT-RELATED POTENTIAL STUDIES OF EXPLICIT MEMORY FOR ASSOCIATIVE INFORMATION

David Ian Donaldson

A Thesis Submitted for the Degree of PhD  
at the  
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# **Event-Related Potential Studies of Explicit Memory for Associative Information**

David Ian Donaldson

Submitted for the degree of Ph.D., in the School of Psychology, at the  
University of St Andrews, July 1998



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## ABSTRACT

Previous studies employing event related potentials (ERPs) have investigated the neural correlates of explicit memory using item recognition and source memory tests. These studies suggest that recollection, the retrieval of information about specific prior study episodes, is associated with two temporally and topographically dissociable ERP old/new effects. First, the 'left parietal' effect (found in studies of item and source memory) which provides an index of the retrieval processes supporting recollection. Second, the 'right frontal' effect (found in studies of source memory) which is thought to be associated with more strategic task-related 'post-retrieval' memory processes.

In the present thesis the ERP old/new effects were investigated in five experiments using tests of explicit memory for associative information. In each experiment subjects studied novel word pairs, and memory for these associations was assessed using associative recognition and associative recall tasks. Consistent with previous behavioural studies that suggest associative recognition is dependent upon recollection, performance on this task was associated with both the left parietal and right frontal old/new effects. Moreover, successful associative recall was associated with equivalent old/new effects, contrary to previous findings that suggest performance on this task is associated with the left parietal but not the right frontal old/new effect.

Whilst the findings support the previous functional account of the left parietal old/new effect, they necessitate the refinement of the account of the right frontal old/new effect. Significantly, the ERP findings suggest that the right frontal old/new effect can be dissociated from an early bilaterally-distributed frontal old/new effect that cannot be accounted for in terms of strategic post-retrieval processing. Finally, an alternative account of the frontal effects is proposed, drawing on evidence from neuroimaging studies, and distinguishing between pre- and post-retrieval support processes.

# CONTENTS

<b><i>ABSTRACT</i></b>	<b>5</b>
<b><i>INDEX OF FIGURES AND TABLES</i></b>	<b>10</b>
<b><i>FOREWORD</i></b>	<b>12</b>
 <b><u>CHAPTER 1: MEMORY</u></b>	 <b><u>14</u></b>
<b>Fractionating memory</b>	<b>15</b>
Long-term and short-term memory	17
Explicit and implicit memory	18
<b>Declarative (explicit) memory</b>	<b>24</b>
Episodic and semantic memory	27
The neuroanatomical basis for episodic memory	32
<b>Models of recognition memory</b>	<b>33</b>
The formal basis of single and dual process models	34
Single process models	38
Dual process models	44
A dual process account of associative memory	59
<b>Summary</b>	<b>62</b>
 <b><u>CHAPTER 2: EVENT-RELATED POTENTIALS</u></b>	 <b><u>64</u></b>
<b>Electrogenesis</b>	<b>66</b>
Individual cells	67
Groups of cells	68
Synchronicity	69
Volume conduction	69
<b>Recording the signal</b>	<b>70</b>
The Placement of Electrodes	70
Methods of Referencing	71
<b>Extracting the signal from noise</b>	<b>72</b>
Signal averaging	73
Analogue to digital conversion	74
Artifacts	75
<b>Defining ERP components</b>	<b>76</b>
Peak Picking	76

Psychological components	77
Physiological components	78
<b>Psychophysiological inferences</b>	<b>80</b>
The invariance assumption	80
Interpreting ERP data	82
<b>Summary</b>	<b>86</b>
 <b><u>CHAPTER 3: ERPS AND MEMORY</u></b>	 <b><u>88</u></b>
<b>The left parietal old/new effect</b>	<b>89</b>
Methodological issues	89
Initial investigations	90
The Familiarity explanation	92
Operational definitions of recollection	98
<b>The right frontal old/new effect</b>	<b>99</b>
Functional accounts of the old/new effects	102
Source memory revisited	105
Associative recall	106
<b>Identifying the generators of the old/new effects</b>	<b>109</b>
<b>Summary</b>	<b>110</b>
 <b><u>CHAPTER 4: GENERAL METHODS</u></b>	 <b><u>116</u></b>
<b>Subjects</b>	<b>116</b>
<b>Experimental materials</b>	<b>117</b>
<b>Experimental tasks and procedures</b>	<b>117</b>
<b>ERP recording and data processing</b>	<b>118</b>
<b>Data Analyses</b>	<b>120</b>
Magnitude analyses	120
Topographic analyses	121
 <b><u>CHAPTER 5: EXPERIMENT 1</u></b>	 <b><u>123</u></b>
<b>INTRODUCTION</b>	<b>123</b>
<b>METHODS</b>	<b>127</b>
Subjects	127
Experimental materials	127
Experimental tasks, procedure and ERP recording	128
<b>RESULTS</b>	<b>129</b>
Behavioural data	129
ERP data	130
Summary of results	134
<b>DISCUSSION</b>	<b>139</b>

<b><u>CHAPTER 6: EXPERIMENT 2</u></b>	<b><u>145</u></b>
<b>INTRODUCTION</b>	<b>145</b>
<b>METHOD</b>	<b>146</b>
Subjects	146
Experimental materials	146
Experimental task, procedures and ERP recording	147
<b>RESULTS</b>	<b>148</b>
Behavioural data	148
ERP data	149
Summary of results	153
<b>DISCUSSION</b>	<b>158</b>
 <b><u>CHAPTER 7: EXPERIMENT 3</u></b>	 <b><u>162</u></b>
<b>INTRODUCTION</b>	<b>162</b>
<b>METHOD</b>	<b>164</b>
Subjects	164
Experimental materials	164
Experimental procedure and ERP recording	164
<b>RESULTS</b>	<b>165</b>
Behavioural data	165
ERP data	165
Summary of results	169
<b>DISCUSSION</b>	<b>174</b>
 <b><u>CHAPTER 8: INTERIM DISCUSSION 1</u></b>	 <b><u>176</u></b>
 <b><u>CHAPTER 9: EXPERIMENT 4</u></b>	 <b><u>181</u></b>
<b>INTRODUCTION</b>	<b>181</b>
<b>METHOD</b>	<b>185</b>
Subjects	185
Experimental stimuli	185
Experimental tasks, procedures and ERP recording	186
<b>RESULTS</b>	<b>188</b>
Behavioural data	188
ERP data	189
Summary of results	193
<b>DISCUSSION</b>	<b>199</b>
 <b><u>CHAPTER 10: EXPERIMENT 5</u></b>	 <b><u>202</u></b>
<b>INTRODUCTION</b>	<b>202</b>
<b>METHOD</b>	<b>203</b>

Subjects	203
Experimental stimuli	203
Experimental procedure and ERP recording	203
<b>RESULTS</b>	<b>204</b>
Behavioural data	204
ERP data	205
Summary of results	208
<b>DISCUSSION</b>	<b>213</b>
 <b><u>CHAPTER 11: INTERIM DISCUSSION 2</u></b>	 <b><u>216</u></b>
 <b><u>CHAPTER 12: GENERAL DISCUSSION</u></b>	 <b><u>221</u></b>
Summary of experimental findings	221
Functional accounts of the ERP old/new effects	224
The left parietal old/new effect	225
The late negative shift	231
The early frontal old/new effect	232
The late right frontal old/new effect	236
A proposal regarding the frontal old/new effects	238
Summary	244
 <b>APPENDIX A</b>	 <b>246</b>
<b>APPENDIX B</b>	<b>253</b>
<b>APPENDIX C</b>	<b>256</b>
<b>BIBLIOGRAPHY</b>	<b>259</b>



# INDEX OF FIGURES AND TABLES

## Tables

1. Chapter 2: Strengths and weakness of the ERP method	65
2. Chapter 5: Experimental design for experiment 1	127
3. Chapter 5: Behavioural results from experiment 1	129
4. Chapter 5: Reaction time data from experiment 1	130
5. Chapter 5: Results of the ERP magnitude analyses from experiment 1	132
6. Chapter 6: Experimental design for experiment 2	146
7. Chapter 6: Behavioural results from experiment 2	148
8. Chapter 6: Reaction time data from experiment 2	149
9. Chapter 6: Results of the ERP magnitude analyses from experiment 2	151
10. Chapter 7: Behavioural results from experiment 3	165
11. Chapter 7: Reaction time data from experiment 3	165
12. Chapter 7: Results of the ERP magnitude analyses from experiment 3	167
13. Chapter 9: Experimental design for experiment 4	185
14. Chapter 9: Behavioural results from experiment 4	188
15. Chapter 9: Results of the ERP magnitude analyses from experiment 4	191
16. Chapter 10: Behavioural results from experiment 5	204
17. Chapter 10: Results of the ERP magnitude analyses from experiment 5	206

## Figures

1. Chapter 2: Two ERP waveforms	87
2. Chapter 2: A topographic map	87
3. Chapter 3: The ERP old/new effect – item recognition	113
4. Chapter 3: The ERP old/new effects – source memory	114

5. Chapter 3: The ERP old/new effects – associative recall	115
6. Chapter 4: 25 electrode recording montage	118
7. Chapter 5: 25 site ERPs from experiment 1	135
8. Chapter 5: ERPs from lateral frontal/parietal electrodes from experiment 1	135
9. Chapter 5: Mean amplitudes of the old/new effects from experiment 1	137
10. Chapter 5: Topographic maps of the old/new effects from experiment 1	138
11. Chapter 6: 25 site ERPs from experiment 2	154
12. Chapter 6: ERPs from lateral frontal/parietal electrodes from experiment 2	155
13. Chapter 6: Mean amplitudes of the old/new effects from experiment 2	156
14. Chapter 6: Topographic maps of the old/new effects from experiment 2	157
15. Chapter 7: 25 site ERPs from experiment 3	170
16. Chapter 7: ERPs from lateral frontal/parietal electrodes from experiment 3	171
17. Chapter 7: Mean amplitudes of the old/new effects from experiment 3	172
18. Chapter 7: Topographic maps of the old/new effects from experiment 3	173
19. Chapter 9: 25 site ERPs for the recognition task from experiment 4	195
20. Chapter 9: 25 site ERPs for the recall task from experiment 4	196
21. Chapter 9: Amplitudes of the old/new effects for from experiment 4	197
22. Chapter 9: Topographic maps of the old/new effects from experiment 4	198
23. Chapter 10: 25 site ERPs for the recognition task from experiment 5	209
24. Chapter 10: 25 site ERPs for the recall task from experiment 5	210
25. Chapter 10: Amplitudes of the old/new effects for from experiment 5	211
26. Chapter 10: Topographic maps of the old/new effects from experiment 5	212

## FOREWORD

**“The prefrontal cortex is puzzling, since it seems to have little importance for man’s behaviour” (Donald Hebb, 1958, p86).**

Forty years on Hebb’s bold statement regarding the functional significance of the prefrontal cortex appears to have been an unfortunate over-statement. Hebb believed that the prefrontal cortex was ‘much more’ important for the behaviour of monkeys than humans - the increased intellectual capabilities found in humans were thought to have rendered the prefrontal cortex a redundant evolutionary hangover. The work presented here takes the opposite view, considering the prefrontal cortex to be an integral component of the human cognitive system. As will become clear however, the difficulty lies not only in establishing *whether* a particular area of the brain is involved in human cognition, but also in elucidating exactly *what* role it plays.

The foregoing paragraph exposes a fundamental issue that underpins the work presented in this thesis. As Kutas and Federmeier (1998) point out, in using any psychophysiological method, one is confronted by the mind-body problem. That is, one attempts to map between the levels of brain function and brain structure (between the psychological and neural levels of analysis), and in doing so one makes strong assumptions. Notably, one makes assumptions about the nature of relationship between the different levels of analysis, and about the nature of inferences that can be made on the basis of psychophysiological data. The work presented in this thesis does not, of course, attempt to solve the mind-body problem. Hopefully, however, in considering such issues this thesis will highlight the nature and complexity of the assumptions upon which such research rests.

The main body of this thesis is organised into four sections. Section one consists of review chapters, providing an overview of the broad theoretical, methodological and empirical framework within which the experimental work fits. These initial chapters are necessarily detailed, discussing the cognitive memory literature, the basic Event-Related Potential (ERP) methodology and ERP studies of explicit memory retrieval. Sections two and three contain the actual experimental work. The nature of the experimental work is such that the studies fall neatly into two sections – the second set of experiments having been inspired by the results of the first set.

Experiments 1 through 3 investigate the ERP correlates of recognition memory for new associations, challenging the functional accounts of the ERP correlates of recognition memory that are discussed in section one. Experiment 1 starts with an introduction that briefly reiterates the most salient aspects of the work discussed in the review chapters. Whilst this necessarily entails some repetition, it serves to provide a succinct, focused, account of the reasons for the experiment. In addition, at the end of the first three experiments there will be an interim discussion section, examining the specific issues that are addressed by the first set of experiments, before moving on to the second set.

Experiments 4 and 5 directly compare the ERP correlates of associative recognition and associative recall, attempting to reconcile the results of experiments 1 through 3 with previous published findings. As for the first set of experiments, experiment 4 will be preceded by an introduction that includes a re-cap of the central issues involved. Similarly, a second interim discussion will be presented, addressing the specific issues raised by the results of experiments 4 and 5.

Finally, section four consists of a broader general discussion, summarising the work presented in the thesis, relating it to the broader literature discussed in the review section, and suggesting ways in which the work could be extended. Hopefully, organising the thesis in this way should serve to highlight the way in which the work developed conceptually, and make it a more manageable, accessible, and pleasurable, experience for the reader.

# Chapter 1.

## MEMORY

What is memory for? As Glenberg (1993) suggests, for most theorists memory is simply for memorising – the ability to store information for later use. This view is perhaps best characterised by the ‘storehouse’ metaphor of memory, which describes memory as a repository of information. By this view, memory is the discrete storage of elements or inputs, a view that encourages a ‘quantity’ oriented approach. As Koriat and Goldsmith (1996a) point out, an alternative view of memory is provided by the ‘correspondence’ metaphor. The correspondence view stems from a concern for whether what is remembered actually corresponds to what was experienced, rather than simply with a concern for how much is remembered. By this account, memory is not simply the passive storage and retrieval of discrete elements, but is a reconstructive process, whereby representations of the past are actively generated, and can deviate from reality in many different ways.

Koriat and Goldsmith (1996a,b) suggest that the storehouse and correspondence metaphors represent two essentially different conceptualisations of what memory is, what purpose it serves, and how it should be evaluated. The distinction is clearly somewhat forced (e.g., alternative conceptions of the correspondence metaphor have

been suggested, see Neisser, 1996; and Conway, 1996) and few memory theorists explicitly endorse one or other approach. However, a consideration of such underlying concepts is important, both in highlighting the implicit assumptions upon which research is based, and in emphasising that memory is not adequately characterised by the conclusion that memory is 'simply for memorising'. As Tulving (1997) forcibly argues, the student of memory must recognise that memory storage is not the whole story.

An important criticism of Koriat and Goldsmith's account of memory is that it is predominantly based upon a consideration of episodic (autobiographic or event) memory, and does not address the other forms or types of memory that exist. As McNamara (1996) suggests, it is difficult to see how the account applies to semantic and repetition priming, where subjects are not explicitly required to remember at all (see also Alterman, 1996). The foregoing criticism highlights a central feature of contemporary research, namely, that memory is not a unitary phenomenon and that some distinction must be drawn between different types or forms of memory. As Tulving (1995, p840) asserts, "no profound generalisations can be made about memory as a whole".

Before discussing episodic memory in more detail, it is important to consider how it relates to other forms of memory. Thus, this chapter starts with a brief review of the taxonomy of memory, providing examples of the evidence on which memory has been fractionated, and highlighting some of the issues raised therein. Subsequently, an overview of the neuroanatomical basis for episodic memory will be provided, leading to a fuller discussion of single and dual process models of recognition memory – a commonly employed test of episodic memory retrieval.

### **Fractionating memory**

As noted above, a central feature of modern memory research has been the demonstration that memory can be fractionated into several different forms or types. As Tulving (1995) notes, current accounts of the different categories of memory have developed from various conceptual dichotomies, such as memory vs. habit and procedural vs. declarative. However, these distinctions have been combined into

broader classification schemes, separating memory into several major memory 'systems'. Two such schemes are described below.

One influential taxonomy of memory comes from Squire and colleagues (e.g., see Squire and Zola-Morgan, 1991; Squire and Knowlton, 1994; Squire, Knowlton and Musen, 1993; Zola-Morgan and Squire, 1993). This model is founded upon a central distinction between 'declarative' (explicit) and 'nondeclarative' (implicit) forms of memory. Explicit, or declarative, memory includes episodic memory for prior events and semantic memory for facts. These two forms of memory are associated with the conscious retrieval of information, that is, retrieval accompanied by the phenomenological awareness that one is remembering. By contrast, implicit or nondeclarative memory includes priming, classical conditioning, associative learning and habit formation, forms of memory that are not associated with the phenomenological experience that one is remembering. That is, experience results in changes in behaviour (e.g., as measured by improvements in reaction time), without necessarily producing any concomitant conscious access to the prior learning experience, or the content of memory.

A similar model has been proposed by Tulving and colleagues (1983, 1985a,b). In several early formulations Tulving proposed just three distinct memory systems, episodic, semantic (two forms of declarative memory), and procedural memory (nondeclarative memory, including motor skills, conditioning and associative learning). More recently Tulving (1993, 1994, 1995) has broadened the classification to include a primary memory system (short-term memory) and a perceptual representation system (responsible for priming). Clearly, the schemes proposed by Tulving and Squire are similar, but not entirely equivalent. One significant difference lies in the classification of priming. Squire views priming as a form of nondeclarative memory, whereas Tulving separates the two. For Tulving there is a critical distinction between procedural memories (skill learning, conditioning and associative learning), which are action systems, and the non-procedural memory systems that are representational systems, which mediate changes in cognition or thought, rather than action.

A second aspect of Tulving's scheme is that the terms 'implicit' and 'explicit' memory refer to forms of expression of retrieved information, rather than memory systems per

se. Although, the terms are used to refer to forms of memory in the present thesis, it is important to recognise that states of awareness cannot necessarily be assumed to map directly onto forms of memory (Blaxton, 1989; Schacter, 1991; Tulving, 1993). Tulving also provides a specific account of the relationship between the different memory systems, both in terms of the evolutionary development of the different systems (see also Sherry and Schacter, 1987) and the way in which information is processed through the different systems. Tulving suggests that information is encoded serially, such that the output from one system is the input for the next system. Thus, information is represented in multiple forms, stored in parallel in each different system. Finally, it is proposed that stored information can be retrieved from each system independently, allowing the retrieval of information from one system without any concomitant retrieval from other systems.

An important element of the classification systems described above is that they are intended to reflect not only functional accounts of the different forms of memory, but also to provide neurologically 'real' accounts of the underlying memory systems that are responsible for the operation of each type of memory. Before considering the details of the neurological account of the declarative/explicit memory system in more detail, it is worthwhile to consider the basis for some of the distinctions that have been drawn between different types of memory and the underlying systems upon which they are based. Obviously, the systems models have been proposed upon the basis of a whole range of empirical data, including experiments on brain damaged patients, animal experiments, and normal subjects. Whilst it is not possible to discuss the entire range of data here, relevant examples will be provided where appropriate.

### **Long-term and short-term memory**

Perhaps the single most significant body of evidence that has contributed to the development of the fractionation of memory is research on brain damaged patients, dating back to Scoville and Milner's (1957) classic account of H.M., an epileptic patient who developed a severe memory impairment following bilateral temporal lobectomy. A central feature of the amnesic syndrome is that the memory impairment caused by damage to the temporal lobes is not global. As Baddeley and Warrington (1970) demonstrated, amnesics are able to remember information over relatively short



time periods, but they are severely impaired at longer delays, especially if any form of interference occurs between initial learning and later testing. Significantly, the opposite pattern of impaired performance has also been demonstrated. For example, Shallice and Warrington (1970) described a patient K.F., who exhibited impaired memory at long but not short retention intervals.

The finding that patients with damage to different brain areas exhibit complimentary deficits in memory performance is a 'double dissociation', providing strong evidence that memory is not a unitary phenomenon. The individual deficits in performance in each group of memory impaired subjects could be accounted for in terms of a single memory system. For example, H.M.'s memory could have been impaired when tested at a long but not short delay because the latter task was simply easier. However, the finding that short and long term memory performance can be differentially impaired allows such an interpretation to be ruled out (e.g., see Weiskrantz, 1989; Ellis and Young, 1989; Olton, 1989; Dunn and Kirsner, 1988; Crowder, 1989; for debate regarding the logic and utility of single and double dissociations). On this basis (and a range of evidence from studies of normal subjects), the distinction between short-term (working) memory and long term memory is perhaps the most widely accepted fractionation of memory (e.g., see Atkinson and Shiffrin, 1968; Milner, 1966; Baddeley, 1986, 1995, 1996; see Gathercole, 1997, for recent discussion of short-term memory models; and see Smith and Jonides, 1997, on neuroimaging studies of short-term memory).

### **Explicit and implicit memory**

Studies of brain damaged patients have also provided evidence for a fractionation of long term memory; the distinction between explicit (conscious) and implicit (unconscious) memory. As noted above, explicit memory refers to forms of memory that are accompanied by an awareness that information has been retrieved from memory, whereas implicit memory refers to the influence of prior experience that occurs in the absence of an awareness (e.g., see Richardson-Klavehn and Bjork, 1988; Schacter, 1987, 1994; Graf and Schacter, 1987; Schacter and Tulving, 1994; Tulving, 1983; Tulving and Schacter, 1990; Squire, 1994; Roediger and McDermott, 1993). The dissociation between short and long term memory (discussed above) was illustrated by

considering differences in performance across different patient groups. By contrast, the distinction between explicit and implicit memory is discussed below, and is illustrated within individual patients, by contrasting temporal lobe amnesics' performance on different classes of memory task, namely, direct and indirect memory tasks.

#### **Direct and indirect memory tasks**

Direct memory tasks are those that explicitly require subjects to remember some aspect of a prior study episode (such as the previous occurrence of an item in a word list). Item recognition is a typical direct memory task; subjects are presented with a list of study items, and at test are instructed to discriminate between studied (old) and unstudied (new) items. By contrast, indirect memory tasks make no overt reference to a prior study episode, and subjects are not explicitly required to remember the previously encountered material. Perceptual identification is a typical indirect task, whereby subjects are required to identify items that are presented under perceptually degraded (e.g., masked) conditions. In this type of task subjects are not told that their memory is being tested, and subjects are not necessarily aware that they have experienced some of the items previously. Thus, in this indirect task the memory effect is a form of priming, measured by an increase in the probability that an item is identified correctly following prior exposure to that item.

A host of experimental evidence suggests that amnesic patients are impaired on direct memory tasks, whilst exhibiting relatively spared performance on indirect tasks (e.g., see Warrington and Weiskrantz, 1970; Weiskrantz and Warrington, 1979; Jacoby and Witherspoon, 1982; Cohen, 1984; Graf, Shimamura and Squire, 1985; for reviews see Moscovitch, Vriezen and Goshen-Gottstein, 1993; and Shimamura, 1986). For example, Corkin (1968) demonstrated that despite being severely impaired on direct tests such as recognition and recall, the amnesic patient H.M. (discussed above) was able to learn a simple motor skill. Similarly, Jacoby and Witherspoon (1982) demonstrated that amnesic subjects are impaired at recognising old items in a direct test of memory, despite being susceptible to a priming effect on an indirect test – they were biased towards particular spelling of homophones (e.g., plate vs. plait).

Evidence of dissociations in performance on direct and indirect memory tasks have also been found in studies of normal subjects (e.g., see Jacoby, 1983; Jacoby and Dallas, 1981; Mitchell and Brown, 1988; Jacoby, Woloshyn and Kelley, 1989; Cave

and Squire, 1992), adding weight to the suggestion that there are distinct explicit and implicit memory processes. Dissociations between direct and indirect tasks are typically shown by the differential effect of a specific experiment variable on one or other type of task, such as differences in performance when the modality in which items are presented is either maintained or changed between study and test, or differences in performance when attention is either full or divided at study. For example, Jacoby and Dallas (1981) used a 'levels of processing' manipulation, requiring subjects to study items either deeply (a semantic categorisation task) or shallowly (a vowel counting task). At test subjects performed both direct (item recognition) and indirect (perceptual identification) tasks. Jacoby and Dallas found that performance on the direct task was affected by the depth of processing manipulation, recognition memory being superior following deep than shallow encoding, whereas performance on the indirect task was unaffected by the manipulation.

Clearly, this form of functional dissociation is consistent with the suggestion that performance on direct and indirect memory tasks is not based entirely on the same processes. However, the extent to which such dissociations necessarily reflect the contribution of entirely independent memory systems is a matter of ongoing debate. As Roediger, Weldon and Challis (1989) point out, the distinction between different forms of memory cannot be safely made on the basis of functional dissociations. As well as dissociations between direct and indirect memory tasks, functional dissociations can also be found between different direct memory tasks. For example, studies have shown that a change in environmental context (i.e., the place/room in which the experiment is performed) between study and test significantly affects recall but not recognition memory performance (e.g., see Smith, 1994). This does not necessitate separate memory systems for each task however; the differences in performance could be accounted for in other ways. For example, both tasks could be reliant on two retrieval processes, with differential engagement of the two processes for each task. Alternatively, the tasks could share a reliance on one common retrieval process, with each task also relying on additional processes that are not shared.

#### **System and processing theories**

An alternative view of memory has been proposed by several authors, based on a processing view of memory. The essence of the processing view is that the

dissociations in performance that are seen across direct and indirect memory tasks reflect differences in the processing demands, rather than differences in the underlying memory systems (e.g., see Blaxton, 1989; Roediger, 1990; McKoon, Ratcliff and Dell, 1986; Roediger et al., 1989; Kolers and Roediger, 1984; McDermott and Roediger, 1996; Crowder, 1989). By this view, the ability to access or make use of memory information is dependent upon the degree to which the processing operations required at test overlap with (or match) those performed at study. This approach to memory retrieval is consistent with the general principles of 'transfer-appropriate processing' (Morris, Bransford and Franks, 1977) and 'encoding-specificity' (Tulving and Thomson, 1973; Wiseman and Tulving, 1976), whereby memory retrieval at test is seen as dependent upon the recapitulation of processing operations performed at study.

Within the transfer-appropriate processing framework performance on a given memory test is seen as dependent upon the overlap between the processing afforded items at study, and the processing requirements imposed at test. For example, Morris et al. (1977) has subjects study a list of words using either a semantic or rhyming task. They found that the semantic study task lead to superior performance on a standard item recognition test, but that the rhyming study task led to superior performance when a rhyming recognition test was employed (i.e., does the word rhyme with one presented at study). At the time, the significance of this experiment was in demonstrating that performance on memory tasks was not simply a function of 'depth of processing' (as per Craik and Lockhart, 1972), because the effectiveness of the deep and shallow encoding tasks depended upon the use to which information was put at test. In the present context however, the experiment also serves to demonstrate that dissociations in performance might reflect the specific retrieval orientation or task demands imposed by particular memory tests, rather than necessarily reflecting a reliance on different memory systems.

Although processing theorists can be characterised as arguing against the fractionation of memory into distinct memory systems, they must nonetheless account for the dissociations in performance found across different memory tasks. Consequently, a critical distinction within the processing view is between 'data-driven' and 'conceptually-driven' processes. Data driven processes are predominantly associated with the sensory and perceptual representations of test items, whereas conceptual

processes are associated with high-order semantic representations. By the processing view, direct memory tasks are more closely associated with (or dependent upon) conceptual processes, and indirect tasks more associated with data driven processes. Moreover, individual direct and indirect tasks vary in their reliance on data and conceptual process, for example, item repetition priming is primarily data driven, whereas semantic priming relies more heavily upon conceptual processes. Thus, by distinguishing between data driven and conceptually driven processing, the transfer appropriate processing framework can account for dissociations in performance across different direct and indirect tasks, and dissociations in performance within each class of task.

At the extreme, the processing view can be characterised as proposing that performance on all memory tasks relies upon a single memory system. Thus, dissociations in performance that result from the effect of different experimental manipulations (both across and within direct and indirect tasks) reflects different modes of processing associated with a single underlying memory system. Even the most hardened processing theorists is unlikely to propose an entirely unitary model of memory however (e.g., see Roediger, Srivinas and Weldon, 1989). Rather, the 'systems versus processes' debate has largely focused upon whether a multiple systems are necessary to account for the distinction between explicit (episodic) and implicit (priming) memory. Moreover, the systems and processing approaches are not inherently incompatible and a combined approach may ultimately be necessary (e.g., see Roediger et al., 1989; Tulving, 1995). In sum, it is generally accepted that a distinction can be drawn between the form(s) of memory assessed by direct and indirect memory tasks, and other forms of memory such as associative learning and classical conditioning, although the appropriate characterisation of the distinction between different forms of memory remains a matter of debate.

Before considering the systems model of memory in more detail, it should be noted that the challenge from processing theorists has led systems theorists to look for alternative forms of evidence to support the distinction between memory systems. Thus, alongside evidence of functional dissociations between different memory tasks, there is also evidence of stochastic dissociations – evidence that measures of memory performance on different tasks are statistically unrelated. That is, demonstrations that

the likelihood that a specific item is remembered on one task is independent of (i.e., not correlated with) the likelihood that it is remembered on a second task. This form of item specific dissociation has been demonstrated between a number of different tasks (e.g., between priming and semantic memory, Tulving, Hayman and Macdonald, 1991; and between priming and episodic memory, Tulving, Schacter and Stark, 1982). For example, Jacoby and Witherspoon (1982, noted above) demonstrated that the semantic priming effects for individual items on an indirect memory task were independent of the subject's ability to recognise the same items on a direct recognition test.

As with the findings of functional dissociations, the value and utility of stochastic dissociations have been challenged. It has been suggested that the presence of stochastic dissociations is dependent upon the particular experimental procedures employed (e.g., see Shimamura, 1985; Ostergraad, 1992) and that the rationale of the approach is logically unsound (e.g., see Hintzman, 1990). For example, stochastic independence can also be demonstrated between different indirect tasks (e.g., see Witherspoon, and Moscovitch, 1989). Nonetheless, it has been claimed (e.g., see Tulving, 1985; Hayman and Rickards, 1995; Schacter, 1995) that stochastic independence provides stronger evidence for multiple memory systems than is provided by functional dissociations because the dissociations are item specific. At the very least, such evidence adds weight to the conclusion that memory retrieval is not an entirely unitary phenomenon, and that some form of distinction (whether in terms of memory systems or memory processes) can be drawn between forms of memory.

### **Process purity**

The discussion of the debate between systems and processing accounts of memory highlights that fact that there are problems with the conclusion that dissociations in performance on direct and indirect memory tasks can be taken as evidence for separate memory systems. The debate has contributed to an important development in the memory literature however. As several authors (e.g., see Dunn and Kirsner, 1988, 1989; Richardson-Klavehn and Bjork, 1989; Jacoby and Kelley, 1992; Reingold and Toth, 1996) have pointed out, individual tasks cannot be assumed to be 'process pure' – that is, if there are multiple memory systems, performance on a given task is unlikely to reflect the isolated operation of a single system. Thus, performance on direct and indirect tasks may involve contributions from multiple memory processes, and because

there may not be a transparent, discrete, relationship between tasks and processes, direct and indirect tasks cannot be assumed to map exclusively onto explicit and implicit (respectively) memory process. For example, performance on a given direct memory task such as item recognition memory may predominantly tap explicit memory processes, but may also be influenced by implicit memory processes such as priming. As will be discussed below, this issue has generated considerable debate in the context of recent models of recognition memory. Similarly, performance on indirect tasks may be influenced by explicit memory, especially if subjects become aware that some items have been previously experienced (e.g., see Bowers and Schacter, 1990).

The foregoing discussion of the fractionation of memory highlights several important issues. Memory is clearly not a unitary phenomenon. Different proposals have been made to account for the dissociations in performance that can be found across different memory tasks, however, it is clear that different forms of memory do exist. Nonetheless, for the systems theorist a fundamental limitation exists in employing purely behavioural investigations of memory – it cannot be assumed that performance on individual memory tasks provides direct access to the neural activity of individual memory systems. Rather, behavioural studies simply measure the combined output of the different memory systems across different memory tasks. As Jacoby (1991) notes, measures of performance on a specific memory test cannot necessarily be assumed to reflect a specific memory process. Even though a range of different dissociations may be demonstrated (stochastically or functionally, using different subjects, tasks or experimental manipulations), this cannot provide conclusive evidence for different memory systems. Behavioural investigations of memory must be integrated with neuroanatomical and neuroimaging data, to provide convergent evidence concerning the underlying neural processes that are engaged by different memory tasks. The neuroanatomical basis of declarative (explicit) memory is discussed in more detail below.

### **Declarative (explicit) memory**

An important element of the systems view of memory has been to characterise the neural basis of behaviour. One of the clearest and most well formulated examples of

this approach comes from work by Cohen, Squire and colleagues (Cohen and Eichenbaum, 1993; Cohen and Squire, 1980; Squire and Zola-Morgan, 1991; Squire and Knowlton, 1992; Squire, Knowlton and Musen, 1993). A great deal of the evidence in support of this model comes from animal lesion studies, and brain damaged patients. The intention here is not to extensively review the evidence, rather the components of the system will be described, providing an overview of the neural basis for declarative memory. Although there is widespread agreement regarding the importance of the medial temporal lobes memory system, the manner in which the system functions and the exact role of the constituent parts remains a matter of ongoing debate. A number of different models of the hippocampal formation have been proposed, including detailed connectionist models and more abstract theoretical accounts (e.g., see McClelland, McNaughton and O'Reilly, 1995; Teyler and Discenna, 1986; Cohen and Eichenbaum, 1993; Damasio, 1989; Foster, Ainsworth, Faratin and Shapiro, 1997).

In essence, declarative memory is thought to be dependent upon the integrity of the medial temporal lobe memory system; the hippocampus and anatomically related structures (including entorhinal and perirhinal cortex, midline thalamus and fornix). The medial temporal lobe memory system refers both to the hippocampus and the major input and output pathways which allow the hippocampal formation to communicate with the rest of the brain. Whilst the fine details of this system are beyond the scope of the present chapter, it is important to note that the hippocampus is reciprocally connected with numerous subcortical structures and higher-order association cortex. For example, the parahippocampal cortical areas (entorhinal and perirhinal cortex) receive inputs from numerous areas of sensory and association areas (including posterior parietal lobes and prefrontal cortex), providing multimodal information about current experiences. Similarly, the fornix provides an important output pathway from the hippocampal formation, projecting to numerous subcortical areas, including the thalamus, septum and hypothalamus.

A critical feature of the hippocampal formation is that it has widespread and reciprocal connections throughout the brain, placing it in an ideal position to receive activity from the multiple areas of cortex in which information is processed during ongoing experience. However, whilst the hippocampus is at the center of the medial temporal



memory system it is not thought to actually store information per se. As evidence from brain damaged patients such as H.M. attests, damage to the hippocampus does not obliterate memory completely. The presence of intact remote memories suggests that the hippocampal system cannot be the ultimate storage site for long term memories. Thus, the hippocampal system is thought to serve as a 'relational processor' or 'convergence zone', storing information ('addresses' or 'indexes') about the pattern of cortical activity associated with ongoing experience. The hippocampal system extracts a concentrated representation of the activity that occurs across multiple regions, associated with the different elements of ongoing experience, allowing that activity to be reactivated at a later date. Thus, by this view, memory retrieval involves the reactivation of the areas of cortex that were involved in processing information at encoding.

An important property of the declarative memory system is that remembered information can be used in a flexible way. That is, information can be accessed in a variety of ways, using different retrieval cues and in novel contexts, such that information can be made available in situations that do not correspond closely to the original learning experience. In contrast, non-declarative memories are inflexible, and can only be expressed in situations that recapitulate the original learning episodes. A central reason for the representational flexibility of the hippocampal memory system stems from the ability to support the learning of relations among perceptually distinct items or events. As Cohen and Eichenbaum (1993, p62) state, "the form or nature of declarative representations is fundamentally *relational*" (their emphasis). At a basic level this corresponds to the 'binding' of information that is represented across multiple areas of cortex. The individual aspects of a stimulus (e.g., shape, colour, and position) are associated with the activity of different cortical areas at encoding. At retrieval the hippocampus acts to simultaneously reactivate these multiple areas of cortex, activating the specific conjunction of stimulus features that represent the original event.

Although the relational 'binding' process can be considered at the level of sensory or perceptual features of a given stimulus, it applies equally at all levels of abstraction. That is, to the relative positions of a given stimuli in time and space, and to the relations between stimuli. Thus, the ability to bind different stimuli together into a

unique memory representation can be considered a fundamental characteristic of the hippocampal memory system. One obvious example of this function of the core memory system can be seen in the impaired memory abilities of amnesic patients. A widely acknowledged aspect of hippocampal amnesia is impaired performance on tests of 'paired-associate learning'. For example, a list of word pairs is presented (e.g., dog-box, wood-fork, blue-inch, etc) and then the first item from each pair is presented, and the subject is asked to report the study associate. Amnesic subjects are notoriously impaired at this form of memory task, as Cohen and Eichenbaum (1993, p69) note, "paired associate learning provides a test that is most revealing of human amnesia".

### **Episodic and semantic memory**

In the context of the present thesis, a particularly important distinction within declarative memory is between episodic and semantic memory. Episodic and semantic memory are both forms of explicit (declarative) memory in that subjects are aware that they are remembering, and retrieval is assessed directly. Nonetheless, there appears to be a general consensus that some form of distinction can be drawn between episodic and semantic memory in terms of the type of information that is retrieved. Episodic (or autobiographical) memory refers to memory for events – specific prior occurrences occupying a distinct spatial and temporal context. By contrast, semantic memory refers to memory for facts – general knowledge.

As with the distinctions between forms of memory discussed earlier, one basis for the distinction between episodic and semantic memory comes from brain damaged patients. For example, De Renzi, Liotti, and Nichelli (1987) reported a single patient, L.P., who became amnesic following encephalitis. L.P. appeared to have normal episodic (autobiographical) memory, short-term memory, speech and perception. However, L.P.'s exhibited impairments in several aspects of semantic knowledge, including naming objects, word meaning and identifying famous people. In contrast, Tulving et al. (1991) report the opposite dissociation in patient K.C., an amnesic subject who exhibited severely impaired episodic memory, but was nonetheless able to learn semantic information (in the form of arbitrary three-word sentences).

More recently Vargha-Khadem, Gadian, Watkins, Connelly, Van Paesschen and Mishkin (1997) presented a striking example of three children who sustained brain

lesions very early in life – at birth, four years, and nine years of age. Despite their early onset, the lesions, which were limited largely to the hippocampus (bilaterally), did not produce general cognitive impairment. The children were competent in speech and language (faring well in educational terms, learning to read, write and spell) and were unimpaired on tests of semantic memory. By contrast, the children failed to remember events of daily life, and were impaired on tests of episodic memory (including delayed recall of stories, verbal and auditory recall, and copying complex figures). Vargha-Khadem et al., suggest that these patients exhibit severe episodic memory impairment in the face of spared semantic memory, and because the damage occurred so early, the formation of semantic memory could not have been reliant upon episodic memory. They suggest that episodic memory is dependent upon the hippocampus proper, whereas semantic memory depends upon the underlying entorhinal, perirhinal and parahippocampal cortices. By this account, the degree of memory loss in amnesia is dependent upon the extent of damage across the medial temporal lobes – episodic and semantic memory are only impaired together when the damage is widespread.

Although some form of distinction between semantic and episodic memory is generally accepted, there is considerable disagreement concerning the precise details of the functional and neuroanatomical relationship between the two forms of memory (e.g., see Tulving, 1986; Doshier, 1984; McKoon and Ratcliff, 1986; Ratcliff and McKoon, 1986). As forms of explicit or declarative memory, it is clear that both episodic and semantic memory are likely to be related to the operation of the brain system underlying this form of memory. Nonetheless, the precise relationship remains a matter of continuing debate. Two related accounts of the distinction between episodic and semantic memory are described below, focussing upon possibility that the frontal lobes play a role in supporting episodic memory.

According to the framework provided by Tulving and colleagues (e.g., see Tulving, 1985a,b; 1986; 1993; Tulving and Schacter, 1990) the distinction between episodic and semantic memory implies more than just the retrieval of different forms of information. Episodic and semantic memory are characterised by a 'mono-hierarchical' relationship; semantic memories are seen as being formed from the gradual accumulation of episodic memories, knowledge from individual experiences being re-

represented to form generalisations about the world<sup>1</sup>. Moreover, episodic and semantic memory can be distinguished by the subjective state of awareness associated with the retrieval of information. Episodic memory retrieval is not simply the explicit remembering of past events, rather, episodic memories are specifically associated with an 'autonoetic' (self-knowing) state of consciousness. By this view autonoetic consciousness is a necessary correlate of episodic memory, providing memory with a self-referential quality (for Tulving, the hallmark of episodic recollection). By contrast, semantic information is associated with a 'noetic' (knowing) state of consciousness, the explicit knowledge of facts without any necessary memory for where or when that information was acquired.

Although the distinction between episodic and semantic memory is intended to reflect separate memory systems, the account provided by Tulving is primarily focused towards a functional account, rather than addressing the underlying neuroanatomical structures responsible for the two forms of memory (although see Wheeler, Stuss and Tulving, 1995, 1997). An alternative account is provided by Squire and colleagues (e.g., Squire and Zola-Morgan, 1991; Squire and Knowlton, 1992; Squire, Knowlton and Musen, 1993). By this account the distinction between episodic and semantic memory is more strongly tied to neuroanatomical systems, rather than in terms of the types of awareness associated with them. In essence, both episodic and semantic memory are seen as being dependent upon the functioning of medial temporal lobe memory system, but episodic memory is thought additionally to depend upon the integrity of the frontal lobes.

Circumscribed damage to the frontal lobes has not traditionally been associated with impaired performance on typical episodic memory tasks such as recognition and recall. However, evidence from a recent meta-analysis of episodic memory in frontal lobe patients suggests that the prefrontal cortex does contribute to performance on these tasks. Wheeler, Stuss and Tulving (1995) reviewed a large number of studies, and found clear evidence of impaired performance on tests of recognition, cued recall and free recall. Significantly, the pattern of impairment was graded, with the smallest disruption on tests of recognition, and the largest on tests of free recall. Moreover, damage to the frontal lobes is known to produce impaired memory performance on a

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<sup>1</sup> Note that the cases reported by Vargha-Khadem et al. (1997) present strong evidence against this view.

range of other memory tasks. For example, frontal lobe lesions are associated with impairments in the ability to judge the temporal order in which remembered items were experienced (e.g., Milner, Corst and Leonard, 1991), and in making meta-memory judgements about remembered items (e.g., Janowsky, Shimamura and Squire, 1989a).

For example, Moscovitch and Melo (1997; see also Shallice and Burgess, 1991; Burgess and Shallice, 1996) examined aspects of strategic retrieval in patients with damage to the frontal lobes. In response to cue words (e.g., battle) subjects were required to describe either an event from their personal life or an event from history. Temporal lobe amnesic patients were impaired at this task relative to normal age matched controls. However, a subset of subjects with additional damage to the frontal lobes were more severely impaired at recovering memories in relation to the cues, benefited less from prompting than the other subjects, and exhibited severe confabulation – producing distorted responses that conflated semantic, historical and personal memories. Thus, Moscovitch and Melo suggest that the frontal lobe damage resulted in impaired strategic retrieval processes that are required to help initiate the search of memory, and to monitor and organise the output from memory.

Another deficit associated with frontal lobe damage is impaired ‘source memory’ – the ability to report the context in which remembered items were previously experienced (Johnson, 1992; Johnson, Hashtroudi and Lindsay, 1993). Impairments in source memory highlight a central feature of episodic memory, i.e., that the retrieved information is autobiographical in nature – the recollection of previous personal experiences that are situated in time and space. Several studies have reported impairments in source memory following frontal lobe damage (e.g., see Janowsky, Shimamura and Squire, 1989b; Schacter, Harbluk and MaLachlan, 1984; Glisky, Polster and Rothieux, 1995). As Squire et al. (1993) note, source amnesia is essentially a disturbance of episodic memory, a disconnection between events and their contexts, and the loss of the autobiographical, recollective, aspect of declarative memory, rather than the loss of information per se. Thus, amnesic patients with severe source memory impairments may nonetheless be able to report as much information about the original learning episode as amnesic patients who show no impairment in source memory (Shimamura and Squire, 1987).

Several authors have suggested a role for the frontal lobes in terms of support processes, rather than memory retrieval per se. For example, Moscovitch (1992, 1995a; see also Moscovitch and Umiltà, 1991) suggests that prefrontal cortex is critically involved in 'working-with-memory', i.e., post-retrieval processes that operate upon information that has been retrieved from the medial temporal lobe memory system. Thus, the prefrontal cortex can contribute to performance on episodic memory tasks, but it is thought to play a supporting role to the more central medial temporal lobe memory. By this view, information retrieved from the medial temporal system is thought to be sufficient for making simple judgements about the 'oldness' of a given stimuli (as might be required by standard tests of recognition memory), but the frontal lobes may be required if more complex judgements are required concerning the 'context' in which an a stimuli was experienced (as might be required in tests of source memory).

An important aspect of Moscovitch's view is that the frontal lobes are thought to play a strategic role in memory retrieval, guiding behavioural in a goal or task dependent manner. Similarly, Shimamura (1995) suggests that prefrontal cortex may be necessary for the control of search and retrieval processes, inhibiting irrelevant or misleading information that has been retrieved from memory. Again, the operation or use of the central medial temporal lobe memory system is characterised as being dependent upon the activity of the frontal lobes. Although there is a great deal of similarity across current views, there is by no means a consensus regarding the fine details. For example, by Moscovitch's account (e.g., Moscovitch, 1995a,b) the hippocampal memory system operates on a 'consciousness in, consciousness out' basis, such that the hippocampus acts as a record of ongoing conscious experience, and consequently 'reactivated' memories are necessarily associated with consciousness. By contrast, in recent proposals Tulving and colleagues (e.g., Wheeler, Stuss and Tulving, 1997) see the frontal lobes as being necessary for episodic memories to be conscious. The prefrontal cortex is thought to play a critical role in 'empowering healthy adults with auto-noetic consciousness'. Nonetheless, by both these views the role of the frontal lobes is 'supervisory' to that of the more central medial temporal lobe memory system.

Despite the straightforward account provided here it should not be forgotten that the frontal lobes have been widely implicated in a range of functions, including, but by no

means limited to, attention, verbal behaviour, executive functioning, motivation, emotion and affect, and working memory (e.g., see Damasio, 1979; Stuss and Benson, 1983; Stuss, Eskes and Foster, 1994; Kertesz, 1994; Schacter, 1987; Shallice, 1988). These functions are generally regarded as 'high-order' cognitive functions, associated with supervisory processes that consciously direct and structure 'lower level' functions towards specific behavioural goals. Although the frontal lobes are widely implicated in supporting high-order cognitive functions, the size and complexity (including widespread connectivity) of the frontal lobes suggest that they are neither functionally nor neurally homogenous. Nonetheless, at present the evidence for specific subdivisions of the frontal lobes in relation to memory is rare. As Wheeler et al. (1997, p334) state, "despite the possibility that lesions in different regions of prefrontal cortex produce different symptoms, much of the available evidence has been drawn from the behaviour of patients with relatively large lesions of the prefrontal cortex."

### **The neuroanatomical basis for episodic memory**

As noted above, the research presented in this thesis is primarily concerned with episodic memory retrieval – the ability to consciously remember past events. Consistent with the foregoing review, a broadly accepted view of the neural basis of episodic memory has developed over recent decades, the idea that multiple, widely distributed neural systems are responsible for the encoding, storage and retrieval of episodic information. As Rubin and Greenberg (1998) note, there is widespread belief that episodic memory retrieval involves the reactivation of the cortical activity that occurred during the original event. The idea of retrieval as 'reactivation' is characterised by a tripartite model of episodic memory. This view appears to be broadly consistent with both the declarative memory systems view, and the distinction between episodic and semantic memory discussed above.

First, the encoding of new experiences is thought to rely primarily upon the 'core' memory system; areas within the medial temporal lobes, especially the hippocampus and adjacent parahippocampal cortex. Damage to this core system is associated with anterograde amnesia, the inability to form new episodic memories. Second, although the medial temporal lobe memory system is necessary for encoding, the information itself is thought to be stored elsewhere, in the areas of cortex that mediated the initial

sensory, perceptual and conceptual processing of the episode. The reactivation of stored information is thought to involve both the core medial temporal memory system and also more strategic control processes mediated by the frontal lobes.

The third component, the frontal lobes, is not thought to contribute to the storage of information, but rather to support the retrieval processes that are required to allow access to episodic memories. Damage to the frontal lobes is associated with impaired source memory, and involvement of the frontal lobes may distinguish episodic from semantic memory. Whilst the core medial temporal lobe memory system may normally be involved in memory retrieval, the gradual consolidation of information in posterior cortex eventually allows memories to be retrieved independently of the core memory system (presumably involving the strategic processes that are supported by the frontal lobes). The process of consolidation is suggested by the fact that amnesics are better able to retrieve older than recently formed memories (although see Nadel and Moscovitch, 1997).

The view of episodic memory described above has provided the framework for neuroanatomical interpretations of the ERP correlates of episodic memory retrieval. As will be discussed in chapter 3, it is thought that the ERP correlates of episodic memory retrieval are generated by the activity of the component parts of the neuroanatomical system described above. However, the investigations of the ERP correlates of episodic memory retrieval that are of interest in the present thesis have predominantly employed item recognition memory tasks (including modified item recognition tasks that allow an assessment of source memory and associative recall). Consequently, functional interpretations of the ERP studies have predominantly been interpreted within a framework based on current models of recognition memory. The following section provides a review of these models of recognition memory.

### **Models of recognition memory**

Of central interest here are theoretical accounts of the retrieval processes that support recognition memory, a direct task that has been primarily associated with the explicit (conscious) retrieval of episodic memories. Recognition memory has been most commonly investigated using a study-test 'item recognition' task, whereby recognition is defined as the ability to correctly distinguish between items (usually words) that



have been studied (old), and items that are unstudied (new). As Mandler (1991) notes, a predominant view of memory retrieval in the 1960s was that recognition judgements were based upon a single strength or familiarity process, whilst recall occurred via a separate retrieval process. As is discussed below, such single process accounts were typically based upon a signal detection model of recognition. Behavioural studies of recognition memory in the early 1970s lead some theorists to abandon single process models in favour of more complex dual process models, based initially on the idea that retrieval processes operate in recognition as well as recall. Although the earliest dual process models were based upon a threshold model of recognition, more recent models have incorporated both signal detection and threshold accounts.

### **The formal basis of single and dual process models**

Numerous different models have been proposed to account for the retrieval process(es) that underlie recognition memory, resulting in considerable debate over the appropriateness of the different models (e.g., see Donaldson, 1992, versus Snodgrass and Corwin, 1988, with regard to non-parametric models). Several different models of recognition memory are described below, illustrating the development from single- to dual-process models, and highlighting the different formulations that the models can take. First however, it is worth considering the formal basis of the different models, which have generally been derived from signal detection and threshold theories.

#### **Signal detection models**

Findings from investigations employing the standard item recognition paradigm have been widely interpreted using signal-detection theory (e.g., see Green and Swets, 1966; Banks, 1970; Macmillan and Creelman, 1991; Snodgrass and Corwin, 1988). Models based upon signal detection theory typically represent the memory trace associated with each item along a single continuum of strength or familiarity. Although there are numerous ways of formulating signal detection models (e.g., representing old and new items as having different variances, or logistic distributions), in the most straightforward case the familiarity of both old and new items are assumed to have equal variance and to be normally distributed, with old items having a higher mean familiarity due to their having been presented at study. To discriminate between old and new items (i.e., to assess the likelihood that a test item is old), subjects must select

a specific level of familiarity (i.e., a response criterion level) above which items will be judged old. By definition the distributions of the old and new items overlap, thus, the use of a response criterion leads a subjects responses to include a proportion of misses (i.e., old items rejected as new due to their having a lower than criterion level of familiarity), and a proportion of false alarms (i.e., new items incorrectly recognised as old due to their having a higher than criterion level of familiarity).

As Macmillan and Creelman (1991; see also Macmillan, 1993) note, signal detection models offer a way of accounting for the decision processes underlying recognition memory. The models provide a measure of the extent to which subjects are able to accurately recognise old items (i.e., discrimination), and an estimate of their willingness to do so (i.e., response bias - how liberal or conservative subjects are in judging items old). For the equal-variance model, discrimination is defined as the difference between the means of the old and new distributions, divided by the common standard distribution. Note that, within this framework signal detection models effectively represent memory as a form of educated guess. That is, there is no way of determining whether a given item is genuinely old, rather, any item that has a familiarity level above the response criteria will be accepted as being old.

#### **Threshold models**

Threshold theories are based on the assumption that there are discrete memory states (rather than a continuum), and that a given test item has a probability of being old – an item will be judged old if it exceeds the memory threshold. As with signal detection theory a number of different threshold models can be formulated (e.g., see Snodgrass and Corwin, 1988, Macmillan and Creelman, 1991). The most straightforward ‘high-threshold’ model assumes a single threshold, however Snodgrass and Corwin (1988) note that the high-threshold model has not been widely employed, being easily falsified by data. Consequently, they focus upon an alternative threshold model, the two-high-threshold model, which has been widely used in studies of recognition memory.

The two-high-threshold model assumes that there are three distinct memory states, delineated by two response criterion levels (i.e., thresholds). The upper threshold determines a level of familiarity above which an item is known to be old. Conversely, the lower threshold determines a level of familiarity below which an item is known to

be new. Significantly, new items cannot cross the upper threshold, and similarly, old items cannot cross the lower threshold. However, both old and new items can lie between the two thresholds, leading to a state of uncertainty. In this state responding depends upon guessing (the response bias towards responding old or new), thus misses and false alarms always occur from this uncertain state.

There are two points worth noting here. First, the introduction of the low threshold is important, because it suggests that subjects are able both to recognise studied items as old, and unstudied items as new. By the two-high-threshold model the subject is able to respond 'new' because the item is genuinely known to be new (e.g., consider the scenario whereby a subject's own name is presented as an unstudied item). Second, although the high and low thresholds in a two-high-threshold model may differ, a single data set does not allow both thresholds to be defined. Thus, in practice, it is commonly assumed that the thresholds are equivalent, an assumption that Snodgrass and Corwin (1988) believe to be supported by the 'mirror effect' phenomenon, the finding that hit rates and false alarm rates vary inversely with one another (e.g., see Glanzer and Adams, 1985; Glanzer, Adams, Iverson and Kim, 1993; but see Green, 1996).

The two-equal-high-threshold model allows the use of a discrimination measure of recognition accuracy that accounts for the fact that the hit rate is composed of responses based upon both veridical recognition and guessing. Because guessing only occurs when an item is not veridically recognised, the false alarm rate provides a direct estimate of the likelihood that an item is judged old on the basis of a guess. Thus, discrimination is assessed by the probability of a hit, minus, the probability of a false alarm.

#### **Retrieval mechanisms versus retrieval content**

It is important to stress that threshold and signal detection models are inherently different ways of accounting for the *retrieval mechanism* underlying recognition memory performance. In essence, signal detection models represent recognition memory as being based upon a graded retrieval process based a continuum of memory states, whereas threshold models assume that there are discrete memory states and therefore that retrieval is an all-or-none process. Thus, for signal detection models there are various levels of familiarity that can occur, with increasing certainty that an

item is genuinely old, whereas for threshold models an item either is, or is not, remembered. It is equally important to recognise however, that the models do not commit the memory theorist to a specific conceptualisation of the *information content* of the memory retrieval process.

The distinction between the mechanism by which information is retrieved and the content of the retrieved information is perhaps best understood by example. Snodgrass and Corwin (1988) describe threshold models in manner that is analogous to signal detection models, based upon the retrieval of familiarity – thus the threshold defines a level of familiarity above which items are accepted as old. However, as Yonelinas et al. (1996) note, threshold theories can also be conceptualised in terms of ‘recollection’, a memory retrieval process that provides qualitative information about recognised items. By this account an item will be accepted as old because information about the prior study episode has been retrieved, including contextual information about when and where the item was encountered, going beyond a sense that the item has been previously encountered. Note however, that whilst threshold models represent retrieval as an all-or-none mechanism, Yonelinas et al. contend that the models do not necessitate that subjects must either remember everything or nothing about a study episode. On both logical and empirical grounds it is clear that different aspects of a given study episode may be remembered under different conditions (e.g., due to different memory cues being presented).

The distinction between retrieval mechanisms and the information content of what is retrieved has not been clearly drawn within the memory literature. Single process models, which typically represent recognition memory as dependent on a signal detection familiarity process, have been challenged by dual process theories. However, as is discussed below, dual process models vary both in terms of the retrieval mechanisms proposed and the information content that is retrieved. For example, ‘two-high-threshold’ models have been widely employed in studies of recognition memory, including item recognition (Atkinson and Juola, 1973; 1974) and source memory (Johnson, Kounios and Reeder, 1994), with the accounts employing equivalent retrieval mechanisms, but proposing the retrieval of different kinds of information. Before discussing dual process theories in more detail however, it is necessary to consider single process models of recognition memory.

### **Single process models**

There are various different forms of single process model of recognition memory, dating back to associative network models that allow direct access to information stored in memory (e.g., Anderson and Bower, 1972), and search models that necessitate a comparison of each test item with a list of items stored in memory (e.g., Tulving, 1976). However, of central interest here are a class of models that are known collectively as 'global matching models', which have been influential in guiding both empirical and theoretical accounts of recognition memory.

There are a number of different global matching models, including TODAM (Murdock, 1982, 1997), SAM (Gillund and Shiffrin, 1984), MINERVA (Hintzman, 1984), and CHARM (Eich, 1982). As Clark and Gronlund (1996, p37) note, "global matching models are quite simple and clear variants of signal detection models". Although the models differ in terms of their specific assumptions and methods of implementation (i.e., whether individual items are stored in distinct or distributed form) they share important common properties. In all of the models mentioned above, recognition memory involves using the cues provided at test to access (or probe) memory broadly, comparing each test item to the entire content of memory. Thus, rather than retrieving specific items from memory, the interaction between the probe and the memory store provides a global index of memory strength or familiarity. That is, a measure of the match between the item and the entire content of memory, or put another way, a measure of the activation of memory generated by the test item.

To take one example, in the SAM model (e.g., see Gillund and Shiffrin, 1984) each studied item is stored as a distinct memory trace (called an image). At study the image for each item is compared to all other images in memory, including itself and an image that represents the experimental context. The familiarity level for each of the comparisons, for all the images, are stored as an array (or matrix) of individual familiarity strengths. To make recognition decisions the information provided by retrieval cues at test is used to probe the stored images. The global match (strength or familiarity index) is given by the product of the strengths of connections between the retrieval cue and all of the images stored in memory. The resulting familiarity value for each test item is then compared to an internal response criterion, determining whether a positive recognition response should be made.

Global memory models such as SAM are able to account for a range of behavioural findings, e.g., the effect of other items in memory, on the retrieval of a specific item. A simple manipulation of list length can have a profound effect upon the recognition of a given test item – that is, recognition of an individual item decreases as more items are added to the study list (e.g., see Atkinson and Juola, 1974; Bowles and Glanzer, 1983). Associative network models of recognition memory that propose a direct access of memory information are unable to account for such list length effects, because the retrieval of individual items occurs directly, and should therefore be uninfluenced by the size of the memory store. By contrast, for the global memory models the familiarity of a test item depends not only upon a match with the stored memory representation of itself, but also upon a match to the stored memory representation of other items in memory. Thus, global memory models can account for list length effects because the recognition of a given item is influenced by the total content of memory (see also Murdock, 1997).

The SAM model illustrates the central assumption of global matching models – that recognition responses are based upon a simple assessment of familiarity. Significantly, it also demonstrates that the models do not distinguish between item and associative (contextual or relational) information. By definition, ‘item information’ represents the occurrence of individual items or events, whereas ‘associative information’ represents the connections or relations between events (cf. Humphreys, 1976, 1978). Because each item is compared to all other items in memory, the familiarity level of a given item includes information about its relationship to other items in memory. Thus, the representation of a pair of items is essentially equivalent to the representation of an individual item. No additional retrieval mechanism is proposed to allow the recovery of associative information beyond that which is available for individual items in memory. When a test probe consists of a word pair, the familiarity index is simply the summation of the joint contributions of familiarity for each item. As Gronlund and Ratcliff (1989, p847) note “item and associative information are treated inseparably in the memory representations of these models”.

#### **Item versus associative information: Experimental findings**

Unfortunately, because global memory models do not distinguish between item and associative information they have difficulty in accounting for findings from a range of

experiments where the two forms of information have been shown to be dissociable (e.g., see Clark and Gronlund, 1996; Gronlund and Ratcliff, 1989; Clark, 1992). For example, item and associative information have been found to exhibit different rates of forgetting in memory (Hockley, 1991, 1992). In these studies subjects studied semantically and associatively unrelated word pairs (e.g., shoe-table) and their memory was tested in two ways. Memory for item information was assessed using a standard 'item recognition' test, requiring subjects to discriminate single old from new items. By contrast memory for associative information was assessed using an 'associative recognition' test, whereby subjects were required to distinguish between pairs presented in the same pairing as at study, and pairs that were presented in rearranged (recombined) pairings. This procedure allowed recognition memory for item and associative information to be compared directly, with item and associative information being derived from a single stimulus event (although the tests were exclusive of each other – individual study items were only employed in one or other test).

Hockley (1991) compared performance on item and associative recognition tasks over various different study-test lags. As would be expected, item recognition performance decreased significantly as the delay between study and test was increased. In contrast however, there was no change in performance on the associative recognition task over equivalent study-test lags. The dissociation in forgetting rates for item and associative information was shown to be independent of both the overall level of recognition accuracy and subjects' confidence in their recognition responses. Furthermore, in a second set of experiments the findings were generalised from a standard yes-no recognition task to a forced choice test procedure (Hockley, 1992).

In a related set of experiments Hockley and Cristi (1996) investigated the degree to which performance on item and associative recognition tests is influenced by the encoding instructions given to subjects. They presented word pairs at study, and emphasised the encoding of either item or associative information. One group of subjects were instructed to remember the items, and were given an item recognition test immediately after the study phase, whereas the other group were instructed to remember associative information and were given an associative recognition test immediately after the study phase. Importantly, a final unexpected memory test was administered, whereby both groups of subjects were tested on both item and

associative recognition tasks. Hockley and Cristi found that emphasising the encoding of item versus associative information had differential effects on performance of the final memory tests. For subjects who were encouraged to encode item information, performance on the item recognition task was considerably better than performance on the associative recognition task. However, the opposite was not true; subjects who were encouraged to encode associative information performed equally well on both item and associative recognition tasks. Indeed, their performance on the item recognition task was equivalent to that for subjects who had emphasised item information.

Item and associative recognition have also been dissociated in several other ways. For example, whilst item recognition is superior for low than high frequency words (e.g., see Gregg, 1976; Mandler, Goodman and Wilkes-Gibbs, 1992), associative recognition has been found either to be equivalent for low and high frequency words, or to be superior for high than low frequency words (e.g., see Hockley, 1994; Clark, 1992). Similarly, performance on item and associative recognition tests are differentially affected when subjects are tested using the response-to-signal procedure. By instructing subjects to respond at various delays after stimulus presentation it is possible to investigate the time course of retrieval on a given task. At very short delays, before information is available from memory, performance is at chance. As the delay is increased performance rises above chance, providing an index of the time by which information has become available from memory. Using this procedure Gronlund and Ratcliff (1989; see also Doshier, 1988) demonstrated that information that can support item recognition judgements becomes available approximately 150 msec before information that can support associative recognition judgements. The difference in the time course of retrieval has been taken to strongly suggest that item and associative information make different contributions to memory.

The experimental dissociations between performance on item and associative recognition tasks, in particular the crossover interaction for the effects of word frequency (and similar findings in relation to the effect of the similarity of distracters, Clark, Hori, and Callan, 1993), are difficult for global memory models to account for. The results suggest that item and associative information make distinct contributions to retrieval, or put another way, that item and associative recognition tests are not



performed on the basis of entirely equivalent retrieval processes. As discussed above however, the models do not distinguish between item and associative information at either the level of representation or retrieval mechanism – both forms of information are retrieved together, as integral to the overall familiarity of a test item (cf. Clark and Gronlund, 1996; Clark, 1992; Murdock, 1997).

#### **Item versus associative information: Accounting for the data**

In attempting to resolve the discrepancy between global matching models and data, Clark and Gronlund (1996) suggest that different cues are responsible for item and associative recognition. Of course, different cues *are* presented at test. However, this is effectively a restatement of the experimental findings, and does not explain why the different cues result in different patterns of performance. Fortunately, the models can be modified to account for the data in two ways. First, at the level of representation, associative information can be stored in higher order units that contribute to recognition memory independently of the information held in units for the individual items constituting the association. Such a modification has been implemented in the case of SAM (e.g., see Shiffrin, Murnane, Gronlund and Roth, 1988), effectively recasting the model such that item and associative information are no longer treated inseparably. A second and even more radical modification is possible however. That is, simply abandoning the 'single process' assumption, and proposing differences in the retrieval processes engaged by tests of item and associative recognition. By this account associative recognition decisions are based, at least in part, upon a recall-like retrieval process, that is not required for item recognition decisions.

To maintain the single process assumption, global memory modellers favour the separation of item and associative information into lower and higher order representations. By this account, the dissociations in performance on item and associative recognition tests are taken to reflect 'information dissociations' rather than 'process dissociations' (cf. Previous discussion of task dissociations as evidence for multiple forms of memory). Whilst this possibility is feasible, it is unattractive because it necessary involves representing contextual information twice, in both the item and associative units. Moreover, when altered in this way, the models require a weighted average of the higher and low order units to be formed at retrieval (providing both item and associative information), which does not account for the differences in the time

course of retrieval discussed above. As Gronlund and Ratcliff (1989, p857) note, "time course data like these cannot be readily incorporated into the existing theoretical frameworks".

The introduction of an additional retrieval process for associative recognition is fundamentally at odds with the idea of a single-process model of recognition memory, and is therefore not favoured by global memory model theorists. Nonetheless, it is an attractive explanation. Whilst global memory models are able to account for performance on item recognition tests on the basis of a familiarity mechanism, the models generally already possess a separate retrieval process that accounts for performance on tests such as cued- and free-recall<sup>2</sup>. Because recall does not involve the presentation of the to-be-recalled item at test, it is clear that this task cannot be performed simply on an assessment of familiarity or item strength, and that a retrieval process is necessary to access stored information directly. Moreover, performance on tests of cued-recall has been shown to dissociate from item recognition in similar ways as associative and item recognition. For example, cued recall is superior for high rather than low frequency stimuli (cf. Clark, 1992; Clark and Burchett, 1994), and differs from item recognition in the effects of encoding instructions (cf. Hockley and Cristi, 1996).

The suggestion is not that associative recognition and cued recall are equivalent; dissociations in performance can easily be found between these two tasks. Rather, a recall-like retrieval process may operate to some degree in supporting associative recognition, in addition to the operation of the familiarity process that supports item recognition. Note however, that if an additional retrieval process is introduced to account for performance on tests of associative recognition, it seems nonsensical to assume that the retrieval process operates exclusively for associative recognition, and cannot contribute to performance on tests of item recognition. Thus, if it is accepted that an additional process operates in associative recognition, single process models

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2 An interesting example is the distributed associative model proposed by Humphreys, Bain and Pike (1989), whereby recognition memory is thought to depend solely upon a matching process that provides an index of familiarity (comparable to global memory models, Humphreys, personal communication). Within this framework differences in performance across recognition tests are accounted for in terms of the task demands placed upon the subject, rather than differences in the processing operations engaged. However, the model also proposes a retrieval process (which provides associative, contextual information) that supports recall and free-associating. Thus, to account for the dissociations between item and associative recognition, the model could be adapted such that both the matching and retrieval process support performance on recognition memory tests.

almost inevitably become dual process models. As will be discussed below, dual process theorists have drawn similar conclusions regarding the involvement of a retrieval process in supporting both associative and item recognition.

In sum, there is much to recommend signal detection models, not least their simplicity and ability to account for a wide range of experimental findings. For example, Snodgrass and Corwin (1988) demonstrate that signal detection theory provides relatively sensitive measures of discrimination and response bias in normal and patient populations. Nonetheless, 'single process' signal detection models of memory have become relatively unpopular within the cognitive memory literature. One reason for the decline of the signal detection models is their inability to account for changes in performance associated with experimental manipulations, including, but not limited to, those involving item and associative recognition. For example, Yonelinas, Dobbins, Szymanski, Dhaliwal, and King (1996) suggest that signal detection models do not adequately account for changes in performance that occur on tests of item recognition when the number of presentations of study items is varied, or when depth of processing is manipulated. Consequently, dual process models have largely supplanted single process models.

### **Dual process models**

Dual process models are firmly based upon the proposal that there are two routes to recognition. Alongside an assessment of familiarity, recognition memory performance can also be based upon recollection, the retrieval of information about the prior episode in which a test item was experienced. To be clear, recollection is defined as the retrieval of contextual information, beyond a simple assessment of familiarity or memory strength. Although both familiarity and recollection can support recognition memory judgements, only recollection provides information about specific learning episodes (as might be assessed by context or source judgements). Thus, dual process models distinguish between different retrieval mechanisms, but this separation incorporates a distinction in terms of the information content that is retrieved. Rather than choose between a distinction at the level of representation or mechanism, dual process models combine the two.

### **Atkinson and Juola: A threshold model**

Atkinson and Juola (1973, 1974) extended two-high-threshold models, exchanging guessing (which occurs when an item's familiarity level lies between the two thresholds) with a separate retrieval process. Atkinson and Juola developed their dual process theory from associative network models, which represent memory as dependent on the accessing of nodes within a lexical store (each node representing a single concept or word). When presented with a list of words, the words are encoded and mapped onto the appropriate node or combination of nodes. Earlier associative network models (e.g., see Anderson and Bower, 1973) proposed that nodes are accessed directly at test. However, by such direct access models, new items can only be correctly rejected if the memorised study list is exhaustively searched, contrary to experimental data demonstrating that speeded correct rejection responses do indeed occur (e.g., see Atkinson and Juola, 1974).

Atkinson and Juola proposed that the accessing of nodes simply results in a change in familiarity (or activation), and an additional memory store is created, containing an array of codes relating to the nodes that were accessed. When presented with a test list, items are mapped to the relevant nodes in the lexical store, providing an index of each item's familiarity. Familiarity levels lying above the high criterion result in positive recognition responses, and familiarity levels below the low criterion result in correct rejections. Thus, familiarity provides a reliable indicator of list membership for very low or high familiarity levels, allowing a rapid response to such items. When an intermediate familiarity value occurs, an extended memory search is implemented, comparing the codes associated with the current item, to the stored codes for the memorised list. This is the second route to recognition (i.e., recollection – the actual retrieval of information from the learning episode), which, because of the extra search/retrieval process, is associated with slower, accurate, and highly confident, responses.

There are several sources of support for the model proposed by Atkinson and Juola. For example, Juola, Fischler, Wood and Atkinson (1971) manipulated the familiarity level of distracter (new) items, by using synonyms of target (old) words as distracters, leading to increased response times compared to when non-related distracters were used. Atkinson and Juola's model accounts for this finding by assuming that increased

semantic relatedness causes the distracter items to have increased familiarity levels, pushing new items above the lower threshold, necessitating more extended memory searches, and thus increasing response times. Similarly, Atkinson and Juola (1973) varied the familiarity level of old items by including these items either once, twice or three times within the study list. Response latencies and error rates were lower for repeated items, compared to those occurring once, reflecting increased familiarity, which reduces the need for extended memory searches (as more items are above the high threshold).

Atkinson and Juola's model marked a significant theoretical development. For example, introducing the concept of relative familiarity; the familiarity level is a function of the time since a node was last accessed, relative to the total number of times the node has been previously been accessed. However, such associative network models have become unpopular. For example, because they are unable to account for memory for entirely novel stimuli that are not represented by an existing node within the lexical store. Nonetheless, the model illustrates that early dual process theorists represented recognition memory as being fundamentally dependent on familiarity. The secondary retrieval process is only employed when the familiarity level of an item leaves the subject uncertain. Whilst Atkinson and Juola characterise recollection as being contingent upon familiarity, Mandler (1980) suggests an alternative account, whereby the two processes are independent.

#### **Mandler: An independence model**

Mandler (1980) illustrates his dual process theory by considering the everyday experience of recognising a person on a bus, identifying them as being familiar, but being unable to remember any specific details about the person until a search of memory has occurred to identify when and where the person has been previously experienced. Thus, whilst recognition can occur on the basis of a familiarity judgement, a retrieval process is necessary if detailed contextual information is to be retrieved. Mandler describes the characteristics of familiarity and recollection in some detail. Familiarity is seen as a process of 'intraitem integration', whereby increased exposure to an event leads to greater structure, organisation and stability amongst the sensory and perceptual features of an event (in contrast with Atkinson and Juola's assumption that semantic information influences familiarity). Mandler (1980, p256) is

equally clear about recollection, proposing that the “retrieval processes involved in recognition are essentially the same as those involved in recall”.

Empirical support for this dual process model comes from experiments by Mandler, Pearlstone and Koopmans (1969). Mandler et al., manipulated the organisation of items in a study list, and then tested memory at varying delays. They found that recognition memory was relatively uninfluenced by organisational effects when tested immediately (i.e., the organisation of study items had little effect on recognition rates), but became more dependent upon them over time. This contrasted sharply with the findings for recall; the organisation of study material had a large impact initially, an effect that decreased over time. Following this Mandler (1980) argued that occurrence information (i.e., familiarity) decays from memory more quickly than does organisational information (i.e., recollection). Increased organisation facilitates recollection, and becomes more important as familiarity decreases (see Mandler, 1991, for further discussion).

Although Mandler’s proposal has much in common with Atkinson and Juola’s (e.g., the notion of relative familiarity), the two models are not entirely equivalent. Whilst Atkinson and Juola employed a ‘two-high-threshold’ model, Mandler rejects this in favour of the simpler ‘two-equal-high-threshold’ model. Formally,

$$P(\text{recognition}) = R + (1 - R) F$$

$$\therefore P(\text{recognition}) = R + F - RF$$

The probability of a correct recognition response equals the probability that an item is recognised on the basis of recollection (R), or recognised on the basis of familiarity (F) given that the failure to recollect. Whilst formally equivalent to the two-equal-high-threshold model described earlier, the model replaces guessing with recollection. Thus, by this account, no responses are made on the basis of guessing. Moreover, Mandler rejects the claim that subjects correctly reject new items on the basis of their low familiarity levels, although it is accepted that certain experimental manipulations may encourage this form of responding (e.g., when time pressures are imposed, as in the studies of Atkinson and Juola, 1974).

Finally, Mandler rejects the idea of sequential processes, whereby familiarity is followed by a conditional search. Rather, recognition is thought to occur on the basis

of two additive and separate processes – a relationship of independence, whereby one or other processes can contribute to performance. However, there appears to be little direct evidence in support of this change, beyond the assertion that it is “more reasonable to suggest that both processes are initiated upon event presentation” (Mandler, 1980, p268). Nonetheless, there is considerable overlap between the proposals of Mandler, Atkinson and Juola, and the modification of single process models discussed earlier. In each case, it is proposed that item recognition is supported by two processes – familiarity and a retrieval process (recollection) – the later of which also supports recall.

#### **Jacoby: The fluency heuristic**

Jacoby and colleagues have formulated a very different dual process model. In support of their model Jacoby and Dallas (1981) start by arguing that a single process model cannot account for the memory impairment found in amnesic patients. As discussed earlier, amnesics show impaired performance on direct tasks such as recognition memory, whilst having normal performance on indirect tasks such as perceptual identification. The comparison of the two processes contributing to recognition memory with amnesics’ pattern of impaired memory performance marks a significant change in the formulation of these processes; familiarity becomes more closely allied to implicit memory processes associated with performance on indirect tasks (i.e., priming, as discussed previously). Whilst this is a quite different conceptualisation of familiarity than was originally intended in signal detection and early dual process models, it has become a widely accepted conceptualisation of familiarity (cf. Hintzman and Curran, 1994; Knowlton and Squire, 1995). The appropriateness of this view, and the potential relationship between familiarity and priming is discussed in more detail below. First, however, the model is worth considering in more detail.

Jacoby and Dallas (1981) proposed that recollection (the retrieval of the episode in which an item previously occurred) is the central process supporting recognition memory, and is influenced by factors such as level of processing. Note that the characterisation of the information content of recollection is equivalent to that proposed in previous dual process models. By contrast, familiarity is seen as dependent on a ‘fluency heuristic’, related to the perceptual processing of an item. Specifically, the easier (i.e., relatively more fluent) that processing is, then the more familiar the

item will be judged to be. Jacoby and Dallas' account of familiarity is clearly very different from the earlier accounts. Notably, the 'fluency heuristic' is an attributional process, whereby changes in fluency only influence recognition when differences in the ease of processing among items are taken to reflect differences in the 'oldness' of the stimuli.

Jacoby and Dallas (1981) originally argued that subjects notice differences in fluency of processing, and an awareness of these differences is (consciously) attributed to past experience. However, the specific characterisation of familiarity has changed significantly over time. For example, in a more recent formulation Whittlesea, Jacoby and Girard (1990) argue that the attribution of fluency information occurs unconsciously. This account is based on a 'constructivist' theory of conscious awareness, whereby unconscious processes are seen as making as much sense as is functionally useful from sensory data, prior to information becoming available to awareness. Importantly, Whittlesea et al., view 'attribution' processes as the basis for subjective experience, rather than as constructed within it. The two accounts of fluency noted above clearly differ as to whether or not the attribution is conscious, a shift in emphasis that seems to match the development of the 'process dissociation procedure' (PDP discussed below), which characterises familiarity as an automatic process that can contribute to recognition memory performance.

According to Jacoby's model, differences in the perceptual characteristics between study and test (such as modality changes, or stimulus degradation/masking) will lead to poorer fluency and thus less familiarity based recognition, whilst factors facilitating fluency (such as frequency of prior experience) will enhance recognition. Note, however, that the attributional basis of familiarity means that differences in fluency only result in increased recognition when subjects both register differences in the fluency of processing for some items, and attribute this difference to those items being old. This means that if changes in fluency do not result in changes in recognition, it is always possible to claim that subjects are not attributing the changes to the past.

Notwithstanding concerns about the conceptualisation of familiarity (including the possibility that it is impossible to falsify) support for a connection between familiarity judgements and relative perceptual fluency can be found in a variety of studies. For example, Jacoby and Whitehouse (1989) tested the influence of subliminal pre-



exposure of an item (i.e., unconscious repetition) on item recognition. At study subjects studied a list of words. At test, a context word (i.e., prime) was briefly (subliminally) displayed prior to presentation of some old words. When the context word was a repetition of the test item processing (as indexed by recognition performance) was facilitated, whereas when it was a different word processing was disrupted. Significantly, the effect even occurred for new items (i.e., pre-exposure to the same context word increased false alarm rates) showing that subjects can be induced to falsely recognise items that they have not seen at study. Moreover, Jacoby and Whitehouse found that, compared to subjects who were naïve, subjects that were made aware of the pre-exposure (prime) produced the opposite pattern of results – presumably because they were able to correctly attribute differences in fluency to the pre-exposure.

Support for the ‘fluency heuristic’ can also be found in experiments that manipulate fluency without the repetition of items. Whittlesea, Jacoby and Girard (1990; although see Watkins and Gibson, 1988) manipulated the subjective experience of familiarity by occluding stimuli with either a heavy or light visual mask. Subjects were not informed of the masking manipulation, which was orthogonal to whether items were old or new. Nonetheless, for both old and new words, recognition performance was impaired for the heavy compared to light mask, suggesting that easier perceptual processing did influence recognition memory. Moreover, as Jacoby and Whitehouse found, when subjects were informed of the variations in visual occlusion, the manipulation no longer had any effect upon recognition memory.

Finally, because familiarity judgements based on the ‘fluency heuristic’ are seen as dependent on an attributional process, Jacoby and Dallas see the current aims and goals of the subject as critically important. Consequently, researchers have manipulated perceptual fluency in a variety of contexts, and found that subjects will misattribute items that have been previously presented (as opposed to novel items) as having longer duration of presentation (Witherspoon and Moscovitch, 1989), as being presented in louder background noise (Jacoby, Allan, Collins and Larwill, 1988), and as being anagrams which others would find more difficult to solve (Jacoby and Kelly, 1987). A particularly interesting example of the misattribution of fluency comes from Jacoby, Kelley and Dywan (1989). In the context of the process dissociation procedure, they

showed that simply reading a name in the first part of the experiment increased the probability that it would later be judged to be famous. This finding is significant, because it suggests that information from a previous presentation can influence responding on semantic memory tasks, not just on episodic memory tasks.

#### **The Process Dissociation Procedure**

Jacoby and Dallas (1981) originally claimed that their dual process model was broadly in agreement with Mandler's. Jacoby has gradually moved away from this position however, arguing that the two approaches are significantly different (e.g., see Jacoby, 1991b; Whittlesea et al., 1990; Jacoby et al., 1989). Specifically, Jacoby and colleagues suggest that Mandler's model is based on 'naïve realism', whereby recognition memory is dependent on the activation of memory traces, giving rise to an output such as the level of familiarity of an item. Importantly, Mandler's model treats familiarity as an explanatory concept, which can account for subjects' performance on recognition tests. Jacoby et al., argue that such a view of memory is insufficient to account for the illusions of memory that changes in perceptual fluency can bring about. More specifically, familiarity simply cannot be the direct consequence of the use (or accessing) of a memory trace, as illusions of recognition can occur when such a trace does not even exist (discussed above). Whilst it is not denied that memory traces play a role in memory, the point is that representations within memory are neither necessary nor sufficient to produce the subjective experience of remembering.

The change in approach noted above appears to coincide with Jacoby and colleagues' (Jacoby, 1991a; Jacoby et al., 1992) developing a method for separating different bases for performance on memory tasks. The process dissociation procedure (PDP) is founded on the belief that experimental tasks are not 'process pure' (as discussed above; see Jacoby, 1991b; Dunn and Kirsner, 1989). More specifically, it is assumed that task performance represents a blend of automatic and intentional processes. In the context of recognition memory, the assumption is made that recollection is a consciously controlled (intentional) use of memory, whilst familiarity is an automatic (unconscious) use of memory, and that the two processes operate independently.

Estimates of the influence of recollection and familiarity on recognition performance can be calculated by applying mathematical formulae to subjects' recognition performance on two experimental tasks, that are designed to vary the consequences of

responding on the basis of recollection and familiarity (the method of opposition). Firstly, subjects study items in two different contexts, a target and a non-target context (e.g., reading words versus making words from anagrams respectively). Subjects are then tested in two different ways. In the 'inclusion' condition, subjects are instructed to respond 'old' to both target and non-target context items. By contrast, in the 'exclusion' condition subjects are instructed to respond 'old' to items from the target context only (e.g., items that were read), but to respond new both to items from the non-target context (e.g., items that were presented as anagrams) and genuinely new items.

On the assumption that recollection (R) and familiarity (F) act as two independent means for responding old to a target item (i.e., read words in the example given above), two recognition scores can be calculated. The inclusion score is the probability of correctly recognising a target word as old. Given the instructions, both recollection and familiarity will serve as bases for recognition responses

$$p(\text{'old'}|\text{inclusion}) = p(R) + p(F) - p(R \cap F)$$

The exclusion score is defined as the probability of the endorsement of a non-target item as a target. Given the task instructions this will only occur when non-target items are familiar but not recollected, because subjects can intentionally use recollection as a means for correctly rejecting non-targets

$$p(\text{'old'}|\text{exclusion}) = p(F) - p(R \cap F)$$

Given that performance measures from the inclusion and exclusion tests are known, the above formulae can be rearranged to calculate the probability of recollecting a target item across the two experimental conditions

$$p(R) = p(\text{'old'}|\text{inclusion}) - p(\text{'old'}|\text{exclusion})$$

Finally, the resulting measure of recollection can be used to calculate the probability of recognising an item on the basis of familiarity, using either the inclusion or exclusion formulae. Looking at the results of Jacoby (1991), the probability of recognition was larger for anagrams than read words in the inclusion condition, whilst the opposite was true in the exclusion condition. Calculated from this, the PDP showed that recognition of anagrams was more reliant on familiarity than was recognition of words.

Jacoby and colleagues have presented a range of evidence in support of the PDP (e.g., see Jacoby, Yonelinas and Jennings, 1996; Jacoby, 1997; for reviews). For example, Jacoby (1991) calculated estimates of familiarity and recollection when recognition memory was tested under conditions of divided or full attention, revealing that divided (compared to full) attention caused a reduction in the probability of recollection, whilst leaving the probability of familiarity unchanged. Similarly, Jennings and Jacoby (1993) compared the performance of young and old subjects using the PDP. They demonstrated that the elderly subjects made significantly fewer recollection-based responses, but equivalent proportions of familiarity-based responses – suggesting a differential impairment in recollection based responding in elderly subjects. Finally, Yonelinas and Jacoby (1994) demonstrated that increasing the length of study lists lead to decreasing levels of recollection based responding, whilst leaving familiarity levels unaffected.

The PDP is an ingenious method for separating the influences of automatic from controlled processing and has become a widely employed across different memory tasks (e.g., word-stem completion, see Jacoby, Yonelinas and Jennings, 1993). Evidence that experimental manipulations can lead to dissociations in the measures of recollection and familiarity have been taken as support for the assumption that performance on such tasks is based upon independent underlying processes. Nevertheless, debate surrounding the process dissociation procedure has been extensive (e.g. see Curran and Hintzman, 1995; Richardson-Klavehn, Gardiner and Java, 1996; Dodson and Johnson, 1996; Mulligan and Hirshman, 1997; Clark and Gronlund, 1996; Jacoby, 1996; Jacoby, Begg and Toth, 1997; Jacoby, Toth, Yonelinas and Debner, 1994; Yonelinas, Regehr and Jacoby, 1995; Jacoby, 1997). For example, the procedure has been modified such that the inclusion and exclusion conditions are embedded in a single testing session, avoiding the possibility that the likelihood of recollection and familiarity could be invariant in the two conditions, a major criticism of the early experiments employing the process dissociation procedure (cf. Graf and Komatsu, 1994; De Houwer, 1997). Similarly, the procedure has been criticised for not accounting for response bias, leading to refinements such as the multi-nomial models proposed by Buchner and colleagues (e.g., see Buchner, Erdfelder, Steffens and Martensen, 1997; Buchner, Erdfelder, Vaterrodt-Plunnecke, 1995).

Debate surrounding the process dissociation procedure is not of central interest here. However, it is worth noting that one of the most significant criticisms of the approach is that it dramatically shifts the focus of the 'dual process' debate. Several authors (e.g., Richardson-Klavehn, Gardiner and Java, 1996) note that the PDP assumes that specific forms of memory are associated with specific forms of awareness, and moreover, confounds awareness with intention – the instructions given to subjects are based upon the ability to *use* information that is retrieved from memory in a controlled manner. As Clark and Gronlund (1996) point out, the procedure essentially amounts to a list-discrimination experiment, and is analogous to a source memory task, whereby information retrieved from memory is used to distinguish between different classes of study item. More significant perhaps is the changing formulation of familiarity.

Whilst the PDP is (in principle) neutral about whether familiarity is an explicit or implicit memory process, the characterisation of familiarity as an automatic process has lead to it being tied to implicit memory processes such as priming. This view is well characterised by Wagner, Gabrieli and Verfaellie (1997, p305), who state that "Dual process theories of recognition posit that a perceptual familiarity process contributes to both explicit recognition and implicit perceptual memory. This putative single familiarity process has been indexed by inclusion-exclusion, remember-know, and repetition priming". However, Wagner et al. go on to suggest that this is an inappropriate view, demonstrating that 'familiarity' associated with recognition memory is facilitated by conceptual (compared to perceptual) processing, whereas 'familiarity' associated with word-identification priming is facilitated by greater perceptual processing.

Whether familiarity can or should be explained in terms of implicit memory processes such as priming is a matter of ongoing debate. For example, Mayes (1991) discusses three possible relationships between the processes involved in priming and recognition memory. Priming and recognition memory may be anatomically and functionally distinct; priming may be involved in supporting familiarity as a basis for recognition, but not in supporting recollection; or, familiarity may be dependent upon priming, but priming may be a necessary but not sufficient condition for accurate familiarity based responding. All three relationships are plausible, however, dissociations between recognition memory and priming suggest that they are anatomically and functionally

distinct. For example, Gabrieli, Fleischman, Keane, Reminger and Morrell (1995; see also Hamann and Squire, 1997; and earlier discussion of explicit and implicit memory) demonstrate a double dissociation between recognition memory and priming. A patient with damage to the right occipital cortex exhibited impaired priming but intact recognition memory, whereas amnesic patients with damage to the medial temporal lobes exhibited impaired recognition memory and intact priming.

More directly, Hintzman and Curran (1994) argue that the reformulation of familiarity as an automatic process is simply inappropriate, because the use of both processes is intentional (i.e., determined by the task instructions). They employed the response-to-signal procedure to show that recognition memory is associated with two classes of response; fast and slow (consistent with the findings of Atkinson and Juola, discussed above). Hintzman and Curran compared item recognition memory performance to target items and very similar distracters, and found that whilst distracter items were falsely recognised at shorter response delays, subjects were able to correctly reject the distracter items when longer response times were allowed. This finding was interpreted as evidence for a fast familiarity process that supported the early responses, and a slower recall process that could be employed when longer response intervals were available, allowing a more accurate check to be made on distracter items.

Hintzman and Curran suggest that both the faster familiarity and slower recollection processes can contribute to recognition performance, with the influence of each process depending on the nature of the task. Moreover, they argue that the apparent dominance of familiarity may be due to its faster availability and simpler uni-dimensional nature, rather than due to it being an automatic process – a suggestion that accounts for a variety of experimental findings, such as the reliance on familiarity during divided attention, without recourse to viewing familiarity as an automatic ‘implicit’ memory process. However, it remains to be seen whether recognition memory should be characterised as being reliant on three memory processes – recollection, familiarity and priming (cf. Rugg et al., 1998).

Notwithstanding the differences between Mandler and Jacoby’s accounts with regard to familiarity, an important similarity between them is that they both propose a relationship of independence between the two bases for performance (see Jones, 1987; and Joordens and Merikle, 1993; for further discussion of the possible relationships).

By contrast, the early dual process models (e.g., see Atkinson and Juola, 1973, 1974) which were developed from previous single process models characterised familiarity as the primary basis for making recognition judgements, with recollection being contingent upon familiarity<sup>3</sup>. A third relationship is also possible however – exclusivity, whereby recognition is associated with one or other, but not both processes. As is discussed below, Gardiner and Java (1993) have proposed an exclusivity model.

#### **Remembering and Knowing: An exclusivity model**

The Remember/Know procedure was introduced by Tulving (1985a), again aimed at distinguishing between recollection and familiarity. This procedure is based on subjects' reports about their phenomenological experience of recognition. Whenever a subjects judge an item to be old, they must report whether this is accompanied by a recollection of previously encountering the item (R - remember), or a general sense of familiarity for the item (K - knowing). Gardiner and Java (1993) propose a relationship of exclusivity between R and K responses, because at the level of conscious experience, recognition memory is necessarily associated with either a sense of recollection or familiarity. The Remember/Know procedure has been used extensively by Gardiner and colleagues, the results being interpreted both as an alternative to PDP, and as the basis for a model of recognition memory. Before looking at the experimental data that has been produced with this method, it is necessary to note the theoretical context in which Gardiner and Java (1983; see also Gardiner, Java and Richardson-Klavehn, 1996) place their work.

Gardiner and colleagues have described the R/K approach to recognition memory as a 'first person' account of memory, concerned with analysing memory at the level of phenomenological experience. By contrast, the dual process models discussed previously are 'third person' accounts, concerned with analysing memory at the level of underlying processes. Based upon a review of psychological approaches to the study of conscious and unconscious processing by Velmans (1991), Gardiner and Java argue that first and third person accounts are not commensurable, both being necessary for a

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<sup>3</sup> The correct characterisation of Atkinson and Juola's model is unclear. The model is clearly not one of exclusivity or independence – recollection is contingent upon familiarity, and recollection based responses cannot occur in the absence of familiarity. Nonetheless, if the relationship was one of redundancy then recollection should, by

full explanation of behaviour and consciousness. Specifically, Gardiner and Java's argue for the 'inconvertibility of terms'. That is, terms should have meaning at either the level of memory task, hypothetical construct, or state of awareness, and should not be used across different levels of analysis, because the transfer of terms across levels presupposes an identity between the levels. Nonetheless, the R/K procedure has been interpreted at both first and third person levels of analysis, and has been employed to provide data that has been interpreted within the dual process debate.

As with the PDP a range of experiments have been performed using the R/K procedure, providing evidence for three forms of dissociations. First, variables have been found that alter recognition levels with the effect being due entirely to changes in R responding, whilst K responding remained constant (e.g., depth of processing Gardiner, 1988; divided attention, Gardiner and Parkin, 1990; and word frequency Gardiner and Java, 1990). Second, variables have been found that influence K but not R responding, (e.g., masked primes, Rajaram, 1993). Finally, variables have been found that have opposing effects upon R and K responding. For example, Parkin and Walter (1992) found that whilst for young subjects recognition responses were associated with more R than K responses, for elderly subjects the opposite was true. Similarly, Gardiner and Java (1990) found that whilst recognition of words depends on higher levels of R than K responding, recognition of non-words depends on higher K than R responding.

The findings from studies employing the R/K procedure are in general agreement with the experimental findings from equivalent process dissociation experiments. However, at the processing level of analysis the two approaches need not provide equivalent results, because their underlying models assume different relationships between the memory processes. For example, Yonelinas and Jacoby (1995) contrasted the PDP and R/K procedures in relation to recognition memory for size congruent and incongruent shapes. Subjects were shown a series of shapes at study, and at test were shown the same shapes in either congruent or incongruent size. As expected, the PDP model showed that both recollection and familiarity based responding increased for size congruent compared to incongruent items. By contrast, the R/K procedure showed that

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definition, never be necessary – familiarity should always be sufficient to support performance (M. D. Rugg, personal communication).



size congruency lead to greater recollection, but less familiarity based responding. Thus, counter-intuitively, by the R/K account changes in stimulus size do not lead to less familiarity.

Clearly, if subjects respond 'Remember' whenever familiarity and recollection co-occur, then the R/K procedure will underestimate the proportion of responses associated with familiarity. Noting this, Yonelinas and Jacoby (1995) produced an alternative R/K procedure, in which the original exclusivity assumption is replaced with an independence assumption. K judgements are no longer measured as the absence of R judgements, rather the proportion of K responses is divided by the opportunity for making such judgements (i.e.,  $1 - R$ ). With this alternative formulation, the 'independent R/K' model produces results that are in agreement with those of the PDP.

A second study that highlights the differences between the PDP based model and the R/K procedure comes from Knowlton and Squire (1995). They investigated the pattern of R and K responding by amnesic patients, and found that both types of response were impaired in amnesics compared to the performance of normal subjects. Moreover, by tracking the responses associated with individual items, Knowlton and Squire demonstrated that a significant number of items that initially receiving R responses become associated with K responses over time. This finding is difficult to reconcile with an 'exclusivity' dual process model, rather, suggesting a relationship of redundancy (see Knowlton, 1998, for further discussion).

Within the framework of memory processes, an independent R/K procedure is more attractive than the original exclusivity version. However, in employing the R/K procedure in this way the independent R/K simply becomes an alternative version of the PDP, using subjective awareness rather than conscious control as a means of separating processes. Note though, that Gardiner and Java (1993) state that they see this as inappropriate, because the R/K procedure was intended to measure phenomenological experience. Unfortunately, recent investigations (e.g., see Donaldson, 1996; Hirshman and Master, 1997) suggest that the majority of findings from the 'third person' exclusivity R/K procedure can be accounted for by a single process signal-detection model that incorporates two response criteria (i.e., old/new

and R/K criteria). By this account the R/K procedure is of questionable worth at either the processing or phenomenological levels of analysis.

### **A dual process account of associative memory**

Notwithstanding the differences between the dual process models described thus far, it would be inappropriate to conclude that the models do not share important similarities. In each case, 'recollection' is an effortful retrieval process that provides contextual information about the specific prior study episode in which an item was experienced, and is associated with the phenomenological experience of remembering. Moreover, there appears to be agreement across the PDP and R/K procedures concerning the measure of recollection, regardless of the exact characterisation of familiarity, or the relationship between familiarity and recollection. Thus, whilst they do so for different reasons, the dual process models discussed above all reject a unitary view of recognition memory.

Of central interest here is the question of how dual process models account for the findings from tests of associative recognition. As was discussed earlier, single process models are unable to account for dissociations between item and associative recognition, and it has been suggested that performance on tests of associative recognition cannot be supported by familiarity. Whilst global memory theorists favour a distinction between item and associative information in terms of the information content or representation in memory, rather than in terms of the retrieval mechanism or process. However, it should be clear that dual process models generally distinguish between item and associative information in terms of both retrieval content and mechanism. Recollection provides contextual information and is a slow effortful process, whereas familiarity provides non-contextual information and is a faster, more automatic process. Given the formulation of dual process models, it should be clear they are ideally placed to account for the dissociations in performance on tests of item and associative recognition.

An explicit attempt to account for the dissociation between item and associative recognition has been made by Yonelinas (1997; see also Yonelinas, 1994; Yonelinas et al., 1996) in the context of a recent dual process model. This 'mixed' model incorporates both signal detection and threshold theory – combining aspects of the

models described above. By this account familiarity is described as an equal-variance signal detection process<sup>4</sup>, whereas recollection is a threshold process. The basis for this model is the assumption that when subjects recollect information about specific study episodes they are in a discrete memory state (they either do or do not retrieve), whereas judgements that a study item is familiar are assumed to be continuous in nature. Recollection based responses are viewed as always being highly confident, whereas familiarity based responses can vary from low to high confidence.

Support for this dual process model comes from studies using receiver operating characteristics (ROC curves, i.e., a plot of the probabilities of correct recognition against false alarms, across response confidence levels). Several studies have investigated the ROC curves for item memory when performance is dependent solely on familiarity, solely on recollection, or on a combination of the two. For example, Yonelinas and Jacoby (1995; see also Yonelinas et al, 1996; and Yonelinas, Kroll, Dobbins and Lazzara, in press, in relation to data from amnesic patients) showed that as performance relies more on recollection, the associated ROC curves move from being curvilinear asymmetrical functions, towards flat functions. Similarly, Yonelinas (1994) employed the PDP procedure in tandem with an analysis of ROC curves. When responding was based primarily on familiarity a symmetrical ROC curve was produced, consistent with performance being based on an equal-variance signal-detection process. By contrast when recollection based responding was introduced (by reducing the length of the study list) the ROC curve became asymmetric, consistent with the additional contribution of a threshold process<sup>5</sup>.

Yonelinas (1997) has provided further support for the distinction between item and associative recognition, based upon three experiments investigating their associated ROC curves. It was predicted, and found, that item recognition judgements lead to curvilinear asymmetrical ROCs. By contrast, associative recognition judgements were found to produce flat ROCs. A dual process model (incorporating familiarity and recollection processes) fitted the item recognition data, whereas a linear threshold

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4 Familiarity is used as an 'umbrella' term, loosely defined as memory in the absence of recollection, which may prove to reflect the combination of both an explicit 'familiarity' process and an implicit 'priming' processes (Yonelinas, personal communication).

5 Note that, alternatively, the asymmetrical ROC curve could be interpreted as evidence that the equal-variance assumption has been violated, and that familiarity is not normally distributed. Thus, a more complex single process

model (representing just recollection) fitted the associative recognition data. Thus, by this dual process model, item and associative memory differentially engage the processes that are thought to underlie recognition memory, with performance on tests of associative recognition relying primarily on recollection – a finding that converges with the conclusions drawn with respect to global memory models.

As was noted above, one significant feature of threshold theories is that they assume subjects are able not only to recognise studied items as old, but also to actively recognise that unstudied items are new. This feature of threshold theory is particularly appealing in the case of associative recognition. Clearly, a subject could recognise a single member of a test pair, and in recollecting the original study associate of this word, correctly conclude that the test pair was not presented at study – hence ‘recollecting’ that a test pair was rearranged. Yonelinas was able to investigate this feature of the threshold account of recollection, manipulating the difficulty of recollecting rearranged pairs across experiments, by presenting each item in one or two pairs at study. Analysis of ROC curves suggested that recollection was not used very often as a basis for responding rearranged, but that when it was made easier for subjects to do so, subjects did use recollection as a basis for recognising rearranged pairs (i.e., more rearranged pairs were recollected when items were presented in two rather than one pairing at study). Thus, Yonelinas’ data provide support for the idea that associative recognition is based upon recollection, and moreover, that recollection is well characterised as a threshold (all-or-none) process. Subjects both recollect that the majority of same pairs were studied together, and also recollect that a smaller proportion of rearranged pairs were not studied together.

Finally, it is worth noting that several earlier experiments investigated recognition memory for associative information itself, further stressing the importance of relational (contextual) information in supporting this form of memory. For example, Humphreys (1976, 1978) had subjects study word pairs, and at test subjects made old/new judgements to same, rearranged, and new, pairs. Humphreys found a recognition advantage for same compared to rearranged pairs, and similar effects were found in a forced choice test comparing just same and rearranged pairs, even when confidence

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model could be proposed to account for the data, incorporating a skewed familiarity distribution, without modelling recollection as a separate threshold process.

judgements were used instead of a yes-no response. Moreover, the differential recognition advantage for same pairs was larger when relational information was stressed in instructions, compared to when item information was stressed, and the recognition advantage for same pairs held regardless of whether associatively related or randomly formed word pairs were employed (e.g., see Underwood, 1974).

## Summary

The discussion of memory presented in this chapter covers considerable ground. The initial discussion of the fractionation of memory highlighted the important distinctions that have been drawn between forms or kinds of memory. In doing so, several important issues were addressed, including debate over the significance of different kinds of evidence in drawing distinctions between forms of memory, and concern that individual tasks cannot be assumed to be 'process pure'. Nonetheless, it is clear that memory is not a unitary phenomenon, and that distinctions can and must be drawn between different forms of memory.

The following section provided a brief account of the neuroanatomical memory systems that are thought to underlie episodic memory, that is, conscious memory for specific prior experiences. The core role of the medial temporal lobe memory system as a 'relational' processor was discussed, along with the suggestion that the frontal lobes may also play a part in supporting episodic memory. Notably, the frontal lobes are thought to be associated with strategic aspects of performance, rather than with the retrieval of information per se.

The final section addressed current models of recognition memory, reviewing both single and dual process models of memory. Data from studies of item and associative recognition memory were shown to be difficult for single process models to account for, necessitating a distinction between item and associative recognition in terms of the content (representation) of information in memory, and/or the processes engaged at retrieval. A number of dual process models were described and compared, highlighting the many differences between the models (e.g., differing in terms the proposed relationship between the retrieval processes), but also revealing some consensus regarding the characterisation of recollection – the explicit retrieval of contextual information about specific prior study episodes. More significantly for present

purposes, dual process models of memory converge with global memory models in suggesting that associative recognition tests cannot be performed on the basis of familiarity; successful performance requires that subjects retrieve contextual (relational) information about the specific prior episodes in which stimuli were experienced.

Thus, from the perspective of dual process models, memory for item and associative recognition differ in terms of both information content and retrieval process. Associative recognition is based upon recollection, whereas item recognition can be based upon either familiarity or recollection. Notwithstanding the significance of this finding in relation to current models of recognition memory, the importance of this finding can be best appreciated in relation to the findings from ERP studies of explicit memory retrieval that are central to the experimental work presented in the present thesis. Prior to a discussion of the relevant ERP literature however, the following chapter introduces the ERP methodology as a tool for investigating cognition.

## Chapter 2.

### EVENT-RELATED POTENTIALS

The human electroencephalogram (EEG), a pattern of changing voltage over time, is recorded by placing two electrodes on the scalp and connecting them to a differential amplifier. EEG is a product of the summation of electrical activity occurring within the brain, activity that is conducted to the scalp, producing an electromagnetic field. The working brain constantly generates EEG, which, when recorded from normal healthy subjects, has an amplitude that varies from -100 to +100 microvolts and a frequency that ranges from DC up to and beyond 40Hz (Coles and Rugg, 1995). Early investigations of scalp recorded EEG by Berger (1929) demonstrated the sensitivity of on-going EEG to changes in mental activity, perhaps the best known example being the different patterns of EEG that accompany different stages of sleep. It is possible to examine EEG in a more analytic way however, experimentally isolating fractions of the on-going EEG (the event-related potential) that are time-locked to the onset of specific identifiable events (such as the presentation of a stimulus).

An event-related potential (henceforth ERP) is a record of the scalp-recorded electrical activity associated with a specific occurrence (Picton, Lins and Scherg, 1994). ERPs can be characterised on a continuum ranging from 'exogenous' to 'endogenous' (Donchin, Ritter and McCallum, 1978), going from activity that is obligatorily

generated by external events (e.g., experimental variables), to activity that is more sensitive to internal events (e.g., cognitive variables). Endogenous ERPs are of particular interest, because they are assumed to be a measurable correlate of mental processing, and as such they allow the non-invasive study of the neural correlates of higher cognitive processes. As Kutas and Dale (1997, p197-198) note, ERPs “can be used within the context of psychological experiments to assess the brain’s sensitivity to various experimental manipulations, and thereby to constrain psychological theories of various cognitive and behavioural phenomena”. Before explaining how ERPs can be used in this way, it is necessary to discuss some of the complexities surrounding the origins of the ERP, methods of recording and extracting the signal, and the different ways in which ERP components can be identified. Hopefully, in doing so, some light will be thrown on the issues and assumptions underlying the research presented in this thesis.

As noted above, the main aim of this chapter is to look closely at the ERP technique. Before doing so however, it is worth briefly considering how it relates to other neuroimaging techniques - in particular the haemodynamic methods of PET (positron emission tomography) and fMRI (functional magnetic resonance imaging). Table 1 illustrates the major strengths and weaknesses of the electrophysiological and haemodynamic methods. As Churchland and Sejnowski (1991) point out, these methods should not be regarded as being in competition with one another. Rather, they provide different kinds of information about how cognitive processes are instantiated in the brain, and should therefore be seen as complimentary methods for investigating the neural basis of cognitive functioning.

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**Table 1.** The complimentary strengths and weaknesses of electrophysiological and haemodynamic neuroimaging methods. Adapted from Rugg (in press).

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<u><b>Electrophysiological</b></u> <u><b>STRENGTHS</b></u>	<u><b>Haemodynamic</b></u> <u><b>WEAKNESSES</b></u>
Provides a direct measurement of neural activity	Provides an indirect measure of neural activity
Provides high temporal resolution	Provides poor temporal resolution
Data can be analysed contingent upon performance	Difficult to analyse data according to performance
<u><b>WEAKNESSES</b></u>	<u><b>STRENGTHS</b></u>
Measures only a fraction of the total neural activity	Measures neural activity more homogeneously
Provides poor spatial resolution	Provides high spatial resolution

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There are two aspects of the ERP technique that are particularly advantageous for those interested in investigating higher order cognitive functions such as memory. Firstly, ERP data provides a real-time record of neural activity; the temporal resolution of electrophysiological data is at least an order of magnitude better than that provided by haemodynamic methods. This is because the temporal resolution of haemodynamic methods is inherently limited by the relatively slow response time of the cerebral vasculature (cf. Raichle, 1998). Consequently, ERPs provide considerably more information about the time course of processing than either PET or fMRI.

The second advantage of electrophysiological methods lies in the ability to average the data contingent upon subjects' performance (i.e., in an event-related manner). As will be made clear in chapter 3, many of the conclusions that have been drawn on the basis of ERP studies rely on the fact that the data can be analysed according to subjects' responses to different classes of stimuli. Similar 'event-related' methods are currently being developed for use with fMRI (e.g., see Buckner, Bandettini, O'Craven, Savoy, Paterson, Raichle and Rosen, 1996; Josepfs, Turner and Friston, 1997; Rosen, Buckner and Dale, 1998; Dale and Buckner, in press), but this techniques have not been as extensively employed as traditional methods.

Finally, table 1 also indicates the major weakness of the electrophysiological methods. Perhaps the most serious disadvantages of the ERP technique are the fact that it samples an unknown fraction of brain activity, and its' relatively poor spatial resolution (discussed in more detail below). Haemodynamic methods provide spatial information that is in the order of millimetres, and sample brain activity relatively homogeneously. By contrast, without the aid of modelling techniques ERP data does not provide any information about the exact sources of neural activity. As will be made clear in the following discussion, the ERP technique is not ideal if one is primarily interested in localising the sources of neural activity.

## **Electrogenesis**

Whilst the exact relationship between what goes on in the brain and what is recorded at the scalp is not fully understood, some discussion of the origins of the ERP is instructive in understanding the data. At a cellular level the change in voltage (i.e., the electrical potential) measured between two electrodes is ultimately due to ionic current

flow occurring across the membranes of active nerve cells, which produces localised electromagnetic fields (see Wood and Allison, 1981; Wood, 1987). The physics of electrical field theory means that local current sources summate to produce a well defined, mathematically unique, electrical field (the so-called 'forward problem', Kutas and Dale, 1997). Moreover, the electrical potential that is recorded at any particular point in time reflects only activity occurring at that point in time, i.e., the propagation of activity is instantaneous (e.g., see Nunez, 1981; Kutas and Dale, 1997). As will be made clear in the following discussion, electrophysiological methods offer a real-time record of on-going neural activity, but the electrical potential that is recorded at the scalp is heavily dependent upon factors such as the geometric organisation and synchrony of the active nerve cells. Electrogenesis, the origins of the signal, can be considered both at the level of individual cells, and of groups of cells.

### **Individual cells**

There are two sources of ionic current flow at the level of individual cells; action potentials, that are all-or-none transmissions along nerve cell axons, and post synaptic potentials, that are graded in magnitude. Whilst both sources of activity contribute to the extracellular potential, it is thought that post-synaptic potentials (both excitatory and inhibitory) are the principal contributors to the scalp recorded potential (e.g., see Allison, Wood and McCarthy, 1986). Indeed, Cooper, Osselton and Shaw (1980) argue that their relatively slow time course and column like structure (e.g., consider pyramidal cells radiating from upper to lower layers of cortex) makes the summation of post synaptic potentials more likely than the summation of action potentials. However, as Wood and Allison (1981) note, in some circumstances highly synchronous action potentials can also influence the scalp recording.

The principles of ionic current flow (and the resultant electrical potentials that are generated) are reviewed in Wood and Allison (1981). They note that the nature of the scalp recorded potential depends upon both the location of the electrodes and the location of the active tissue. For example, if the distance between electrode and active tissue varies then so will the amplitude of the EEG. Similarly, the polarity of the EEG is dependent upon both electrode placement and the source of the current flow (e.g., see Wood et al., 1986). In sum, the polarity of scalp-recorded EEG provides

information that is ambiguous about the cellular events involved. Notably, it does not allow one to distinguish between excitatory and inhibitory post-synaptic potentials.

### **Groups of cells**

Activity arising from different sources throughout the brain summates linearly, hence the local electromagnetic fields generated by individual neuronal events undergo spatial summation. Physical variations between neurons (e.g., differences in the numbers, shape and size of dendrites and axons) can influence the flow of current, and thus influence the recorded potential (Wood, 1987). More significantly however, the structural organisation of the neurons, as a group, plays a major role in determining the scalp recorded potential. Lorento de No (1947) investigated the principles of volume conduction (i.e., how current passes through a space) in relation to extracellular potential fields, demonstrating that different cellular field configurations give rise to either 'open' or 'closed' electrical fields (see also Kutas and Dale, 1997).

The physical arrangement of neurons in 'open' field structures means that their electromagnetic activity can be recorded at a distance. For example, where cell bodies and dendrites are orientated in the same parallel direction current flows along the axis of orientation, resulting in a potential field akin to that produced by a charge dipole (a field with positive and negative charges between which current flows). This kind of structure is found in groups of pyramidal and Purkinje cells within the neocortex, hippocampus and cerebellum (Wood, 1987), thus the activity of such structures is in principle measurable from the scalp. However, if the orientation of the cells in such a field is not all the same, then the summation of electrical potentials can be radically altered. For example, if alternate parallel neurons had opposite orientations to each other, then the field would be 'closed'; electrical potentials would sum to zero, preventing measurement of activity at the scalp. A second example of a closed field structure is when cell bodies are clustered centrally, with dendrites radiating outward. This physical arrangement means that current flows inwards, towards the centre of the group of neurons, and the potential measured outside the structure is zero. This kind of configuration is not unlike that in nuclear structures, and only recording with electrodes placed within such a structure would reveal any activity (Wood, 1987).

## **Synchronicity**

As Wood and Allison (1981) note, the effect of cellular geometry has important implications when ERPs are being interpreted. Any given neural activity may or may not be measurable at the scalp depending upon the organisation of cells. Hence, the absence of activity at the scalp does not mean that no activity is occurring within the brain. Unfortunately, such interpretative difficulties increase when one considers the summed activity of a number of neurons over time. In particular, it is important to consider the effect of how temporally synchronous the neural activity is, because this can influence both the amplitude and latency of the summated potential. The foregoing discussion of the effects of geometric organisation was based upon the assumption of synchronous neural activity, but in reality temporally asynchronous activity is likely to occur. Wood and Allison (1981) note that the summation of potentials from individual neurons is critically dependent upon how synchronous that activity is; going from rapid to slow voltage bursts, there is a reduction in the probability of summation, thus greater synchrony is required for summation to occur.

## **Volume conduction**

As noted above, the voltage differences that are recorded between electrodes at the scalp are due to the summed activity of voltage changes occurring within groups of synchronously active neurons distributed throughout the brain. These electrical potentials can only be recorded because the brain and its coverings act as volume conductors, resulting in neural activity being projected onto the scalp. However, there is some variability in volume conduction throughout the brain tissue, skull and scalp. For example, Robinson, Bryan and Rosvold (1965) produced a sliding scale (of least-to-most conductive material), going from white matter, through grey matter, to blood. Moreover, differences in the thickness of the skull and scalp across electrode sites can influence the potential recorded at each site. Hopefully, new techniques such as finite element deblurring (which estimates and removes the effects of spatial smearing produced by conduction through the cerebral meninges, skull and scalp) should eventually become available to counter this problem (e.g., see Cooper et al. 1980; Gevins et al. 1995; Picton et al, 1994).

Clearly, the electrogenesis of the ERP is a complex phenomenon. Neural activity occurring within the brain can only be recorded from the scalp if a number of conditions are met. Active neurons must be organised in a (non-radially) symmetric manner, and they must be synchronously active. As Kutas and Dale (1997) point out, the main brain structure to satisfy these conditions is the neocortex (cortical mantle). The neocortex consists mainly (about 70%) of pyramidal cells, which are organised in column-like groups, orientated perpendicular to the surface of the cortex. It is activity of these neurons (*en masse*), that is believed to be the primary source of scalp recorded ERPs.

### **Recording the signal**

Having described the origins of the EEG it is possible to discuss the actual recording process. There are two crucial issues here, where should the electrodes be placed, and which electrodes are the electrical differences to be measured between? These issues are discussed in turn below. For further discussion of these issues (and related technical details, such as different types of electrodes, and amplification systems), see Cooper et al. (1974), Pivik et al. (1993), and Picton et al. (1994).

#### **The Placement of Electrodes**

As is the case in the research reported in this thesis, ERPs are generally recorded from a number of electrodes, and electrode placement is usually based on Jasper's (1958) 'international ten-twenty system' (see figure 6, chapter 4, for the electrode montage used in the present studies). The ten-twenty system is aimed at ensuring a standard placement of electrodes, to facilitate comparisons of data across laboratories. It specifies a set of standard points and also provides a method for adding as many extra points as is required. As Coles and Rugg (1995) note however, whilst the brain area that it sits over can (nominally) be used to specify an electrode site, this does not mean that the activity it records comes from just that brain area. Whilst the scalp recorded potential is more sensitive to activity the closer the generators of that activity are to the recording site, the principles of volume conduction mean that activity generated at one location can be projected and recorded at another, possibly distant, location.

Regardless of questions about the source of the ERPs relative to the electrodes (discussed in more detail below), the ten-twenty system is primarily aimed at removing any uncertainty about the placement of electrodes. Yet, Binnie (1987) argues that the ten-twenty system fails to achieve even this, because it rests on the assumption of cranial symmetry for accurate electrode placement. Binnie, Dekker, Smit and Van Der Linden (1982) show that cranial symmetry is not the norm, rather, individuals usually exhibit both asymmetrical circumference and plagiocephaly (i.e., frontal and occipital regions being larger on one side than the other). Similarly, Homan, Herman and Purdy (1987) found that there is considerable cranial asymmetry and variation in cerebral structure underlying each electrode site. Given the lack of suitable alternatives however, and the original justification for a standardised system, the ten-twenty system seems to be a reasonable, if not ideal, compromise. It is clear though that increasing attempts to relate ERPs to brain systems will lead to the use of increasing numbers of electrodes (for example, Tucker, 1993, discusses the geodesic net, an alternative system that covers a larger area of the cortex, using 64, 128 or even 256 electrode sites).

### **Methods of Referencing**

To determine the electrical field across the scalp, the recording from each electrode site are taken with respect to a common reference point. As Binnie (1987) makes clear, this produces relative measures of potential difference, not absolute measures of electrical activity. This is an important point. For example, it is often tempting to state that differences in activity across the scalp reflect positive or negative potentials arising in specific locations, whilst in practice one area is simply relatively more negative or positive, which could be due to changes in electrical activity at either, or both, locations. This is not simply a linguistic or terminological issue. The fact that the measures are relative means that the use of different reference points will produce different patterns of activity (providing, one would think, justification for the use of a standard system for referencing similar to that for electrode placement). Note, however, that whilst the reference electrode has a large impact upon the absolute amplitude of activity measured at each electrode, the relative distribution of amplitudes across a set of electrodes is reference independent.

The research reported here employs the most widely used method, 'common reference' recording, whereby each scalp electrode is connected to the same reference, and the difference in electrical potential is measured between each site and that reference (Coles and Rugg, 1995). Whilst almost any position can be chosen for the reference (e.g., the tip of the nose), the aim is to minimise the influence of the 'signal of interest' upon the reference, whilst maintaining the same background activity. This method typically involves using either a single electrode (e.g., placed on the right or left mastoid bone) or, as in the studies presented here, double electrodes (e.g., 'linked mastoids', based on the average of the left and right mastoids). Several alternative, less widely used, reference techniques do exist. For example, average reference derivations use the average of all the recording sites as the reference for each site, whereas source derivation uses the weighted average of electrodes surrounding the site of interest, as the reference for that site (both methods eliminating the need for a separate reference channel). Cooper et al. (1980) note however, that whilst all these methods are electrically equivalent, different methods can appear to give different patterns of activity. Any comparisons of data across research laboratories must therefore take account of the derivation methods used.

### **Extracting the signal from noise**

Having discussed the origins of the electrical activity and the methods of recording, it is now possible to address the way in which the actual ERP is extracted from the on-going EEG (see Pivik, et al., 1993; Picton et al, 1994; Rugg and Coles, 1995; Kutas and Dale, 1997). The electrical activity recorded from the scalp is not a pure record of the signal of interest; many other on-going electrical potentials are also present (i.e., background noise). The signal of interest is the ERP (time locked to the beginning of the recording epoch), whilst background noise consists of both residual brain activity and extra-cerebral potentials, notably artifacts such as muscle activity and eye movements. As Coles and Rugg (1995) note, the signal of interest is small in relation to the noise (microvolts to tens of microvolts respectively). Thus, a crucial element in the recording of ERPs is the extraction of the signal from the background noise. As with electrode placement and referencing, a number of techniques are available. For example, Picton (1987) discusses frequency based techniques, such as 'dynamic time-

warping', which involve creating a template (based on previous data) of expected activity within the recording epoch and searching for any sign of activity that matches this template. However, the experiments reported within this thesis are based upon signal averaging, the most commonly used method.

### **Signal averaging**

Signal averaging requires the repetition of experimental trials, allowing repeated time-locked epochs of EEG to be recorded, which are then averaged together. Given the assumption that the signal of interest is invariant across trials, but that background noise is random, the averaging procedure reduces the prominence of background noise and reveals any activity that is time-locked to the experimental task. Clearly, the greater the number of trials used, the higher the signal-to-noise ratio becomes. Cooper et al. (1980) show that the averaging procedure actually decreases the noise by a factor of the square root of the number of trials used. The signal to noise ratio of ERP data is not usually reported explicitly in the cognitive ERP literature. Rather, to ensure an acceptable signal to noise ratio, it is common practice to set a criteria specifying the minimum number of trials from which an ERP can be formed – a procedure that is employed in the research presented in this thesis. Such procedures assume however that the background noise is 'white noise', i.e., containing all frequencies, and the introduction of large transients (artifacts such as eye blinks), can seriously undermine the signal to noise reduction. To avoid this problem trials that contain artifacts are typically removed from the averaging process (discussed below).

Unfortunately, data averaging has drawbacks. The averaged signal is not a direct measure of the electrical activity occurring on individual trials, and thus the averaged waveform may actually show little relation to that of individual trials. Such distortion through averaging can lead to serious difficulties as to how ERP findings should be interpreted. For example, consider two averaged ERPs that contain the same effect (a specific component), except that the effect is larger in one case than the other. The difference between the two averaged ERPs could be taken to reflect the presence of an underlying neural process that is graded, i.e., with greater processing in one case than the other. This need not necessarily follow however. Rather, the averaged ERPs could reflect the activity of the same all-or-none neural process (producing an effect of the



same size in both cases), with the difference between the ERPs lying in the proportion of trials in which the effect is present.

Consider a second example, where the averaging process has an impact in the temporal domain. If individual trial-by-trial waveforms have a bimodal distribution (e.g., two peaks with differing latencies), this will be observed as a unimodal distribution (i.e., one peak, with latency somewhere between the two that are present in the individual waveforms). This phenomena is called 'latency jitter', and can be countered using analytic procedures, such as cross correlating each trial against the average, and shifting the latency of each trial to best fit that average, then re-averaging, to give a more accurate average (Woody, 1967). An alternative way in which latency jitter can be estimated is via reaction time data. If the experimental task employed in a study allows the collection of reaction time data, then the distribution of reaction times on trials making up an ERP can provide an estimate of the amount of jitter. Whilst this is not as rigorous a method as using analytic procedures, it does provide a useful, if rough and ready, estimate of jitter.

### **Analogue to digital conversion**

Traditionally EEG was written onto paper as it was recorded. However, modern equipment converts EEG from an analogue to digital signal. The analogue signal is sampled at regular intervals, and the amplitude at each point in time is stored in digital form, and used to recreate the EEG waveform. Thus, the signal averaging procedure described above is performed on a time-point by time-point basis. Clearly this digitising process has the effect of making the accuracy of recording dependent on the frequency of sampling, i.e., the time between points. A particular problem with digitising is 'aliasing', the appearance of spurious low frequency components due to sampling with long point to point intervals. The theoretical maximum temporal resolution of averaged data is half of the sampling rate (e.g., for a sampling rate of 50 points per second, only frequencies below 25Hz can be identified). The sampling rate must therefore be set so as to capture all frequencies containing activity of interest, including any extra-cerebral activity that must be filtered from the signal (see Nilsson, Panizza and Hallett, 1993).

## **Artifacts**

As noted above, one element of background noise is transient artifacts (including eye movements, muscle effects, alpha waves, and pulse artifacts), which can be a major influence on the ERP if they are not removed. One of the first means of removing artifacts is through filtering the signal, which can improve the signal to noise ratio, and removes any artifacts that have a different frequency than the ERP. For example, mains electrical activity is removed by using low-pass amplifier filtering. Secondly, the signal averaging method discussed above relies upon the assumption that such noise is random, whilst the signal of interest is not. Thus, averaging over a large number of trials will reduce the influence of random artifacts (such as muscle activity and alpha waves), as well as general background noise, on the averaged signal. As with the removal of general noise this means that the more trials are averaged, the clearer the signal. As Picton (1987) notes however, this method does not remove any artifacts that are temporally related to the stimulus, and it cannot entirely remove the effects of artifacts with very large amplitudes (of which eye blinks and eye movement are the prime example). For this reason, some artifacts are dealt with more directly.

As is the case in the studies reported here, electro-ocular artifacts are normally monitored using a separate recording channel. Techniques have been developed to calculate the influence EOG has on each recording site, allowing the EOG to be subtracted from the ERP recording at each site (e.g., see Picton, 1987; and Berg and Scherg, 1994). Once again however, these approaches are not widely used at present. The more common approach (again, the method used in the work presented in this thesis) is to monitor and reject all trials that show evidence of the artifact. This involves recording EOG activity, in order to identify and remove (from the averaging process) those trials in which eye movements exceed a pre-set criterion. Rugg (1992) notes that this can make averaging impossible in subjects who find restricting their eye movements difficult (as too many trials are likely to be rejected), and may prevent ERPs being formed for a particular experimental condition if only a few trials are available. Furthermore, in order to reduce the number of trials that must be rejected, this method generally involves asking subjects to perform the extra task of monitoring and consciously controlling their eye movement and blinking. Clearly, whilst such

procedures are far from ideal, it is necessary to remove such artifacts from the ERP waveform.

### **Defining ERP components**

The preceding discussion illustrates some of the difficulties inherent to the process of recording and extracting ERP data. However, the question of how ERP components can be identified and used presents an even more daunting challenge. Figure 1 shows an example of two cognitive ERP waveforms, recorded from a single electrode site. The x-axis indicates time (in milliseconds), time zero indicating the onset of the experimental stimulus, whilst the y-axis indicates voltage (in microvolts), plotted positive-up. Figure 2 shows a topographic map (analogous to a contour map of terrain or temperature). The topographic maps presented in this thesis are based upon subtraction waveforms (the difference between two ERPs), and illustrate the distribution of activity across the scalp, showing the position of the maximum and minimum amplitude differences. The map is shown as if looking down onto the top of the head, with relative levels of voltage shown using a greyscale. The use of mapping requires three-dimensional data to be plotted into a two-dimensional picture, and the data between the actual recording points must be interpolated from the data recorded at each electrode site. The topographic maps employed in the work presented here are produced using a spherical spline algorithm (see Perrin, Pernier, Bertrand, Giard, and Echallier, 1987; although other methods are available, e.g., using the nearest neighbour algorithm; see Picton et al., 1994, for more details).

### **Peak Picking**

The traditional approach to ERPs focuses upon the morphology of the waveform; variations in polarity, latency, amplitude, and distribution are used to identify specific deflections within a waveform. This approach is typified by a descriptive nomenclature, based on the time course, polarity and distribution of individual peaks and troughs, e.g., a waveform that is negative going, maximal over centro-parietal electrodes, and has a latency peaking at 400 ms, would be called a centro-parietal N400. This basic approach is based upon research findings that demonstrate how particular peaks and troughs are sensitive to different experimental manipulations (e.g.,

see Kutas and Dale, 1997, for a recent review). There are serious problems with this approach though. As Picton, Lins and Scherg (1994) note, this is a simplistic and often misleading approach to identifying the components of an ERP.

Kutas and Dale (1997) describe a typical misunderstanding that can arise from the use of the peak picking approach. If a peak is thought to reflect a specific process, then it is tempting to assume that variations in the latency of that peak at different locations on the scalp reflect some form of propagation of that process across the scalp. Kutas and Dale demonstrate however that such changes in the latency of a peak across the scalp can also result from the activity of multiple (but fixed) generators, each of which has a different (but overlapping) time course. Clearly, to label a specific deflection as a component, with functional and physiological significance, ignores the possibility (indeed, the high probability) that at a neural level it may be a combination of several individual components, varying in either (or both) location and time course.

Accepting the difficulties inherent to the peak picking approach, interpretations of ERP data can be viewed as stemming from attempts to understanding either their psychological (functional) or physiological (neural) significance (e.g., see Johnson, 1995; Rugg and Coles, 1995; and Kutas and Dale, 1997). Psychological approaches attempt to identify the different cognitive processes that cause variation in the activity of the generators of the waveform, whereas physiological approaches attempt to identify the specific neural generators, or sources, responsible for the waveform. Note, however, that researchers rarely make an explicit choice between the two approaches, rather (as in the research presented here) they compromise somewhere between the two approaches to component identification – although see Donchin (1981) and Naatanen and Picton (1987) respectively, for extreme examples of the psychological and physiological approaches.

### **Psychological components**

The aim of the psychological approach is to identify specific functional (cognitive) processes that are associated with ERP components. As Kutas and Dale (1997) point out, at the extreme of this approach the fact that the brain generates ERPs can be considered as irrelevant. From this perspective it is simply necessary to be able to isolate specific variations in the ERP. As Donchin, Ritter and McCallum (1978) note, a

component can simply be defined as a “source of controlled, observable variability”. One way in which such an approach can be aided is by using analytic techniques such as Principle Components Analysis (PCA). This is a general statistical technique that can be used to identify common sources of variance within data sets (see Picton, et al., 1994; Wood and McCarthy, 1984; Collet, 1989; and Donchin, 1989, for debate on the utility and appropriateness of the PCA method for ERP research). Whilst the details of PCA are beyond the scope of this chapter, it is instructive to consider that the technique simply identifies sources of variance (orthogonal components) and it is up to the researcher to interpret them. Consequently, an analysis of behavioural performance and a proper understanding of the functional significance of the experimental manipulations are required if one wishes to correctly interpret the ERP data.

### **Physiological components**

The aim of the physiological approach is to identify the anatomically circumscribed neural generator (or set of generators) that give rise to the scalp recorded ERP. There is considerable interest in identifying the neural sources of ERP components, and numerous methods have been devised to aid attempts to identify the neural generator(s) of ERPs. One of the most straightforward means of improving information about the sources of ERPs is to increase the number of recording channels, and hence increase the resolution of the scalp field. Gevins et al. (1995) point out however that it is only when over 100 electrode channels are used that fine enough spatial information exists to distinguish the contribution to the scalp recorded ERP of small discrete cortical generators. Yet, whilst attaining high levels of spatial sampling is important, even this does not provide unequivocal information, due to the distortion of discretely generated sources during volume conduction. A number of analytical techniques have been developed however, such as finite element deblurring (described earlier) and dipole source modelling, to aid the search for the sources of scalp recorded ERPs.

Some discussion of source modelling is instructive in understanding the difficulties presented by a purely physiological approach to ERP research. Wood and Allison (1981) note an early attempt at source modelling by Wilson and Bayley (1950). They applied the principles of volume conduction to a model of the brain and scalp, to formulate an equation that described a given scalp recorded electrical field in terms of

the activity of a single dipole, specifying both the location and orientation of the dipole. Clearly, in order to model the sources of an ERP numerous assumptions must be made. For example, Kutas and Dale (1997) explain the physics underlying why the generators of scalp recorded ERPs can be represented as an electrical 'charge dipole'. Other, less realistic assumptions have also to be made, for example about how one models the shape and conductive properties of the brain and its coverings.

Unfortunately, a more serious difficulty exists. Even if one has an appropriate (i.e., sufficiently realistic) model, the problem of identifying the neural generators of a given scalp recorded ERP is mathematically ill posed (see Gevins et al., 1995; Coles and Rugg, 1995; Kutas and Dale, 1997). This is the 'inverse problem' (opposite to the 'forward problem' noted earlier), which states that for any given pattern of scalp activity there is no unique solution in terms of generators; rather there are a number of possible sources or combinations of sources that could account for the observed data. Although the seriousness of the inverse problem should not be underestimated, the set of possible solutions can be constrained by 'adding-in' information from other sources. For example, information from intracellular recording, animal experiments, lesion studies, and other neuroimaging techniques can all be employed (but see Donchin and Coles, 1991, for a critique of the use of information from animal models).

Despite the considerable problems involved, Johnson (1995) argues that modern versions of source modelling, such as brain electrical source analysis (BESA, Scherg, 1990), can nonetheless provide highly accurate localisation estimates. For example, Miltner, Braun, Johnson, Simpson and Ruchkin (1994) show that the spatial accuracy of source models is fine enough for it to be used in conjunction with PET and fMRI. Yet, as Scherg (1990) suggests, the search for scalp distribution models simply shifts the problem of component definition, as researchers now have to select appropriate latencies for which simple source configurations can be created. As recent attempts to co-register the data from ERP and PET studies show, source modelling that is constrained by neuroimaging data may produce a solution that is more accurate for one latency region than another (e.g., Mangun, 1997).

Clearly, there are various techniques that can be used to obtain greater information about the sources of ERP activity. Ultimately, these methods should allow both the time course, and origin of activity to be identified with increasing accuracy. In

particular attempts to co-register information from electromagnetic and haemodynamic techniques seems likely to continue (e.g., see Mangun, Hopfinger and Heinze, 1998). It should be remembered however that there are limits to the information provided by scalp recorded ERPs. As Scherg (1990) states, neither the activity of single neurons, nor the activity of distinct cortical layers, can be distinguished. It is only the summated activity within different brain regions that can be distinguished using these techniques. Whilst better source localisation may be possible by combining methods such as finite element deblurring and source dipole modelling, alternative methods must be employed if one wishes to obtain very high resolution information about the neural sources of scalp recorded activity (see Vaughan, 1987; and Snyder, 1991, for further discussion of source modelling).

### **Psychophysiological inferences**

Coles et al., (1990) consider the component definition approaches discussed above as different means of establishing the validity of ERPs as an index of cognitive processing. As Rugg (1994) points out however, most researchers do not explicitly state their philosophical perspective, and moreover, the two approaches do not necessarily have to produce equivalent results. For example, they will not do so if activity from different neural (physiological) sources can produce the same functional (psychological) effects. In essence, the two approaches will only provide equivalent results if there is an invariant, isomorphic mapping (i.e., that is a straightforward one-to-one relationship) between the cognitive and neural levels of analysis. Before considering the nature of the inferences that can be drawn in ERP research, it is instructive to briefly examine this assumption.

#### **The invariance assumption**

Opinions differ widely concerning the appropriate view of the relationship between the neural and functional levels of analysis. For example Rugg and Coles (1995) consider the 'invariance assumption' as a simple, defensible and parsimonious assumption that follows from the (standard) materialist view that cognitive processes are caused exclusively by physical activity in the nervous system. They note however, that whilst this assumption is necessary if one is to make even simple inferences on the basis of

ERP data, it is an assumption that is open to empirical refutation. At the opposite extreme, Kutas and Federmeier (1997) explicitly state that there is no isomorphism between cognitive functions and neural processes. Yet, strangely, they do not offer an alternative account. Rather, they argue that psychophysiological methods (when used in combination with one another) can nonetheless provide useful insight into the nature of the relationship between cognition and physiology.

Mesulam (1990) presents a more convincing rejection of the invariance assumption, offering a clear alternative account, namely that there is a 'one-to-many' and 'many-to-one' mapping between the neural and cognitive levels of analysis. This view is based upon a neural network approach to cognition, whereby the mapping from anatomy to behaviour is considered to be both localised and distributed. Any given behaviour is viewed as being represented across multiple neuroanatomical sites, with each of these sites playing multiple functional roles. By this view multiple networks interact to produce (emergent) behaviours, and a given behaviour cannot be localised to an individual neuroanatomical substrate. If correct, such a view could seriously undermine the utility of neuroimaging techniques (including ERPs), because knowledge about neural states would not provide any information about corresponding functional states.

Mehler, Morton and Jusczyk (1984) provide a similarly sceptical view. They argue that there is simply no empirical justification for making the invariance assumption. Indeed, they suggest that the exact relationship between the cognitive and neural levels of analysis is precisely what is under investigation in the cognitive neurosciences. They note that the mapping between the different levels of analysis can take a variety of forms (e.g., one-to-one, one-to-many, many-to-one, or many-to-many), and it is not necessarily clear exactly what elements at each level are to be mapped on to each other (e.g., the neural level can be considered at various different grain sizes, from individual neurons, through networks, to whole cerebral hemispheres). Thus, Mehler et al. argue that it is premature to assume a one-to-one mapping, and that making such an assumption may ultimately impede scientific progress. Moreover, as they point out, localisation of activity at the neural level does not necessarily constitute, or even contribute to, an explanation of behaviour at the psychological level.



Whilst that the invariance assumption is clearly open to refutation, and under attack from some quarters, it is by no means untenable. As Rugg (in press) points out, there is no empirical evidence against it. However, it is certainly true that the levels at which the cognitive and neural elements are defined is under constant change (i.e., as psychological theories evolve, and imaging techniques develop). Thus, at the very least, considering the relationship between the cognitive and neural levels of analysis as fixed would be unwarranted. A more profitable perspective is proposed by Churchland and Sejnowski (1991; see also Churchland, 1986). They argue for a 'co-evolutionary' approach, whereby investigations at one level constrain and guide investigations at another, in a reciprocal manner. This does not mean that cognitive models of memory can be simply reduced to neuroanatomical accounts of processing, but rather that research will lead to the refinement of our understanding of both the cognitive and neural levels of analysis, and of the relationship between them. A similar point is made by Sarter, Berntson and Cacioppo (1996 p16), who state that "the optimal development of cognitive neuroscience will require a progressive tuning of concepts derived at both the cognitive and neuronal levels of analysis".

### **Interpreting ERP data**

Notwithstanding the concerns about the invariance assumption discussed above, the research presented in this thesis is (loosely) predicated on this assumption. At the very least it is assumed that there is some form of systematic relationship between the neural and cognitive levels of analysis, a relationship that is amenable to scientific investigation. Following Rugg and Coles (1995), the research presented here draws on elements of both the psychological and physiological approaches to ERPs discussed above. Critically, the work rests upon the use of inferential statistics to draw conclusions on the basis of ERP data (like that shown earlier in figures 1 and 2). As will be made clear however, the inferential status afforded ERPs is highly constrained by their inherent limits, as discussed earlier in terms of their electrogenesis, recording and extraction.

As a framework within which to discuss the inferences that can be made on the basis of ERP data, consider an experiment in which ERPs are recorded in two experimental conditions associated with a given cognitive task (note that analogous arguments can

be applied to the ERP for a single task analysed over successive time periods). Inferential statistics (such as Analysis of Variance) can be used to establish if there are any reliable differences between the waveforms for each condition. Remember that, necessarily, a given neural generator (or set of generators) produces a well defined, mathematically unique, electrical field (the forward problem). Consequently, the presence of differences between ERPs strongly suggests that there are differences in the neural correlates associated with each condition and, therefore, that there is some form of concomitant difference in the cognitive processing associated with the performance of each experimental condition.

In comparing ERPs inferential statistics can provide evidence of differences that are either 'quantitative' or 'qualitative' in nature (i.e., in degree, or in kind, respectively). In terms of ERPs, a qualitative difference can be demonstrated by revealing a change in the topography (distribution) of the scalp fields associated with two experimental conditions (or in one condition over two latency periods). If qualitatively distinct patterns of neural activity are found this must reflect differences in the underlying generator(s). This is taken as evidence that the experimental conditions engaged functionally distinct cognitive processes. Again, note that this conclusion rests on the invariance assumption. It is assumed that a given cognitive process cannot be instantiated in multiple ways at the neural level of analysis, and therefore cannot give rise to multiple neural correlates; conversely, multiple neural correlates must reflect multiple cognitive processes.

Even if the ERPs associated with two experimental conditions are not found to differ qualitatively, they may nonetheless be found to differ quantitatively. A quantitative difference can be demonstrated by revealing differences in the magnitude (amplitudes) of the waveform for each condition, in the absence of differences in distribution. In this instance, the same neural generator (or set of generators) is active, but to differing degrees in each case. Thus, if differences in the magnitude of activity are found, this is taken to suggest that the experimental conditions engage functionally equivalent cognitive processes, but that these processes are engaged to a different degree in each condition. Once again, this conclusion rests squarely on the invariance assumption – a single neural correlate is assumed to correspond only to a single cognitive process.

The foregoing discussion of the way in which ERPs can provide evidence of quantitative and qualitative differences is, on the face of it, relatively straightforward. There are serious constraints to the inferences that can be made however (cf. Rugg and Coles, 1995; Sarter et al., 1996; Kutas and Federmeier, 1998). A crucial point here regards the use of the null hypothesis in contrasting two experimental conditions (or two time periods). If differences in the ERPs associated with two experimental conditions are found then there is a strong basis for inferring some (either quantitative or qualitative) difference in processing between two experimental conditions. By contrast the absence of a significant difference (the null result) is not a solid basis for making the opposite conclusion, i.e., that there are absolutely no differences in brain activity.

As noted above, much distortion and attenuation of activity occurs due to variations in the synchronicity of active tissue, and variations in the volume conduction to the scalp. If this is considered alongside the fact that both open and closed electrical fields exist within any given brain area, then it is clear that an unknown quantity of neural activity is hidden from all scalp recording. Thus, in practice, the absence of differential activity in the scalp recorded potential may be due to the insensitivity of the ERP method to particular kinds of neural activity, despite its presence within the brain. Moreover, the ability to detect a difference may in practice depend upon the precise methods used. For example, increasing the number of recording sites increases the spatial resolution of the data, and therefore increases the likelihood of observing differences in distribution.

Coles and Rugg (1995) consider the fact that ERPs represent a subset of the total intracranial neural activity as having both positive and negative implications. Whilst it means that there will often, if not always, be neural activity that is not recorded, they argue that the remaining measure should be less complex and thus more analysable. As should be clear however, this can make the scalp recorded ERP more difficult to interpret, not less (even disregarding issues surrounding the invariance assumption). As Johnson (1995) points out, the insensitivity of the ERP measure to some forms of neural activity means that it is even difficult to draw straightforward conclusions about the temporal order of processing, the domain in which ERPs are most sensitive. If two ERP components occur in succession this can be taken as evidence for two stages of

processing, but it cannot be interpreted as evidence for two successive processing stages, because other additional processing may have occurred that simply cannot be recorded at the scalp.

Consider a second example, whereby the time course of the difference between two conditions is examined (again using inferential statistics, such as multiple t-tests). Typically, this involves stating a time by which the waveforms, and by implication the underlying processing, begins to differ. Yet, ERPs do not provide a definitive index of the timing of processing, they can only provide an upper bound on the timing of any differences. As Rugg (1995) points out, because the ERP method measures an unknown subset of the total intercranial activity, evidence of a point in time when observable differences are present does not mean that the cognitive processes do not differ prior to this point in time.

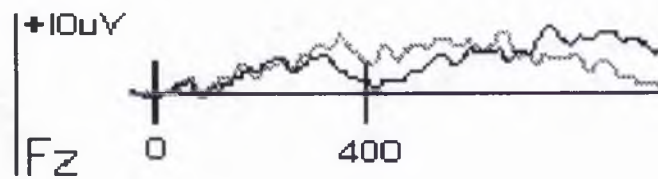
Clearly, the conclusions that can be drawn on the basis of a null result are constrained by the inherent limits of the ERP method. As Rugg (in press) notes however, the significance of positive findings (both quantitative and qualitative differences) is usually dependent upon the particular theoretical context in which the research is performed. In terms of quantitative differences, exactly what it means to posit differences in the degree or amount to which a cognitive process is engaged is not necessarily clear. For example, it does not follow that graded changes in the engagement of a cognitive process (as indexed by improvements in performance) are simply due to an increased activity of a single neural generator (or set of generators). Rather, the improvement at a behavioural level may be attributable to the recruitment of additional processes. Similarly, it is not clear to just how (qualitatively) different neural activity must be to warrant the conclusion that functionally distinct operations have been engaged. For example, the topography of effects may be similar in terms of its gross distribution (with clear commonalities) but still differ statistically in relatively subtle ways.

Finally, there are also circumstances where qualitative dissociations would be expected but would nonetheless be considered relatively uninteresting or uninformative from a psychological perspective. For example, the effects of priming in different modalities can be viewed as relying on functionally equivalent processing from a cognitive perspective, yet the instantiation of priming could still be expected to arise in

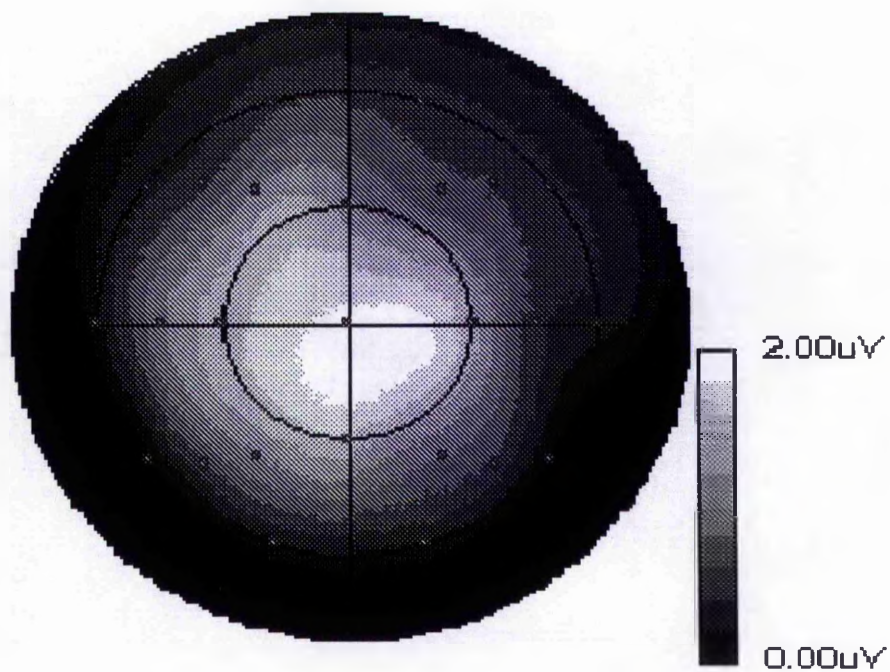
qualitatively different brain areas for each modality, giving rise to qualitative differences in the associated ERPs. In essence then, the functional interpretation that is applied to a given ERP component must take into account the particular circumstances in which it is elicited. Without a proper appreciation of the psychological factors involved, ERP research is unlikely to reveal anything other than a confused picture of the neural basis of cognitive functioning.

### **Summary**

Whilst there is not the space to consider the philosophical issues in great detail, it should be clear from the foregoing discussion that ERP research is based upon strong assumptions about the mapping between the neural and cognitive levels of analysis. Whilst these issues are not unique to ERP research (i.e., they are common across cognitive neuroscience research in general), the present chapter also illustrates the fact that the way ERPs can be defined and used is further constrained by issues surrounding the electrogenesis, recording and extraction of ERP data. Despite these constraints however, information can be derived, both about quantitative and qualitative changes in the ERP, and this information can be used to constrain interpretations of the cognitive processes under investigation. Whilst ERPs do not always provide unequivocal information, they provide a useful means of investigating the possible neural bases of higher order cognitive processes such as memory.



**Figure 1.** Two ERP waveforms, recorded from a single electrode (Fz). The scale bar indicates a 10 $\mu$ V range, plotted positive up. Zero indicates the onset of the experimental stimuli. Note that the waveforms do not diverge until approximately 300 msec post-stimulus.



**Figure 2.** A topographic map, illustrating the scalp distribution of the differences between two ERPs. The map is shown as if looking down onto the top of the head. The scale bar to the right of the map indicates the maximum and minimum of the voltage range, and electrode locations are indicated by small squares.

## **Chapter 3.**

### **ERPS AND MEMORY**

Whilst the ERP technique is not the best known of brain imaging methods, it has a relatively long history, extending over 30 years of research into the electrophysiological correlates of sensory, perceptual, motor, and cognitive processes (for recent reviews see Rugg and Coles, 1995; Kutas and Dale, 1997). In particular, several areas of memory research have been supplemented by ERP studies, including implicit memory, short-term (working) memory, and encoding in long term memory (e.g., see Rugg, 1994, 1995a,b; Johnson, 1995). Central to the research reported here are ERP studies of explicit retrieval from long-term memory, primarily employing direct tests of explicit memory including recognition and cued recall.

The research presented in the present thesis follows directly from the ERP studies reviewed in the present chapter. Indeed, the experiments were explicitly designed to test the theoretical interpretations of the findings discussed below. Clearly, a careful consideration of previous work is necessary to provide an appropriate context in which to understand and evaluate the significance of the work presented in this thesis. The following review is also intended to indicate the way in which the ERP findings have developed, highlighting the changing nature of this research, both in methodological and theoretical terms. The review is selective however. Recent research published after

the experimental work was undertaken, is not reviewed here, but will instead be considered in the discussion sections.

### **The left parietal old/new effect**

The basic experimental finding, from studies employing old/new recognition memory tests, is the ERP 'left-parietal old/new' effect (e.g., see Johnson, 1995; Rugg, 1991, Rugg, Cox, Doyle and Wells, 1995; Smith, 1993; Paller, Kutas and McIssac, 1995; Wilding, Doyle and Rugg, 1995; Neville, Kutas, Chesney and Schmidt, 1989). The effect is shown in figure 3; it is a modulation in the ERP waveform that takes the form of a positive shift in ERPs for items are correctly recognised as old (hits) compared to those rejected as new (correct rejections). In studies of item (old/new) recognition the effect has typically been found to emerge around 300-400 msec post-stimulus, to be temporally restricted to a 400-600 msec latency region, and to be maximal over left temporo-parietal electrodes.

Crucially, the left parietal old/new effect is not found in the ERPs for old words which are not recognised (misses), or new words incorrectly identified as being old (false alarms), indicating that the effect is associated with the veridical retrieval of information from memory. That is, the fact that the effect is not found in the ERPs to misses indicates that it does not simply reflect the fact that a given item has been repeated (the subject must be able to consciously report having experienced the item before). Similarly, the absence of the effect in the ERPs to false alarms indicates that the effect does not simply reflect the fact an 'old' decision has been made (the subject must veridically remember having experienced the item before).

### **Methodological issues**

Before discussing the various interpretations of the left parietal old/new effect, it is important to note a number of methodological issues. Clearly, there are limitations to the use of ERPs in investigations of the neural correlates of memory. For example, if one wished to study free recall, uncertainty would arise over what 'event' the ERPs should be time locked to. Moreover, a range of methods and procedures has been used across different experiments. For example, Bentin, Moscovitch and Heth (1993) collapsed their ERPs across hit and miss responses, and simply compared ERPs to old



and new words at test, regardless of the accuracy of recognition judgements. Such differences can make comparisons of data sets across different experiments difficult (if not impossible).

One problem that derives from the developing nature of the ERP method is variation in the number of recording sites employed in different studies. Recent investigations generally employ lateral and midline electrodes (up to 64 electrode sites), allowing the distribution of effects to be well characterised, and in the case of old/new effects, highlighting any hemispheric asymmetries. Because most early research only employed midline sites, it can be difficult to establish if the ERP effects found in recent studies are equivalent to those found in earlier experiments. Finally, methods of analysis also vary widely across different research laboratories. For example, a recent study by Duzel, Yonelinas, Mangun, Heinze and Tulving (1997) reported topographic differences in the pattern of old/new effects in the ERPs associated with Recollection and Knowing judgements. As will become clear below, such a finding would be of considerable interest if it were sustainable. However, Duzel et al. performed their topographic analyses without first rescaling their data – a practice that calls into question their interpretation of the findings (cf. McCarthy and Wood, 1985; discussed in more detail in chapter 4).

### **Initial investigations**

Research into the functional significance of the left parietal old/new effect initially focused on attempts to dissociate the effect from potential confounding factors, including modulations of the 'classic' ERP components (e.g., the P300), and implicit memory effects associated with repetition priming. For example, Rugg and Nagy (1989; see also Johnson, 1995) reported that there are two distinct components to the ERP old/new effect, with different scalp distributions and time courses; the 'early' and 'late' components respectively. The two components could be functionally dissociated by manipulating the lag between the first and second presentation of the test items. The early effect was found to be sensitive to item repetition only when the delay between study and test presentation was relatively short, whereas the late part of the effect remained even after a delay of 45 minutes. Thus, the functional characteristics of the early effect make it an unlikely correlate of long-term memory. Moreover, Rugg,

Roberts, Potter, Pickles and Nagy (1991) showed that whilst the late recognition related effect was attenuated in temporal lobectomy patients, the early repetition sensitive effect was not. As Rugg et al. (1991) note, their data suggests that the two effects likely arise from different intra-cerebral generators (issues surrounding the generators of effects are discussed in more detail below). Given the functional and neural differences described above, investigations concerning the early and late effects have diverged, with the two areas of research having little impact upon each other (see Rugg and Doyle, 1994, for more on the early ERP repetition effect).

As noted above early studies also investigated the possible contribution of the classical ERP components to the left parietal old/new effect. The old/new effect overlaps temporally with the P300 and N400 components, and these components are known to be influenced by factors such as stimulus and subjective probability, 'targetness', and response requirements (e.g., see Donchin and Coles, 1988; Johnson, Pfefferbaum and Kopell, 1985; and Kutas and Dale, 1997, for reviews). For example, the P300 (or P3b) is functionally related to various cognitive factors that could potentially distinguish the old and new items in a recognition memory task. Notably, the amplitude of the P3b is inversely related to the relative probability of the class of stimuli that evokes it (the rarer the stimulus, the larger the amplitude of the P3b becomes), whilst the peak latency of the component appears to be related to the time which subjects require to categorise the eliciting stimuli.

Given the functional characteristics of the P300 it is easy to see why the left parietal old/new effect could appear to be, at least in part, a reflection of this ERP component. If subjects take different amounts of time to categorise the old and new stimuli, or if the relative proportion of old and new responses differed, then the left parietal old/new effect would indeed be confounded with the P300. Experimental manipulations suggest however that these factors do not account for the presence of the left parietal old/new effect. For example, Smith and Guster (1993) reported that the left parietal effect is present even when the subjective probability of experiencing an old item is much higher than that for new items, a circumstance that should lead to a larger P3b component in the ERPs to new items. Research also suggests that the old/new effect does not reflect variation in stimulus probability (Friedman, 1990) or decision confidence (Karis, Fabiani and Donchin, 1984). Moreover, the old/new effect has been

shown to have a different scalp distribution to both the P300 and N400 components (e.g., Friedman, 1990; and Smith and Guster, 1993).

In sum, the left parietal old/new effect cannot simply be accounted for in terms of modulations of the classic ERP components, and it also appears to be distinct from the ERP effects associated with repetition priming. The dissociations discussed above, in terms of the functional properties and scalp distributions of the various ERP effects, provide evidence that the left parietal effect is specifically related to processes associated with memory retrieval. There are unresolved issues however; for example it is debatable whether many of the studies discussed above employed sufficient recording sites to satisfactorily determine the scalp distribution of the various ERP effects. Nonetheless, the research discussed below is based upon the assumption that the left parietal effect reflects brain activity contributing to, or contingent upon, the retrieval of information required to make accurate recognition memory judgements (an assumption that is predicated upon the findings reviewed above).

### **The Familiarity explanation**

Having accepted that the left parietal old/new effect is closely related to processing associated with successful recognition, a more precise functional account of the effect was clearly required. Debate about the functional role of the effect was influenced by dual process models of recognition memory (discussed in chapter 1). To recap briefly, according to dual process theories of recognition memory (cf. Atkinson and Juola, 1974; Mandler, 1980; Jacoby and Dallas, 1981) there are two retrieval mechanisms upon which retrieval can be based – subjects may be able to recollect having studied an item, or the item may simply be familiar. As was noted in chapter 1, recollection is clearly defined as the ability to remember contextual information about prior study episodes, whereas the precise formulation of the familiarity process is less clear (particularly concerning its relationship to implicit forms of memory such as priming, e.g., see Mayes, 1992).

Debate initially centred on whether the old/new effect reflected processing associated with either familiarity or recollection. Several early studies of the left parietal effect were interpreted as providing evidence in support of a familiarity account (i.e., that the effect reflected processes associated with or contingent upon a familiarity process; cf.

Friedman, 1990; Potter, Pickles, Roberts and Rugg, 1992). For example, Rugg and Doyle (1992) provided support in favour of the familiarity account. They tested recognition memory using low versus high frequency words, and found that only low frequency words elicited a left parietal old/new effect. The prominence of the left parietal old/new effect in the ERPs to low frequency words was interpreted as evidence in support of a familiarity account. Crucially, this interpretation of the ERP findings was based on an explanation of the well-known recognition memory advantage for low frequency words, i.e., that a greater relative increase in familiarity occurs between study and test for low frequency words than for high frequency words (e.g., Mandler, 1980; Mandler, Goodman and Wilkes-Gibbs, 1992; Jacoby, 1991; Jacoby and Dallas, 1981; discussed in chapter 1). Thus, Rugg and Doyle (1992) interpreted the prominence of the left parietal effect in the ERPs for low frequency words as a reflection of the greater increase in familiarity that was thought to occur for these items.

As noted above, Rugg and Doyle's account of the left parietal effect was predicated on the assumption that the low frequency recognition memory advantage was due to changes in relative familiarity between study and test. However, this account of the old/new effect was seriously undermined by a series of behavioural studies, which suggested that the word frequency effect reflects the superior recollection of low frequency items (e.g., see Gardiner and Java, 1990; Guttentag and Carroll, 1994, 1997; Chalmers, Humphreys and Dennis, 1997). These later behavioural findings suggested a re-interpretation of the ERP findings; by this account, the presence of the left parietal effect in the ERPs to low frequency words reflected the fact that these items were more likely to be recollected than were high frequency words.

Support for the 'recollection account' of the left parietal effect was provided by a further study comparing the ERP old/new effects for high and low frequency words. Rugg, Cox, Doyle and Wells (1994) found that the left parietal effect was more prominent in the ERPs for low frequency words, replicating the findings of Rugg and Doyle (1992). However, Rugg et al. also demonstrated that low frequency items were associated with more confident responses, and were more accurately assigned to their study context, than were high frequency items. Based upon the assumption that subjects would not have been able to accurately report the study context of the old

items if performance was based upon familiarity, these findings were judged to be more consistent with a recollection, than familiarity, account of the low-frequency recognition advantage. Thus, Rugg et al., concluded that the ERP old/new effect most likely reflected processes associated with recollection rather than familiarity.

Several other ERP investigations also suggest that the old/new effect reflects processes associated with recollection rather than familiarity. A crucial indication that the familiarity account was wrong was provided by Rugg, Doyle and Wells (unpublished, cited in Rugg, 1995a) in a further replication of the word frequency experiment of Rugg and Doyle (1992). Rugg et al. employed the R/K response procedure (discussed in chapter 1; cf. Tulving, 1985; Rajaram, 1993) as an alternative means of isolating the functional locus of the word frequency effects. At test subjects were asked to judge whether each item was old or new, and if an item was judged old, to report whether they could consciously Remember the item (i.e., recollect the study episode), or whether they just Knew that it must be old. Contrary to expectations based on Rugg and Doyle's (1992) study, the low frequency recognition memory advantage was only found for items receiving Remember responses. Furthermore, the left parietal old/new effect was more prominent in the ERPs to low frequency words, despite the fact that ERPs were only formed for items receiving Remember responses. Even given doubts over the extent to which the R/K procedure accurately isolates recollection based responding (see below), these findings provide little support for a familiarity account of the old/new effects.

A second study employing the R/K procedure also provided little support for the familiarity account. Smith (1993) recorded ERPs using the R/K procedure with a study-test recognition task, and found an old/new effect for recognition accompanied by both Remember and Know judgements. Whilst the effect was present in the ERPs associated with both class of judgement, it was almost twice as large for Remember than Know responses, a fact that Smith interpreted as evidence that the old/new effect reflected the degree to which subjects recollected the prior study episodes. Whilst the data are clearly inconsistent with a familiarity account, they do not unambiguously support a recollection account either. By Smith's account the difference between the ERPs to remember and know responses would have been expected to be qualitative, not quantitative in nature, with the left parietal effect only present in the ERPs to R

responses. Given the finding of an old/new effect for Know responses (when no recollection is meant to have occurred) an interpretation in favour of a recollection account need not necessarily be correct. Smith's interpretation is plausible, but only if it is accepted that the R/K judgements are not 'process pure' (cf. Gardiner and Java, 1993), and thus that Know responses are to some extent contaminated with recollection, resulting in an attenuated old/new effect for Know responses. However, given that the rationale for employing the R/K procedure was to separate the two processes, process impurity renders it a less than satisfactory technique for isolating the locus of the ERP old/new effect.

Two alternative investigations, which are not based on phenomenological self-reports, also count against the familiarity account of the left parietal old/new effect. First, Paller and Kutas (1992) investigated the old/new effects in the context of an indirect memory test – perceptual identification. A depth of processing manipulation was employed at study (orthographic versus imaging tasks) and at test subjects had simply to identify old and new items (words were presented too briefly for performance to be highly accurate), but not make overt old and new judgements. As expected, Paller and Kutas found that the depth of processing manipulation had little effect on perceptual identification. However, the ERPs exhibited an old/new effect that was larger for items that were deeply encoded (imaged). Whilst both classes of old item were equally well primed (as indexed by the behavioural performance), words from the deep encoding task were nonetheless associated with the larger old/new effect. Thus, Paller and Kutas argued that the old/new effect provides an index (or ERP signature) of conscious recollection, even under conditions where explicit memory is not directly assessed.

Paller and Kutas' findings are important, in that they provide support for the idea that the old/new effect does not simply reflect the requirement to overtly discriminate between old and new items. The conclusion that the effect reflects processes associated with recollection does not necessarily follow however, unless it is assumed that deeper encoding facilitates recollection but leaves familiarity unaffected. As with Rugg and Doyle's word frequency study and Smith's R/K study however, it is not necessarily clear how the experimental manipulation employed by Paller and Kutas should be interpreted. Specifically, Allan, Wilding and Rugg (in press) criticise the Paller and Kutas study on the grounds that depth of processing does not selectively influence

recollection. In support of their critique they cite Toth (1996), who suggests that measures of recollection and familiarity based responding are both influenced by depth of processing.

The evidence in support of Allan et al.'s critique is itself open to question however. In Toth's depth of processing studies a response-deadline manipulation was employed to separate processes associated with recollection and familiarity. When a long response deadline was provided it was assumed that responding could be based on the slower recollection process, whereas a short deadline was assumed to only allow faster familiarity based responding. Toth suggested that by employing the response deadline procedure provided it was possible to show that depth of processing manipulation influenced both familiarity and recollection based responding. Yet, the findings were based upon experiments in which the critical response deadline manipulation was performed using a between-subjects experimental design, rather than the standard within-subjects design (e.g., see Hintzman and Curran, 1994, for a relevant example). Given the sensitivity of memory retrieval effects to this form of alteration in experimental design (cf. Greene, 1996), it is not at all clear that Toth's findings can be taken at face value.

A further source of evidence against the familiarity account of the left parietal effect comes from Smith and Halgren (1989), who investigated the ERP effects associated with recognition memory. They compared left and right temporal lobectomy patients with matched control subjects. Smith and Halgren employed a study-test paradigm, which involved repeating the same 10 study words throughout 9 test blocks, introducing 10 new words for each block. The repetition of the same 10 study words across test blocks was designed to investigate the idea that the ERP old/new effect reflected familiarity based responding. The critical assumption was that repetition selectively increases familiarity based responding, and this should therefore be reflected in changes to the old/new effect. Smith and Halgren found that for the normal control subjects the repetition of items across successive test blocks did give rise to an increase in recognition accuracy, yet there was no concomitant alteration in the old/new effect as a function of the repetition of items. Results for the right temporal lobectomy patients showed an equivalent pattern of results. In contrast, the left temporal lobectomy patients showed no evidence of an old/new effect, despite the fact

patients showed no evidence of an old/new effect, despite the fact that their (much poorer recognition memory performance) was sensitive to the repetition of test items.

Smith and Halgren's findings are inconsistent with a familiarity account of the old/new effects in two ways. Firstly, the results for the control and right temporal lobectomy subjects suggest that the old/new effect was not sensitive to the familiarity of the test items, because whilst their behavioural performance was affected by the repetition of test items, there was no concomitant change in the ERP effects. Secondly, the relatively poor levels of performance in the left temporal lobectomy patients suggest that they may have been more reliant upon familiarity (or perceptual fluency) as a means of making recognition memory judgements. The absence of an old/new effect for these subjects was therefore interpreted as evidence that the effect was related to recollection rather than familiarity based responding.

Taken together, the studies described above demonstrate that the effect is sensitive to whether items in a recognition memory test have been previously studied. Furthermore, the findings suggest that the left parietal old/new effect may be a reflection of processes associated with recollection rather than familiarity (as was first thought). Unfortunately, they do not unambiguously reveal the functional locus of the effect. The Paller and Kutas, and Smith and Halgren studies both rely upon a representation of familiarity as an implicit (priming) process. Paller and Kutas assumed that a depth of processing manipulation at study would not effect familiarity, whilst Smith and Halgren assumed that the repetition of stimuli would influence familiarity. As noted above however, it is not clear what relationship exists between familiarity and priming. Similarly, the studies of both Rugg and Doyle (1992), and Smith (1993) were based on the R/K procedure, a technique that is intended to measure the phenomenological experience of subjects, rather than the underlying memory process themselves (cf. Gardiner, Java and Richardson-Klavehn, 1996).

It is not always necessarily clear how particular experimental manipulations should be interpreted. One reason for this is that the interpretations often rely heavily on the behavioural literature. For example, the interpretation of the ERP findings from the studies comparing the old/new effects for low and high frequency words were reliant upon current behavioural accounts of the low frequency recognition advantage. As behavioural findings lead to a shift from a 'relative familiarity' to a 'recollection'



account of the low frequency recognition advantage, accounts of the left parietal old/new effect changed accordingly. Given these difficulties it should be clear that an alternative means of isolating recollection based responding was needed. The study of Rugg, Wells and Doyle provides perhaps the first example of an alternative approach, whereby recollection was operationally defined according to subjects ability to report information about the prior study episodes.

### **Operational definitions of recollection**

Perhaps the strongest evidence in support of the recollection account of the left parietal old/new effect comes from studies by Wilding and colleagues, employing operational definitions of recollection. Critically, their approach does not rely upon subjects' phenomenological experience, or on assumptions concerning the relationship between familiarity-based recognition and priming. Rather, these studies employed source memory tasks as a means by which recollection can be operationally defined, allowing ERPs to be separated according to the likelihood that they are associated with episodic recollection. The hallmark of this approach is the use of a 'two-stage' retrieval task, whereby subjects make an initial old/new recognition judgement, and are then required to make a subsequent source judgement. The use of a two-stage task allows ERPs to be compared on the basis of subjects' ability (given accurate recognition) to accurately discriminate between different classes of studied item – items that differ solely in terms of experimentally manipulated contextual information. The basic rationale behind these studies is that it is only possible to perform the source memory task accurately if the initial recognition of an old item is associated with recollection of the study episode. Different classes of old item are intended to be equally familiar, differing only in terms of the context in which they were presented.

Wilding, Doyle and Rugg (1995) presented words at study in either the visual or auditory modality, and at test presented items either visually (experiment 1) or auditorally (experiment 2). Subjects were required to discriminate old from new items, and for items judged old, to report the modality in which they had been studied. The critical assumption was that subjects would only be able to report the modality of study presentation when they had recollected contextual information about the study episode, and not when they items were recognised on the basis of familiarity. Thus, from the

perspective of a dual process framework, trials on which source memory was successful are more likely to be associated with recollection than are trials on which source memory was unsuccessful – the later being more likely to be based upon familiarity.

In both experiments Wilding et al. found that, relative to the ERPs to correctly rejected new items, a left parietal old/new effect was present in the ERPs to items that were accurately recognised and for which the modality of study presentation was accurately reported. A weaker and less temporally extended left parietal old/new effect was also found in the ERPs to items that were recognised but which received inaccurate source judgements (experiment 2). Crucially, the topographic distribution of the old/new effects did not differ as a function of the accuracy of the source judgement – suggesting that the processes associated with the two kinds of responses differed quantitatively, but not qualitatively (i.e., in degree rather than in kind).

Wilding et al. interpreted their results as showing that recognition accompanied by incorrect source judgements was the result of partial or weak recollection (allowing subjects to make accurate old/new recognition judgements but not accurate source judgements). Unfortunately, the type of information that was used to distinguish the different classes of old item (half the items maintaining the same modality at study and test, half changing modality) introduced a possible confound. Maintaining the modality of presentation between study and test is thought to engender greater priming than does changing the modality (cf. Richardson-Klavehn and Bjork, 1988), a critical problem, given at least the possibility of a link between familiarity and priming (cf. Mayes, 1992). Thus, it remained arguable that the ERP effects could simply reflect priming based familiarity, rather than recollection. As is discussed below however, the recollection account of the left parietal old/new effect received further support from the results of a further study of source memory (Wilding and Rugg, 1996).

### **The right frontal old/new effect**

The study by Wilding et al. (1995) described in the foregoing paragraphs was the first to operationally define recollection using a two-stage retrieval task that required subjects to discriminate between different classes of old item. Wilding and Rugg (1996) employed this procedure in two further experiments that attempted to separate

recognition with and without the retrieval of contextual information. Importantly, these experiments employed a source judgement that did not involve changes in study-test modality; rather, words were heard at study in either a male or female voice. At test subjects saw old and new words, and had to make an old/new judgement, followed by a source (voice) judgement. Thus, these studies allowed recognition with and without recollection to be separated more cleanly than in the Wilding et al. study (i.e., without the possible confound of priming effects).

The findings from the Wilding and Rugg (1996) study are shown in figure 4. As expected on the basis of previous findings, a left parietal old/new effect was present, the magnitude of which was larger in the ERPs to source correct (hit/hit) than source incorrect (hit/miss) responses. Importantly, in contrast to previous findings (although see Johnson, 1995, for the first hint of a right frontal component) an additional positive shift is evident over frontal scalp sites. This second old/new effect was also larger in magnitude in the ERPs to source correct than source incorrect responses. The frontal effect appeared to onset at around the same time as the left parietal effect, but unlike the parietal effect, did not abate by the end of the recording period. Moreover, it exhibited the opposite asymmetry over the scalp, being larger over the right than left frontal electrodes.

Several issues arise from the findings of Wilding and Rugg (1996). First, why had the 'right frontal' old/new effect not been found in previous studies? The effect onsets at the same time as the parietal old/new effect, suggesting that it should have been seen in previous studies. Indeed, there was some sign of a frontal positivity in the data of Wilding et al. (1995). In this study the positivity could however have simply reflected the contribution of the parietal old/new effect to more anterior electrodes. By contrast, Wilding and Rugg (1996) were able to demonstrate that the old/new effects dissociated into two topographically and temporally distinct components. That is, the frontal and parietal effects were shown to differ both in terms of their time course (the frontal effect continuing beyond the duration of the parietal effect) and distribution (the frontal effect becoming significantly larger over the right than left hemisphere from ~900 msec post-stimulus). Note that one reason for the dissociation of the old/new effect into two components was a change in the recording procedures employed over the four experiments reported by Wilding and colleagues. In their first experiment they

employed a 13 site electrode montage and a post-stimulus recording epoch of just 904 msec, whereas in their final experiment they employed a 19 site montage and 1434 msec post-stimulus recording epoch.

The second question raised by the results of Wilding and Rugg (1996) concerns the interpretations of the findings. As is clear from figure 4, the magnitudes of both the left parietal and right frontal old/new effects were larger in the ERPs associated with correct source judgements. Thus, as in the study of Wilding et al. (1995) the difference between the ERPs associated with correct and incorrect source judgements was quantitative rather than qualitative. Consequently, Wilding and Rugg (1996) argued that their results supported the findings of Wilding et al. (1995) in suggesting that successful recognition memory engages the same processes, regardless of whether contextual information about prior study episodes is retrieved.

In a radical departure from earlier interpretations, Wilding and Rugg argued that the lack of a qualitative difference between the ERPs associated with accurate and inaccurate source judgements provides no support for dual process models of recognition memory. Rather, the effects were interpreted as being consistent with the view that the distinction between recognition memory with and without the retrieval of source (contextual) information is quantitative rather qualitative (after Moscovitch, 1992; and Squire, Knowlton and Musen, 1995). Indeed, Wilding and Rugg characterised accurate source responses as primarily reflecting recollection based responding, and inaccurate source responses as primarily reflecting familiarity based responding. Thus, given that the pattern of effects associated with the two response categories differed in degree, rather than in kind, it seems reasonable to conclude that familiarity is simply weak or partial recollection (allowing accurate old/new recognition judgements, but not accurate source judgements, to be made).

Support for this view comes from a reinterpretation of one of the Remember/Know experiments discussed earlier. Smith (1993) found larger old/new effects for Remember than Know responses, a finding that can be interpreted as evidence for a single retrieval process that is weaker for Know than Remember responses. However, as Allan, Wilding and Rugg (in press) note, it would be unwise to interpret the ERP data as providing strong evidence against the dual process view of recognition memory. As should be clear from chapter 2, the ERP method detects only a fraction of

the total neural activity occurring within the brain. Thus, the absence of an ERP correlate of familiarity may simply be due to fact that the neural correlates of this form of memory are not recordable at the scalp.

A more positive conclusion can be made however. The ERP data can be taken as evidence against a dual process model in which recollection and familiarity are viewed as exclusive processes. By an exclusivity model (note that this argument applies only to a third person, not first person, account of memory, cf. Gardiner et al., 1996) familiarity and recollection are distinct functional processes, with distinct neural correlates. Moreover, an exclusivity model necessitates that accurate performance is only associated with either one or the other process. Assuming that the ERP old/new effects reflect recollection, then the effects will only be seen when performance is associated with recollection. Even if the neural correlates of familiarity were not registered at the scalp, responses based upon familiarity would not be associated with the neural correlates of recollection, because the two bases for responding are exclusive of each other. Thus, an exclusivity model cannot account for Wilding and Rugg's assertion that responses based upon familiarity appear to be associated with weak or partial recollection (as indexed by the ERP old/new effects).

### **Functional accounts of the old/new effects**

Leaving aside arguments about the validity of dual process models of memory, the experiments performed by Wilding and colleagues provided clear evidence in support of a recollection account of the left parietal old/new effect. The studies of source memory also revealed a second old/new effect, the right frontal effect, which was temporally and topographically dissociable from the left parietal effect. Consequently, the functional account provided by Wilding and Rugg focused on accounting for the distinction between these two old/new effects. In interpreting their results Wilding and Rugg (1996) were inspired by neuropsychological accounts of memory that distinguish between processes associated with the retrieval of episodic information (recollection), and 'post-retrieval' processes that are required to generate or maintain a representation of the study episode (such that retrieved information can be strategically employed). This distinction between retrieval and post-retrieval processes was taken to map directly onto the two old/new effects.

Looking first at the functional account of the left parietal effect, consistent with previous proposals, Wilding and Rugg interpreted it as a neural correlate of the successful retrieval of episodic information. As discussed above, the finding that the effect was larger when source information was successfully remembered (relative to when source memory was not remembered) provides strong support for the recollection account; after all, the retrieval of contextual information is the defining feature of episodic recollection. Wilding and Rugg further argued that the quantitative difference in the magnitude of the left parietal effect suggested that recollection was a graded process (rather than an all-or-none process).

The conclusion that the left parietal effect reflects the activity of a graded retrieval process is puzzling for two reasons. First, the graded nature of the ERP effects could simply have occurred as an artifact of the averaging process (cf. chapter 2). That is, the magnitude differences could reflect a single (all-or-none) effect that was present on a larger proportion of trials for the source correct than source incorrect response category (rather than a graded process that was larger in the trials for the source correct response category). As Rugg et al. (1994) note, the ERP data only suggest that recollection is a graded process, if it is assumed that the averaged ERPs are representative of the single trials that contribute to the average.

The second reason why Wilding and colleagues interpretation of recollection as a graded process is puzzling is that the dual process models of memory such as that proposed by Gardiner and Java (1990) and Yonelinas and Jacoby (1995) represent recollection as an all-or-none process (as discussed in chapter 1). Although Wilding and Rugg concluded that their findings were not inconsistent with a dual process model, their characterisation of the retrieval process was nonetheless contrary to the dual process view. However, the contradiction between ERP and dual process accounts of recollection may be more apparent than real. As Rugg et al. (1994) note, although the experience of recollecting may be all-or-none, the information content of such experiences may nonetheless be graded. In sum, whilst the magnitude of the averaged ERP old/new effect is predictive of subjects' ability to retrieve source information, and the effect may reflect a graded recollection process, the findings are not inconsistent with an interpretation of recollection as an all-or-none retrieval process (cf. Chapter 1).

Turning to the right frontal old/new effect, Wilding and Rugg proposed that, like the left parietal effect, it too was associated with recollection. Importantly, the absence of the right frontal effect in previous studies of item recognition (reviewed earlier) was taken to suggest that the effect is less closely tied to the actual retrieval of episodic information than the left parietal effect is. Rather, the presence of the right frontal effect in the studies of source memory was thought to result from the differing task demands that source judgements require compared to item recognition judgements. That is, reflecting the requirement explicitly to retrieve contextual information about the study episode in which each item was first experienced. This conclusion receives support from a study by Senkfor and Van Petten (1995), who contrasted item and source memory, and showed that the ERPs associated with successful performance on the two tasks differed over frontal electrodes.

In interpreting the right frontal effect Wilding and Rugg suggested that it may reflect operations that are necessary to generate and maintain a representation of prior study episodes, such that recollected information can be used to perform the source memory task. This account receives support from a study by Johnson, Kounios and Nolde (1996), who also investigated the ERPs associated with source memory for words and pictures. At study one group of subjects performed an imagery task (how easy each item would be to draw), whilst the other group performed a function task (how many functions each item could serve).

Johnson et al. found that the ERPs associated with successful source memory did not differ for words and pictures, but did differ as a function of encoding task. The ERP differences were particularly pronounced over frontal electrodes, consistent with the suggestion that frontally distributed ERP effects reflect strategic processing differences, related to the retrieval of different source attributes. Unfortunately, Johnson et al. did not report the ERPs associated with correctly recognised new items, making comparison with the old/new effects reported in the present review somewhat difficult. That is, the ERP differences associated with the different study tasks may have reflected general aspects of processing common to both old and new test items, rather than being associated with the strategic retrieval of different types of source information per se.

Finally, as for the left parietal effect, Wilding and Rugg interpreted the fact that the right frontal effect was present to differing degrees for correct and incorrect source judgements as evidence that it reflected a graded rather than all-or-none process. Clearly, the argument regarding the graded nature of left parietal effect (discussed above) also applies to right frontal old/new effect; the ERP data are consistent with either a graded or an all-or-none account of the processes associated with the right frontal effect.

### **Source memory revisited**

One final study of source memory should also be considered. Wilding and Rugg (1997a) investigated the old/new effect using a recognition memory 'exclusion' task (based upon the process dissociation procedure, e.g., Jacoby and Kelley, 1992; discussed in chapter 1). The study phase of this experiment was the same as in Wilding and Rugg (1996); subjects heard words in either a male or female voice. Old and new items were presented visually at test, however rather than the previous two-stage response task, only a single response was required. Subjects were instructed to respond differently to the two classes of study item, items spoken in one voice were designated as 'targets' and responded to as old. Items spoken in the other voice were designated as 'non-targets' and, along with genuinely new items, were responded to as new. Thus, as in previous source memory studies, to perform the exclusion task successfully subjects must recollect the prior study episode of each old item – familiarity will not allow the old targets to be distinguished from old non-targets.

The critical experimental finding from the source memory 'exclusion' study was that the pattern of old/new effects differed for the target and non-target items. The ERPs to old items designated as targets elicited both left parietal and right frontal old/new effects, whereas the ERPs to old non-targets elicited only the left parietal effect. The fact that both classes of old item elicited the left parietal effect provides further support that this effect is closely tied to recollection. More importantly, the fact that only old 'targets' elicited the right frontal effect suggests that subjects were able to correctly classify old 'non-targets' without employing the processes reflected by the right frontal effect. This finding is significant, because assuming that it is not simply a type II error, it suggests that the retrieval of source information may be necessary, but is not



sufficient, to elicit the right frontal old/new effect. Rather than reflecting operations necessary to generate and maintain a representation of study episodes per se, the data suggest that the right frontal old/new effect may be associated with strategic or task related aspects of such operations. Moreover, the use of an exclusion task revealed that the right frontal old/new effects was elicited under conditions where only a single response judgement was required to each test item. Thus, the presence of the right frontal effect in tests of source memory, but not item recognition, cannot be attributed to the use of a two-stage retrieval task – an important finding in its own right.

Finally, Wilding and Rugg (1997a) also demonstrated the presence of an additional ERP component – a late onsetting, negative going shift, maximal over centro-parietal electrodes – that was present in the ERPs to both classes of old item. This effect was not associated with mnemonic processing. Rather, the magnitude of this negative going shift was found to correlate with the mean RT to each response category, regardless of the items' study status, or subjects' responses to each class of item, suggesting that the effect reflects response related processes.

### **Associative recall**

All of the studies performed by Wilding and colleagues discussed above employed a source memory task as a means of operationally defining recollection. In combination with the development of the ERP recording procedures, the source memory approach allowed considerable advances to be made, providing strong evidence in support of the link between the left parietal effect and recollection. Moreover, the studies permitted the discovery of a second component, the right frontal effect, which appears to reflect strategic post-retrieval processing of recollected information. An alternative to the source memory approach has also been employed however, using the successful retrieval of associative information as a means of operationally defining recollection. Associative retrieval provides an equally powerful, if different, definition of recollection to that provided by the use of a source memory task.

A study employing an associative recall task performed by Rugg, Schloerscheidt, Doyle, Cox and Patching (1996). Subjects were presented with a series of arbitrarily paired words, and required to form associations between the words by forming a short sentence incorporating each pair. At test subjects were presented with single old and

new words, and, as in the studies of Wilding and colleagues, a two-stage retrieval task was performed. Subjects were required to discriminate old from new items, and for items judged old, to attempt to recall the word with which it had been paired at study (the study associate). This procedure employed the same logic as in the source memory studies; recollection was operationally defined as the ability to accurately recall the study associate of a recognised old item. Familiarity based responding would not allow subjects to report the study associate, and thus items that were recognised, but for which the study associate was not recalled, must have been recognised either on the basis of familiarity or weak (partial or incomplete) recollection. Moreover, Rugg et al. (1996) were able to make specific predictions regarding the right frontal old/new effect. If the effect was simply associated with successful recollection, then it should be present in the ERPs to successfully recognised items in the study of associative recall. By contrast, if the effect reflects processing that is more sensitive to the specific tasks demands imposed by tests of source memory, then it should be absent in the ERPs for associative recall (as is the case in studies of item recognition).

The ERP findings from this study are illustrated figure 5, shown for the same electrode sites as for the source memory data (see figure 4). As can be seen from the figure, relative to the ERPs for correctly rejected new items, the ERPs to old items that were recognised, and for which the associate was successfully recalled, elicited a left parietal old/new effect. By contrast, a much smaller (and statistically non-significant) left parietal old/new is evident for the ERPs to words that were recognised but for which the study associate was not recalled. Note, however, that from approximately 800-900 msec post-stimulus the left greater than right parietal asymmetry is characterised by a right-sided negative going shift.

Although the negative going effect had been seen in the previous studies of source memory, the present study provided additional information about it. As Rugg et al. (1996) note, the fact that the magnitude of the negative going shift did not differ between the two old response categories suggests that it is dissociable from the left parietal effect. Thus, whilst the two effects may be temporally overlapping, they appear to be functionally distinct, consistent with the suggestion that the negative going shift is linked more closely to response- than memory-related processes (cf. Wilding and Rugg, 1997, discussed above).

Significantly, the associative recall data revealed no sign of the right frontal old/new effect in the ERPs for either class of recognised old item (cf. figure 5). Careful examination of the data does reveal a small transient positive-going shift, maximal over fronto-central electrode sites. However, even with targeted analyses Rugg et al. found that this was not statistically significant (M. D. Rugg, personal communication). Thus, Rugg et al. concluded that, as in studies of item recognition, the generators of the right frontal old/new effect were not active in the case of associative recall. This finding is important because it provides further evidence that the left parietal and right frontal effects are dissociable, supporting the suggestion that the left parietal effect is more closely tied to recollection than is the right frontal effect.

The findings of Rugg et al. also provide further evidence about the functional characteristics of the right frontal old/new effect. The fact that the right frontal effect was not elicited by successful associative recall adds weight to the suggestion made by Wilding and Rugg (1997a) that the effect is particularly sensitive to task related factors. As Rugg et al. note, one of the important differences between tests of source memory and associative recall lies in the nature of the information that is retrieved in each task. Subjects are required to retrieve episodic (contextual) information in both tasks. Moreover, in both cases, contextual information that is recollected must be used to meet the demands of the task.

Crucially, the associative recall task requires the retrieval of contextual information that is intrinsic to each study episode, whereas for source memory the information is extrinsic to each episode. That is, the contextual information retrieved in tests of associative recall is trial unique (i.e., integral to individual study episodes), whereas in source memory the information is background context (i.e., common to a whole classes of study episodes, such as items presented two different voices). Thus, Rugg et al. (1996) suggested that the right frontal effect reflects post-retrieval operations that are engaged selectively, depending on the type of contextual discrimination that is required to perform source memory tasks (i.e., by the retrieval of extrinsic, but not intrinsic, context). Clearly, this conclusion fits well with the idea that the post-retrieval operations are employed to generate a representation of the prior study episode, allowing retrieved information to be used in a strategic, goal directed, way.

## **Identifying the generators of the old/new effects**

An issue that has not been addressed so far concerns the possible intracerebral generators of the old/new effects. As was discussed in chapter 2, scalp recorded ERP data do not, in themselves, provide much information about the location of ERP generators. Consequently, as Allan et al. (in press) note, much of the discussion of the sources of the effects has been inspired by the functional accounts of the effects, and should be considered as little more than informed speculation at present.

As noted above, by Wilding and Rugg's account, the left parietal effect indexes the functioning of the medial temporal lobes to the retrieval of episodic information. Some support for this hypothesis comes from the study by Smith and Halgren (1989) discussed earlier, in which it was found that the old/new effect was absent in left temporal lobectomy patients (although see Rugg, et al., 1991, who found that the old/new effect was attenuated in both left and right temporal lobectomy patients).

Certainly, the fact that the effect is lateralised to the left hemisphere is at least consistent with the finding that it is absent in left, but not right, temporal lobectomy patients. The generators of the left parietal effect are unlikely to be located within the medial temporal lobe memory system itself however, because scalp recorded ERPs are insensitive to activity within the hippocampus and related parahippocampal structures (cf. Rugg, 1995d). Nonetheless, studies employing depth electrodes placed within the medial temporal lobes suggest that activity within these structures is sensitive to the repetition of items during recognition memory tasks (e.g., see Smith, Stapleton and Halgren, 1986; Guillem, N'Kaoua, Rougier, Claverie, 1995). Consequently, Wilding and Rugg (1996) suggested that the effect might index cortical activity that is caused by the cortical-hippocampal interactions that are thought to result from retrieval-related activity of the medial temporal lobe memory system (e.g., see McClelland, McNaughton and O'Reilly, 1995; Teyler and Discenna, 1986).

The functional interpretations discussed above have also inspired accounts of the generators of the right frontal old/new effect. Wilding and Rugg interpreted the presence of the effect as reflecting the demands of the source task, and suggested that the effect may be generated by activity within the right prefrontal cortex. This suggestion fits well with evidence from lesion studies that show source memory to be

disproportionately impaired by damage to the prefrontal cortex (e.g., Janowsky, Shimamura and Squire, 1989; Stuss, Eskes and Foster, 1994). Moreover, as Allan et al. (in press) note, the link between the right frontal old/new effect and activity of the prefrontal cortex also fits well with evidence from neuroimaging studies of memory retrieval employing PET.

Neuroimaging studies have consistently revealed evidence of memory related activity within the right dorsolateral prefrontal cortex (e.g., see Buckner and Tulving, 1995; and Fletcher, Frith and Rugg, 1997 for reviews). Whilst these findings have been interpreted as a sign of retrieval effort or mode (e.g., see Kapur, Craik, Jones, Brown, Houle and Tulving, 1995; Schacter, Alpert, Savage, Rauch and Albert, 1996), there is also evidence that the activity of the right prefrontal cortex varies as a function of whether recognition is successful or unsuccessful (Rugg, Fletcher, Frith, Frackowiak and Dolan, 1996). The fact that activity within the prefrontal cortex varies with retrieval success is significant, because otherwise there could be no corresponding ERP old/new effect (indexing the difference between the correct rejection of new items and the successful recognition of old items). In sum, both lesion and neuroimaging studies provide converging evidence in support of the idea that the generators of the frontal old/new effect are located in the right prefrontal cortex. Notwithstanding the difficulties of inferring the location of generators from scalp recorded ERP data, the scalp distribution of the right frontal effect is at least consistent with the foregoing hypothesis.

## Summary

The studies reviewed in this chapter provide the context for the research presented in this thesis. The findings from a variety of studies suggest that there are two temporally and topographically dissociable ERP old/new effects, which index dissociable memory processes, but which are both associated with the successful retrieval of contextual information. First there is the left parietal effect, which indexes recollection, and can support the ability to make simple old/new judgements concerning the prior occurrence of items in a memory test. Second, there is the right frontal effect, which indexes post-retrieval processing, is thought to operate on the products of the retrieval process, and is associated with the recovery of contextual information. This later process supports

the ability to make source judgements, where subjects are required to use retrieved information in a strategic (task or goal directed) way, and is not elicited in tests of item recognition or associative recall. In combination, the functional characteristics, along with the topographic distribution and time course of the ERP effects, provide convergent evidence in support of this framework.

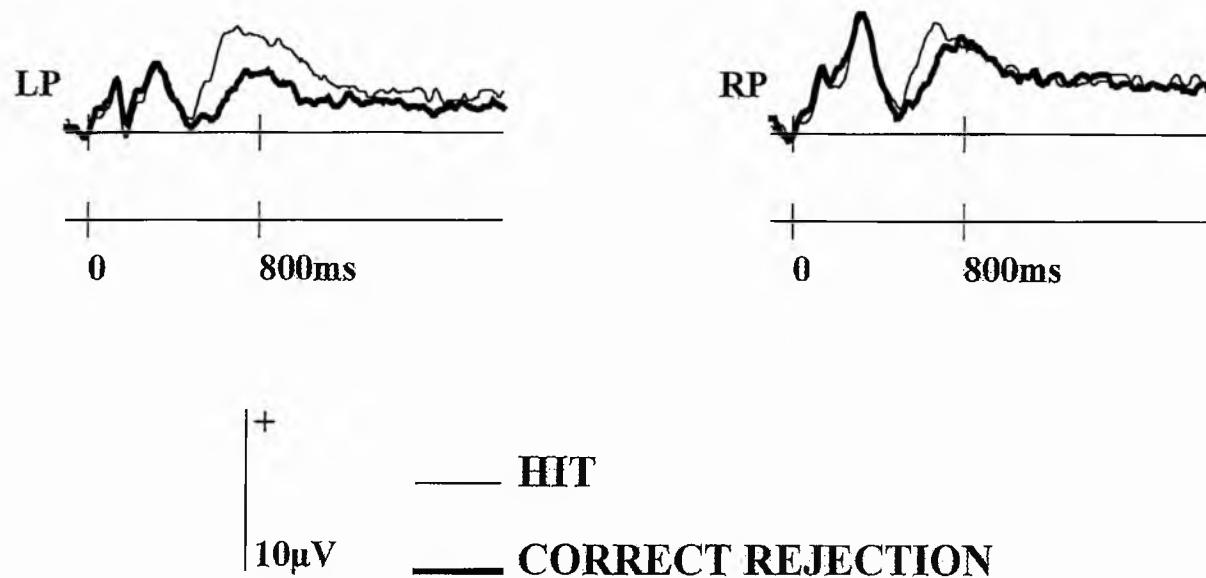
It should be clear that the foregoing account of the functional significance of the ERP old/new effects has developed over time. The ERP methods employed have also developed, such that significantly more information has become available about both the time course and distribution of the effects. Finally, the distinction between the left parietal and right frontal old/new effect, and the mapping of the effects onto a neurologically inspired account of retrieval and post-retrieval memory processing, has allowed an explicit model of memory retrieval to be formulated. The left parietal effect is thought to reflect the activity of the medial temporal lobe memory system, critical for the retrieval of episodic information. By contrast, the right frontal effect is thought to reflect the activity of the prefrontal cortex, critical for more strategic 'post-retrieval' aspects of memory.

The research presented in this thesis follows directly from the work reviewed here, investigating the functional interpretations of the ERP old/new that have been formed on the basis of the studies of item recognition, source memory and associative recall. The five experiments reported here all employ tests of associative memory; starting with ERP studies of associative recognition, and going on to compare associative recognition and associative recall.

As was discussed in chapter 1, associative or relational processing is a fundamental characteristic of the medial temporal lobe memory system, and associative memory tasks have been widely cited as paradigmatic tests of episodic memory (e.g., see Tulving, 1983, Cohen and Eichenbaum, 1993; Gaffan, 1994). Moreover, experiments involving the retrieval of associative information memory have been important in the rejection of single process models of recognition memory, providing evidence in support of dual process models of recognition memory.

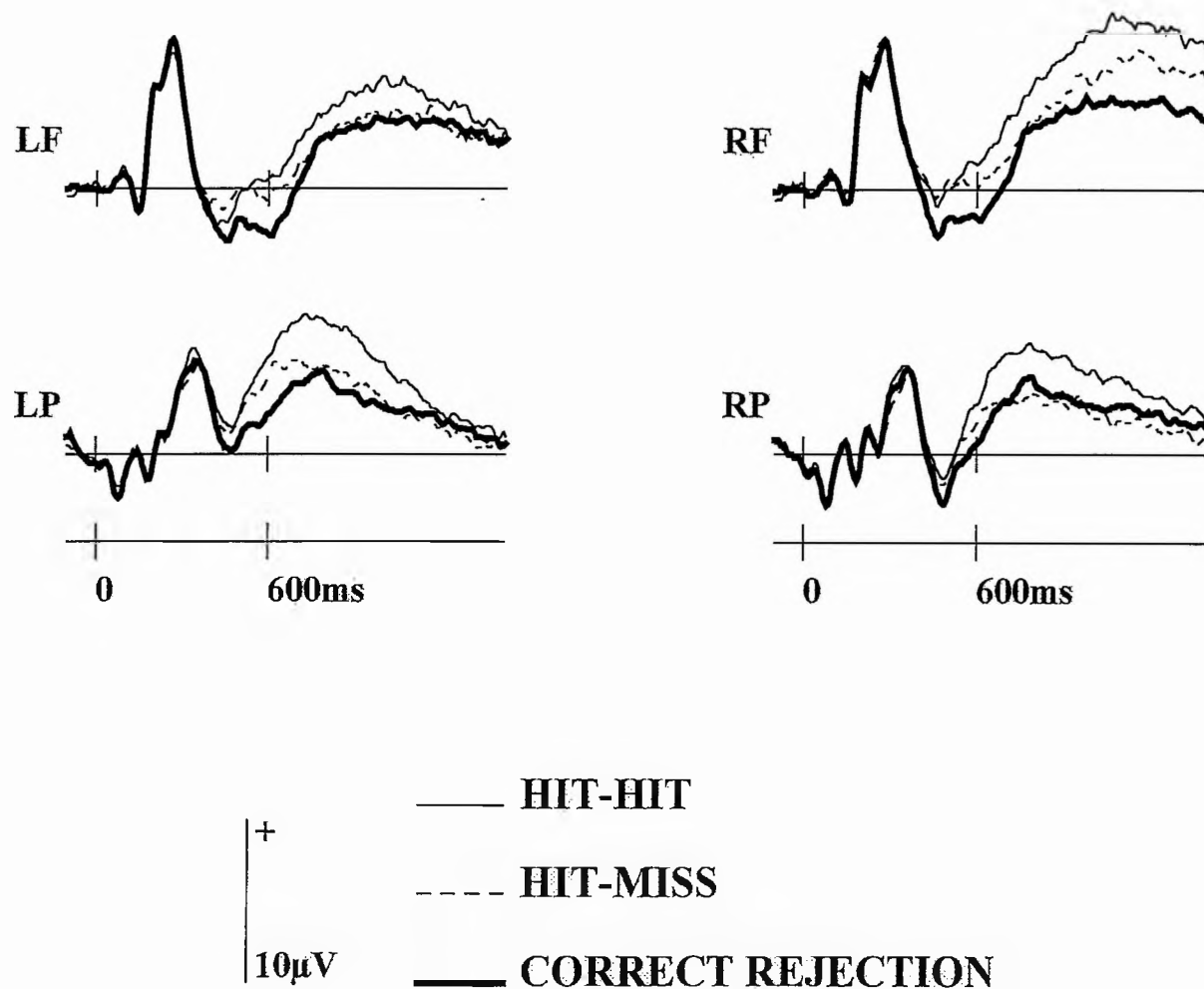
Finally, one advantage of testing associative memory in all five experiments is that the same study procedure is employed in each case – consequently, any differences in the

ERPs at test cannot be attributed to differences at encoding, rather, they must reflect differences at retrieval. Before the introducing experiment 1 in detail however, chapter 4 provides details of the general methods employed in each of the subsequent empirical chapters.

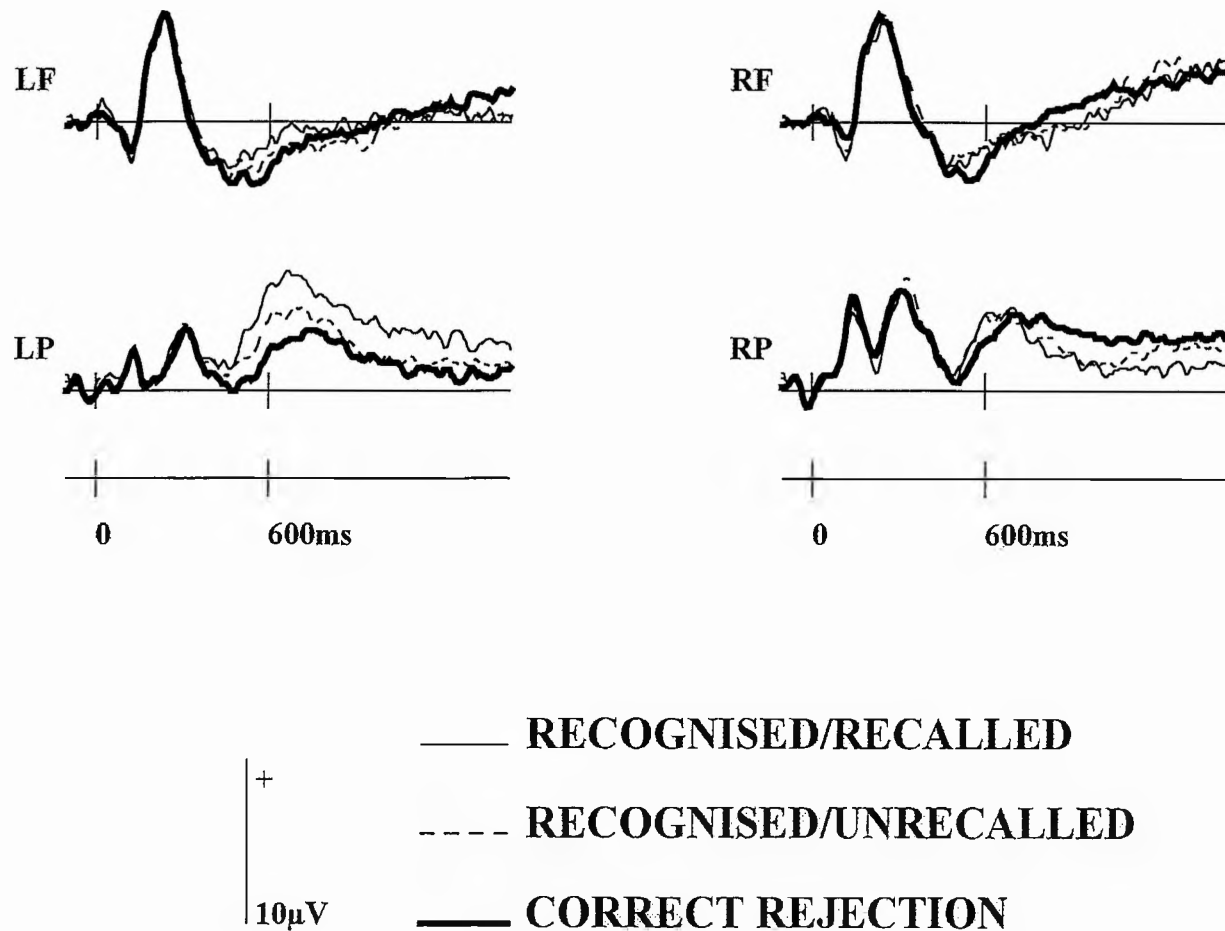


**Figure 3.** The ERP old/new effect: Item recognition. ERPs for correctly recognised old items (hits), and new items (correct rejections). ERPs are shown from the left and right parietal electrodes (LP and RP respectively), illustrating the left greater than right hemispheric asymmetry that characterises the left parietal effect found in studies of item recognition. Reproduced with permission from Allan (1996) unpublished doctoral thesis.





**Figure 4.** The ERP old/new effect: Source memory. ERPs for correctly recognised new items (correct rejections) and correctly recognised old items receiving correct (hit/hit) and incorrect (hit/miss) source judgements. Waveforms are shown from the left and right parietal and frontal electrodes (LP/RP and LF/RF respectively), illustrating the differences in the time course and scalp distribution of the left parietal and right frontal old/new effects. Reproduced with permission from Wilding and Rugg (1996).



**Figure 5.** The ERP old/new effect: Associative Recall. ERPs for correctly recognised new items (correct rejections) and correctly recognised old items receiving correct (recognised/recalled) and incorrect (recognised/unrecalled) associative judgements. ERPs are shown from the left and right parietal and frontal electrodes (LP/RP and LF/RF respectively), illustrating the presence of the left parietal old/new effect, and the absence of the right frontal old/new effect. Reproduced with permission from Rugg et al. (1996).

## **Chapter 4.**

### **GENERAL METHODS**

This chapter provides details of the core methods that are employed in the 5 subsequent experiments. Of particular significance are the details of the study phase, and the procedures employed in the recording and analysis of the ERP data. Each experimental chapter will contain an additional method section, explaining any procedures specific to that study.

#### **Subjects**

Subjects were recruited from the student population in St Andrews, using the following selection criteria: right handed, native English speakers, aged between 16 and 35 years old, with normal (or corrected-to-normal) vision. Subjects were also screened for a history of neurological or psychiatric illnesses, and recent drug or alcohol use. Subjects were paid either £3.50 per hour (experiments 1-3), or £5.00 per hour (experiments 4 and 5), for participating.

## **Experimental materials**

Stimuli were drawn from a set of 1000 medium frequency nouns and verbs (mean 19.1 per million, range 10 to 30 per million, 4 to 8 letters in length) selected from the Francis and Kucera corpus (Francis and Kucera, 1982). These words are provided in appendix A. In each experiment this word list was manipulated to produce a set of semantically and associatively unrelated word pairs (see individual methods sections for details of the procedures used to create study-test lists).

All experimental stimuli were presented as pairs in central vision (separated by approximately 0.7 degrees), just above and below a central fixation point. Stimuli were displayed in white capital letters against a black background, subtending a maximum vertical visual angle of approximately 0.7 degrees and a maximum horizontal angle of approximately 2.0 degrees.

## **Experimental tasks and procedures**

Subjects were initially fitted with an ERP recording cap (described below). It was then explained that they were taking part in a memory experiment, and that the aim of study task was to ensure that they remembered word pairs. The study phase was identical in all 5 experiments, and involved a self-paced 'sentence generation' task. All aspects of the study procedure were kept constant, except that subjects were given slightly more time in experiments 4 and 5 (shown in square brackets below).

For each trial an initial fixation character (!) was displayed, signalling that the subject could initiate the beginning of a trial. When the appropriate response button was depressed this character was replaced with a second fixation character (+) for a duration of 500 msec [800 msec for experiments 4 and 5]. This character was replaced with a word pair, displayed for 500 msec [1000 msec for experiments 4 and 5], followed by the original fixation character. Subjects were instructed to read each pair as it was presented, and then to generate and say out loud a short sentence that incorporated the two words. Subjects were then free to begin the next trial.

In all experiments, prior to the test phase subjects were instructed to relax, maintain fixation, minimise body and eye movement, and blink only when an exclamation

character (!) was present on the monitor. It was stressed that these instructions were intended to reduce the number of ERP trials containing artifacts (see below).

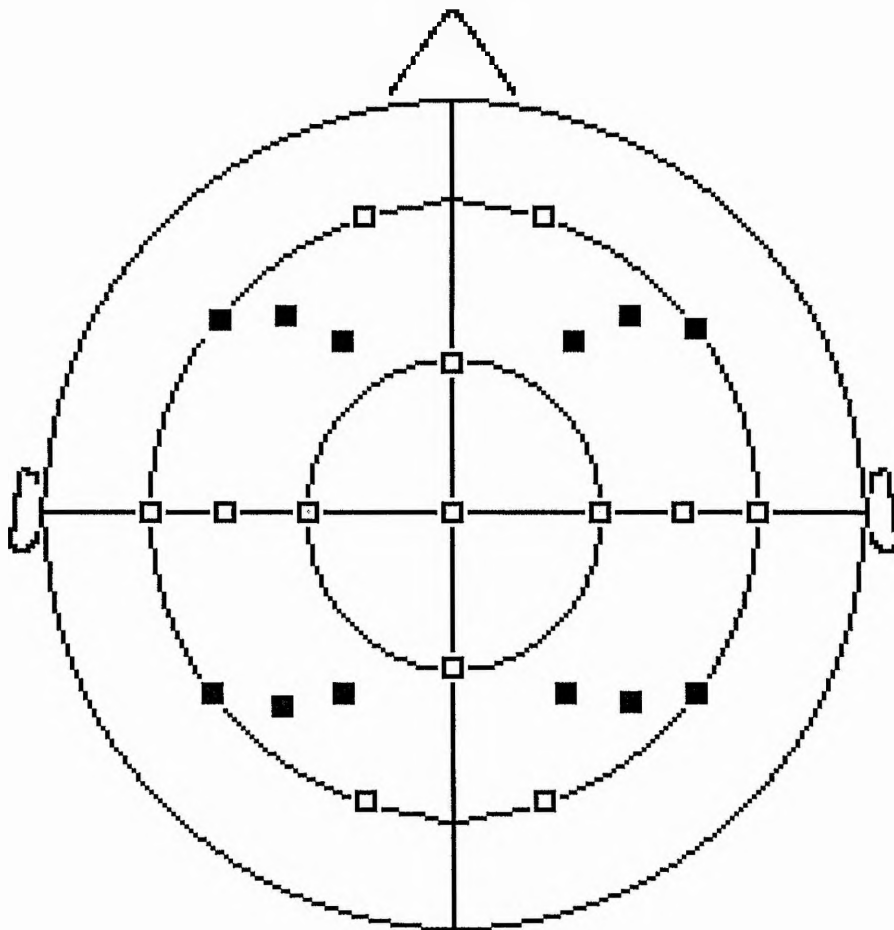
### ERP recording and data processing

Scalp EEG was recorded from 25 tin electrodes embedded in an elasticated head cap (Electro-Cap International). The recording montage, illustrated in figure 6, was based on the International 10-20 system (Jasper, 1958). Midline sites were Fz, Cz and Pz. Left and right hemisphere sites were: Fp1/Fp2; F3/F4, F7/F8, LF/RF (frontal, 75% of the distance between Fz and F7/F8); C3/C4, T3/T4, LT/RT (anterior temporal, 75% of the distance between Cz and T3/T4); P3/P4, T5/T6, LP/RP (parietal, 75% of the distance between Pz and T5/T6); and O1/O2.

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**Figure 6.** Electrode montage, viewed as if looking down onto the top of the head. All 25 electrodes are shown (shaded electrodes are those employed in the subsidiary analyses performed in each experiment).

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An additional channel recorded EEG from the right mastoid. All EEG channels were recorded with respect to an electrode placed on the left mastoid, but were re-referenced off-line to represent recordings with respect to linked mastoids. EOG was recorded bipolarly from electrodes positioned above the supra-orbital ridge of the right eye, and adjacent to the outer canthus of the left eye. Inter-electrode impedance levels were kept below  $5k\Omega$ , and EEG and EOG were each amplified with a bandwidth of 0.03Hz to 35Hz (3dB points).

In experiment 1 signals were sampled for 1536 msec, at a rate of 6 msec per point. Sampling began with a 102 msec pre-stimulus baseline, allowing a total post-stimulus recording epoch of 1434 msec. In experiments 2-6 the post-stimulus recording epoch was extended to 1944 msec (sampling at 8 msec per point, for 2048 msec with a 104 msec pre-stimulus baseline).

ERPs were formed only for the selected response categories in any given experiment (see individual method sections for details). Response categories were defined by the type of item presented (e.g., old vs. new words presented at test) and the response made to those items (e.g., correct vs. incorrect old/new judgements). When forming ERPs trials were excluded if there was substantial EOG activity (i.e., if base-to-peak EOG amplitude exceeded  $98\mu V$ ), or if one or more channels exhibited excessive drift from baseline (i.e., if the difference between first and last data points exceeded  $60\mu V$  (experiments 1 to 3) or  $55\mu V$  (experiments 4 and 5)). These two constraints ensured that any trials containing large artifacts did not contribute to the averaged ERP.

To ensure an acceptable ERP signal/noise ratio, a minimum of 16 artifact-free trials was required in each critical response category, from each subject. Subjects that did not contribute sufficient ERP trials to each critical response category were excluded. Prior to EEG averaging the DC offset (pre-stimulus baseline drift) was removed from each recording channel. This required subtracting the mean amplitude of the pre-stimulus baseline from the voltage measure at each sample point, resulting in the pre-stimulus baseline being normalised to zero (as can be seen in the grandaverage ERPs). Finally, averaged ERP data were smoothed, using a 5-point binomial filter.

## **Data Analyses**

Behavioural and ERP data were analysed using repeated measures ANOVA. Unless otherwise stated, post hoc contrasts were performed with the Newman-Keuls test, and employed a significance threshold of  $p < 0.05$ .

To reduce the probability of a Type-I error in the analysis of the ERP data the Greenhouse-Geisser correction for non-sphericity was used, and associated F ratios are reported with corrected degrees of freedom where necessary (Howell, 1992). This correction is necessary because ANOVA model assumes that the data being analysed exhibits sphericity, i.e., that the variance within the levels of a factor, and covariance between factors, are homogenous. The ANOVA model is robust in the face of minor violations of this assumption, however, when applied to ERP data this assumption is usually broken. For example, the amount of variance shared by any two electrodes is highly dependent upon their location relative to one another; generally the closer they are the greater variance they share. Thus, in any analysis involving a number of electrode sites the covariance between each pair of electrodes is unlikely to be homogenous (e.g., data measured from two anterior electrodes is likely to share more variance with each other than with data measured from a posterior electrode). The Greenhouse-Geisser procedure provides an estimate of the degree to which the assumption of sphericity is violated, and reduces the degrees of freedom accordingly.

In each experiment analysis of the ERP data typically involved comparing the ERPs for each pair of critical response categories (e.g., correct rejections vs. correct recognition), over a series of latency regions. ANOVAs were conducted on the mean amplitude of the averaged ERPs, relative to the mean amplitude of the pre-stimulus baseline. There were two elements to the analyses of each data set, comparison of the magnitudes (size) of effects, and comparison of the topographies (scalp distribution) of the effects.

### **Magnitude analyses**

The magnitude analyses were performed to elucidate any differences in the amplitudes of the ERPs, beginning with a global ANOVA, employing the factors of response category and site (all 25 electrodes, cf. Figure 6). The global ANOVA was then

followed by targeted subsidiary ANOVA, employing a subset of sites. In experiments 1 to 3 these were lateral electrodes over left and right, frontal and temporo-parietal, scalp (i.e., chains of 3 sites in each of four locations, highlighted in figure 6) and the ANOVAs employed the factors of location (anterior vs. posterior), hemisphere (left vs. right) and site (inferior vs. mid-lateral vs. superior). In experiments 4 and 5 the analysis was performed separately for anterior and posterior chains, employing the factors of hemisphere (left vs. right) and site (inferior vs. mid-lateral vs. superior). In each experiment the results of these subsidiary magnitude analyses are reported in a table. Only significant effects involving the factor of response category are reported, because interest lies solely in differences between response categories (i.e., old/new effects).

### **Topographic analyses**

Following the analyses of the magnitude of effects, additional analyses were performed to investigate the scalp topography of any old/new effects that were found. The structure of the topographic analyses typically followed the same pattern as that for the magnitude analyses. However, the topographic analyses were performed on 'difference waveforms' (i.e., the difference between the ERPs to old and new response categories), allowing the distribution of the old/new effects to be compared across latency regions, and across response categories. Importantly, prior to the topographic analyses these data were 'rescaled'.

Rescaling the data is necessary because of a second disparity between the properties of scalp recorded ERPs and the assumptions of the ANOVA technique (McCarthy and Wood, 1985). Any change in the degree to which a generator is active has a multiplicative effect upon voltage measurements made at the scalp. As applied to ERP data however, the ANOVA model assumes that a change in the activity of a generator would have an additive effect at the scalp. Thus, analyses performed upon raw data can misrepresent (quantitative) changes in magnitude as (qualitative) changes in distribution. ERP data must therefore be rescaled to remove the confounding effects of changes in the magnitude of effects, on changes in the distribution of the effects. Following McCarthy and Wood (1985), the data were rescaled by calculating the magnitude of the ERP effect at each electrode site relative to the magnitude of the



effect at all other sites (the max-min method). This procedure was performed separately for each response category and each latency region, transforming each data set into a zero-to-one range, whilst maintaining the relative distribution of activity across the scalp whilst removing differences in size.

## **Chapter 5.**

### **EXPERIMENT 1**

#### **INTRODUCTION**

As should be clear from the review in chapter 1, the idea that recognition memory is based on two distinct processes, recollection and familiarity, is central to 'dual process' theories of recognition (cf. Atkinson and Juola, 1973; Gardiner and Java, 1993; Jacoby and Dallas, 1981; Mandler, 1980). Recollection refers to conscious retrieval of the original study episode in which an item (usually a word) occurred. Thus, recollection provides information both about the prior occurrence of an item, and the context of that occurrence. By contrast, familiarity-based recognition is not accompanied by information from specific study episodes, and therefore provides no means for making discriminations on the basis of contextual information. Recollection is commonly viewed as the outcome of a relatively slow, effortful, search-like, process which can be brought under conscious control, whereas familiarity is seen as reflecting a faster, more automatic, process (e.g., Hintzman and Curran, 1994; Jacoby and Kelley, 1992).

Dual process theory has provided the framework for the interpretation of findings from several recent ERP studies of recognition memory (e.g., Rugg et al., 1995; Smith, 1993; Wilding et al., 1995; for reviews see Allan et al., in press; Johnson, 1995; Rugg

1995). These studies have revealed a characteristic pattern of scalp-recorded neural activity - the ERP 'old/new effect' - that is associated with successful recognition. The old/new effect takes the form of a positive shift in the ERPs for words which are correctly recognised as old (hits), compared to those correctly judged new. The effect typically onsets between 300 and 400 msec post-stimulus, lasts for around 400-600 msec, and is maximal over left temporo-parietal sites. The effect is not found for unrecognised old words (misses), or for new words incorrectly identified as old (false alarms). It therefore appears to be a reflection of brain activity contributing to, or contingent upon, the retrieval of information required to make accurate recognition responses.

A range of evidence supports the idea that the ERP old/new effect is an electrophysiological correlate of recollection (e.g., see Paller and Kutas, 1995; Paller et al., 1995; Rugg et al., 1995; Smith, 1993; Smith and Halgren, 1989). Perhaps the most convincing evidence comes from studies in which recollection has been operationalised as the ability to make accurate source judgements (Wilding et al., 1995, Wilding and Rugg, 1996, 1997a). The rationale behind such studies is that items can be assigned to their correct source only if their encoding context is successfully retrieved. Hence, differences between ERPs elicited by items attracting correct and incorrect source judgements can be taken to be ERP correlates of recollection. In the experiments of Wilding and Rugg (1996), subjects heard words at study that were presented in either a male or female voice. At test, subjects were required to judge whether items were old or new, and, for each item judged old, to report the gender of the voice in which it had been presented at study. Wilding and Rugg found that the magnitude of the left parietal old/new effect was larger in the ERPs associated with recognition that was accompanied by an accurate source judgement than when it was accompanied by an inaccurate judgement.

In addition to the left parietal effect, the data of Wilding and Rugg (1996) demonstrated the existence of a second old/new effect, which was also sensitive to whether or not recognition was accompanied by recollection. This effect also onset around 400 msec post stimulus, but was dissociable from the left parietal effect by virtue of its more extended time course, and its right frontal scalp distribution. Like the

left parietal effect, the 'right frontal' old/new effect was larger in ERPs associated with correct rather than incorrect source judgements.

Wilding and Rugg argued that the prominence of the right frontal effect in their studies of source memory reflected the fact that, unlike standard tests of recognition memory, source judgements necessitate the explicit retrieval of study context. They argued that the right frontal effect reflects processes, which operate upon recollected information to generate a representation of the retrieved episode (cf. Squire et al., 1993). They further argued that such representations are necessary for accurate source discriminations, but not for making simple old/new discriminations, hence the absence of a prominent right frontal effect in previous ERP studies of recognition memory.

The present experiments extend previous findings by employing an associative recognition task to vary the likelihood that experimental items will be recollected. Tests of recognition memory for associative information (associative recognition) involve memory for word pairs rather than individual words. At test subjects must distinguish pairs composed of the same words as were presented at study (same pairs) from pairs composed of new combinations of studied words (rearranged pairs). In contrast to old/new recognition (item recognition), where subjects are presented with a mixture of old and new words, all the words in a typical associative recognition test have been studied. Thus, it is memory for the relationship between the members of a pair that is critical for accurate performance.

As already noted, the dual-process framework proposes that accurate item recognition can be based on either familiarity or recollection. By contrast, it has been argued that associative recognition is based solely on recollection, as the recovery of information about word pairing is only available if memory for the original study episode is retrieved (cf. Clark, 1992; Hockley, 1992). Thus, according to this argument, familiarity-based recognition cannot support associative recognition judgements.

This argument has recently received support from the findings of Yonelinas (1997), who contrasted the receiver operating characteristics (ROCs) for item and associative recognition memory. Yonelinas found that ROC curves for item recognition were best fitted by a model of performance which assumes a contribution from both familiarity and recollection (see also Yonelinas and Jacoby, 1995), whereas the ROC curves for

associative recognition were best fitted by assuming that performance was based on recollection alone. Thus, Yonelinas' data support the suggestion that performance on tests of item recognition can be based on either recollection or familiarity, but that only recollection can support accurate associative recognition.

Yonelinas' findings also provide an important insight into how rearranged pairs are detected in an associative recognition test. Since recollection is more probable for same than for rearranged pairs, 'rearranged' responses could be made by default, whenever a test pair fails to engender recollection. In line with this analysis, Yonelinas' findings suggest that responses to rearranged pairs are indeed more likely to be made on the basis of a 'default' strategy than upon veridical recollection of a study episode.

In summary, the findings from behavioural studies suggest that accurate performance on tests of associative recognition is based predominantly on the recollection of previous study episodes. Associative recognition thus provides a means of further investigating the putative ERP correlates of recollection. Specifically, if the ERP effects described by Wilding and Rugg (1996) do indeed reflect processes linked to recollection of specific prior episodes, the effects should be more prominent, relative to unstudied pairs, for word pairs that maintain their pairing between study and test than for those in which the pairing is changed. The two experiments reported below explore this hypothesis.

Experiment 1 was designed to be analogous with the source memory procedure employed by Wilding and Rugg (1996). To this end the standard associative recognition paradigm was modified by including pairs of new words (new pairs) in the test task, thus providing an ERP baseline equivalent to that used by Wilding and Rugg. At study, subjects viewed a series of unrelated word pairs and at test they were presented with same, rearranged, and new pairs. The test requirement was first to categorise each pair as either old or new, and, for pairs judged to be old, to perform an associative recognition judgement. According to the reasoning outlined in the previous paragraph, ERPs to pairs correctly judged 'same' should resemble those associated with correct source judgements in Wilding and Rugg's study (1996). In contrast, the ERPs to pairs correctly judged 'rearranged' should show little or no sign of the ERP correlates of recollection.

## METHODS

### Subjects

18 students participated in the experiment. Data from 2 subjects were discarded due to there being insufficient artifact-free trials in the critical response categories. Of the remaining 16 subjects, 10 were female. The mean age of the subjects was 19.6 years (range 17 to 23 years).

### Experimental materials

The experimental design, examples of stimuli and correct responses are shown in table 2. 800 words were selected at random from the word pool (cf. Appendix A) and used to form 400 semantically and associatively unrelated pairs. These pairs were then randomly allocated into one of two study lists. Each study list was paired with two test lists, each of which contained 400 critical pairs. Of these pairs 200 were drawn from the alternative study list, and constituted the new pairs. One hundred of the study pairs maintained their pairing between the study and test lists, and the remaining 100 pairs were repaired so as to generate the rearranged pairs. The items that were used to form the rearranged pairs in one of the test lists were employed to form the same pairs in the other, and vice-versa.

**Table 2.** Experimental design, showing the different classes of stimuli, and associated correct responses.

<u>Phase</u>	<u>Class of Item</u>	<u>Example</u>	<u>Response</u>
Study List	200 word pairs:	doll-bush	
		charm-glue	
		paint-ride	
		green-honey	
Test List	100 same pairs:	doll-bush	Old: Same
	100 rearranged pairs:	charm-ride	Old: Rearranged
	200 new pairs:	rock-steam	New

By rotating study and test lists over subjects, it was possible to ensure that every word pair was presented equally often as old or new, and when old, equally frequently as same or rearranged. An extra 40 words were selected for use as filler items, forming 20

word pairs. Four different orderings of the two study lists were created, padded by 5 filler pairs before each set of 100 critical items. The 8 test lists were generated so as to have different quasi-random orderings of items and experimental conditions, and again contained a sequence of 5 fillers prior to each set of 100 critical pairs.

### **Experimental tasks, procedure and ERP recording**

The experiment consisted of a single study-test cycle (details of the study procedure are provided in chapter 4). The test phase followed the study phase after an interval of approximately 10 minutes. Each test trial consisted of the presentation of a fixation character (!) for 2.4 seconds, followed by a second fixation character (+) for 500 msec. There then followed a 182 msec blank period, following which the test items were presented for a duration of 300 msec. The screen then remained blank until 1 sec after the first response, at which time a third fixation character (?) was presented for 2.5 seconds, signalling the need to give the second response if appropriate. The original fixation character then returned, signalling the beginning of the next trial.

Subjects were instructed to make an initial speeded old/new judgement to each test pair, responding old to pairs that contained studied words, and new to pairs of unstudied items. They were instructed to make this judgement as quickly but also as accurately as possible. The instructions further specified that for pairs judged to be old, a second response should be given when cued to do so. The requirement now was to judge whether the words were in the same pairing as when seen at study, or whether the pairing had changed. The test list was administered in four blocks of 105 pairs, with a short rest break intervening between each block.

Responses were made with the left or right index fingers, which rested on microswitch response keys. The mapping of keys to responses was counterbalanced across subjects such that there was no correlation between hands used for positive responses for each of the two judgements. Details of the ERP recording procedures are provided in chapter 4.

## RESULTS

### Behavioural data

Table 3 shows the probability of an old judgement to same, rearranged, and new pairs. A one way ANOVA of these probabilities revealed a significant main effect ( $F_{2,30} = 181.69$ ,  $p < 0.001$ ). Post hoc tests revealed significant differences between each pair of means; subjects were able to discriminate both classes of old pair from new pairs, but did so more accurately for same pairs.

**Table 3.** Mean probability (standard deviations in brackets) of an old response for the initial old/new judgement, and the subsequent probability of a correct associative recognition judgement, for same, rearranged and new pairs. For new pairs, the associative recognition score shows the probability of a 'rearranged' response to false alarms.

<u>Judgement</u>	<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>New</u>
OLD/NEW	Old:	0.81 (0.15)	0.73 (0.12)	0.18 (0.26)
ASSOCIATIVE	Correct:	0.75 (0.14)	0.84 (0.13)	0.89 (0.1)

Table 3 also shows the probabilities of correct responses for the associative recognition judgement (conditionalised on initial recognition performance), as well as the proportion of false alarms receiving a 'rearranged' response. Initial analysis of the associative recognition judgements compared the probability of a correct response for all old pairs (i.e., averaged across same and rearranged pairs) against the chance level of 0.5. This revealed that subjects were able reliably to discriminate same from rearranged pairs ( $t(15) = 15.48$ ,  $p < 0.001$ ). Responses to false alarms showed a strong (0.89) and statistically significant ( $t(15) = 11.71$ ,  $p < 0.001$ ) bias towards judging such pairs as being 'rearranged'. To elucidate differences in responses to same and rearranged pairs, the probability of correct associative recognition responses for each class of pair was contrasted with the probability of making the same response to a false alarm. This analysis revealed that the same pairs received significantly more 'same' responses than did false alarms (0.75 vs. 0.11,  $t(15) = 15.45$ ,  $p < 0.001$ ), whereas rearranged pairs received slightly fewer 'rearranged' responses than false alarms (0.84 vs. 0.89,  $t(15) = 2.57$ ,  $p < 0.025$ ).



Table 4 shows mean RTs for the initial recognition responses. These are shown according to the accuracy of the initial old/new recognition judgement, and also according to the accuracy of the subsequent associative recognition judgement. For the former set of RTs, ANOVA revealed main effects of word pair type and accuracy ( $F_{1,44,30} = 4.57$ ,  $p < 0.05$ ; and  $F_{1,15} = 33.70$ ,  $p < 0.001$ , respectively). The main effect of accuracy reflected faster correct than incorrect responses. Post hoc tests revealed that the main effect of word pair type reflected significant differences in RTs between each pair of means. The mean RTs were slowest for the rearranged pairs (1788 msec), and fastest for new pairs (1645 msec), with same pairs occupying an intermediate position (1737 msec).

**Table 4.** Mean reaction times (msec) separated according both to the accuracy of the initial old/new recognition judgement and the subsequent associative recognition judgement.

<u>Judgement</u>	<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>New</u>
OLD/NEW	Correct:	1583	1686	1574
	Incorrect:	1890	1889	1716
ASSOCIATIVE	Correct:	1492	1715	
	Incorrect:	1734	1629	

ANOVA of the RTs conditionalised on accuracy of the associative recognition judgement revealed no main effects. However, the interaction between pair type and accuracy was significant ( $F_{1,15} = 12.22$ ,  $p < 0.01$ ). Post hoc tests revealed that for same pairs, RTs were faster for correct than incorrect responses, whilst there were no such differences for rearranged pairs. In addition, for correct responses, same pairs received faster RTs than rearranged pairs, but no such differences were found for incorrect responses.

### **ERP data**

ERPs were formed for 3 critical response categories: correctly classified new pairs (*new pairs*); same pairs correctly classified as old and same (*same pairs*); and rearranged pairs correctly recognised as old and rearranged (*rearranged pairs*). The mean number of trials contributing to the grand average ERPs in the new, same, and rearranged response categories were 129, 49 and 51 respectively.

Figure 7 shows these ERP waveforms for all 25 recording sites. Figure 8 shows the ERP waveforms in more detail from those sites - lateral frontal and lateral parietal - most important for demonstrating the existence of the left parietal and right frontal old/new effects observed by Wilding and Rugg (1996). The figures show that the waveforms begin to diverge from one another approximately 600 msec post-stimulus onset, with the ERPs for the same and rearranged pairs becoming more positive than those for new pairs. For same pairs, this positive shift is larger over the left than the right hemisphere at posterior electrodes, but exhibits the opposite asymmetry at anterior electrodes. The positive shift in the ERPs to rearranged pairs is smaller in amplitude, more restricted in time, and confined to posterior electrodes. From around 900 msec, it is replaced by a sustained negativity, which is maximal over the right centro-parietal scalp.

ERPs were quantified over three successive latency regions: 600-900 msec, 900-1200 msec and 1200-1434 msec. These regions were chosen to allow changes in the pattern of effects over time to be elucidated, and to be roughly comparable with the measures employed by Wilding and Rugg (1996). The differences in the mean amplitude of each latency region between the ERPs to each category of old pair and those to new pairs (the old/new effects) are shown for lateral frontal and temporo-parietal electrodes in figure 9.

The analysis of the magnitude of effects during each latency region involved an initial global ANOVA of the data from all 25 sites, followed by subsidiary analyses targeted at the data from lateral frontal and temporo-parietal electrodes (cf. chapter 4). Topographic analyses were also performed, testing for differences in the scalp distribution of the old/new effects associated with same and rearranged pairs, and asking whether the topography of these effects changed over time. These analyses followed the same structure as the magnitude analyses.

#### **Amplitude analyses**

For the 600-900 msec latency region, the global ANOVA revealed a main effect of response category ( $F_{1.9,28.8} = 13.67, p < 0.001$ ). For the two subsequent regions, the global ANOVA gave rise both to a main effect of response category (900-1200:  $F_{1.7,24.8} = 9.52, p = 0.001$ ; 1200-1434:  $F_{1.7,26} = 8.77, p < 0.005$ ) and to interactions between category and site (900-1200:  $F_{4.7,70.2} = 2.44, p < 0.05$ ; 1200-1434:  $F_{5.3,78.8}$

= 2.90,  $p < 0.025$ ). In light of these significant effects, subsidiary ANOVAs, contrasting each pair of response categories, were performed for each latency region. The results of these analyses are shown in table 5 and elucidated in the following sections.

**Table 5.** Results of the amplitude analyses, comparing each pair of response categories, over each latency region. Only significant effects involving the factor of response category (RC) are reported. HM = Hemisphere, L = Location (Anterior vs. Posterior), ST = Electrode site (Inferior vs. Mid-Lateral vs. Superior).

<u>LATENCY REGION</u>	<u>PAIRWISE COMPARISON</u>		
	<u>Same v New</u>	<u>Rearranged v New</u>	<u>Same v Rearranged</u>
<u>600-900 msec</u>			
RC	$F_{1,15} = 24.58, p < 0.001$	-	$F_{1,15} = 12.84, p < 0.01$
RC x ST	$F_{1.2,17.3} = 16.50, p < 0.001$	-	$F_{1.1,17.0} = 12.42, p < 0.005$
RC x HM	$F_{1,15} = 8.34, p < 0.05$	$F_{1,15} = 6.09, p < 0.005$	-
RC x HM x L x ST	$F_{1.8,27.0} = 4.45, p < 0.05$	-	-
<u>900-1200 msec</u>			
RC	$F_{1,15} = 9.15, p < 0.01$	-	$F_{1,15} = 21.04, p < 0.001$
RC x ST	$F_{1.1,16.4} = 5.12, p < 0.05$	-	$F_{1.1,17.0} = 14.18, p < 0.001$
RC x HM x L	$F_{1,15} = 13.83, p = 0.005$	$F_{1,15} = 5.63, p < 0.05$	$F_{1,15} = 5.82, p < 0.05$
RC x HM x L x ST	$F_{1.8,27.0} = 3.87, p < 0.05$	-	-
<u>1200-1434 msec</u>			
RC	$F_{1,15} = 9.32, p < 0.01$	-	$F_{1,15} = 16.80, p = 0.001$
RC x ST	$F_{1.1,16.7} = 5.10, p < 0.05$	-	$F_{1.4,21.3} = 20.84, p < 0.001$
RC x L x ST	$F_{1.9,28.8} = 5.95, p < 0.01$	-	-
RC x HM x L	$F_{1,15} = 23.71, p < 0.001$	$F_{1,15} = 11.64, p < 0.01$	$F_{1,15} = 15.90, p < 0.001$

Same vs. New: The ANOVAs comparing the ERPs to same and new pairs for the 600-900 and 900-1200 msec latency regions revealed several significant effects, including four way interactions between category, hemisphere, location and site (see table 5). As can be seen in figure 9, in each case these effects reflect the greater positivity of the ERPs to same pairs. This positivity is markedly asymmetric in favour of the left hemisphere at temporo-parietal sites, but is almost symmetrical frontally. The combination of asymmetric old/new effects posteriorly, and bilateral effects frontally, accounts for the involvement of the factors of category, hemisphere, and location in the four way interaction. Not illustrated in figure 9, but evident in figure 7, is the reason for the involvement of electrode site in the four way interactions. This reflects the fact that at both anterior and posterior sites, old/new effects were greater in magnitude at the electrodes nearest to the midline.

The ANOVA comparing for the 1200-1434 msec latency region revealed a three-way interaction between category, hemisphere, and location, and between category, location and site. These interactions reflect variations across the scalp in the magnitude of the old/new effects for the same pairs. The interaction with hemisphere and location arose because the old/new effects show a left hemisphere maximum at the posterior electrodes, whereas at frontal sites the old/new effect exhibits a right hemisphere maximum (see figure 9). The interaction with location and site reflects the fact that the old/new effects increases in size as electrodes get nearer to the midline at anterior electrodes, but that this is not the case at posterior electrodes (see figure 9).

Rearranged vs. New: The ANOVA comparing the amplitudes in the 600-900 msec latency region revealed a single interaction, between response category and hemisphere (see table 5). As figure 9 shows, this effect reflects the fact that the ERPs to rearranged pairs are the more positive going, but only over the left hemisphere. By contrast, for both the 900-1200 and 1200-1434 msec latency regions the subsidiary ANOVA revealed a single significant interaction between response category, hemisphere and location. For both latency regions this interaction reflects the fact that, other than at left posterior electrodes, the old/new effect associated with rearranged pairs tends to be negative- rather than positive-going, an effect that is especially pronounced at right posterior sites (see figure 9).

Same versus Rearranged: For the 600-900 msec latency region, the ANOVA contrasting the ERPs to same and rearranged pairs gave rise to a significant effect of category, and a reliable category by site interaction (see table 5). As can be seen in figure 9, these effects reflect the greater positivity of the ERPs to same than to rearranged pairs, and the fact that this difference is smaller at lateral electrodes than at sites nearer to the midline. Table 5 also shows that the ANOVAs for the 900-1200 and 1200-1434 msec latency regions gave rise to several significant effects, including interactions between response category, hemisphere and location, and between category and site. In each case, the three way interaction reflects the fact that the ERPs for same pairs are more positive going than those for rearranged pairs, a difference that is larger over the right hemisphere at the frontal sites, but larger over the left hemisphere at temporo-parietal sites (cf. figures 7 and 9).

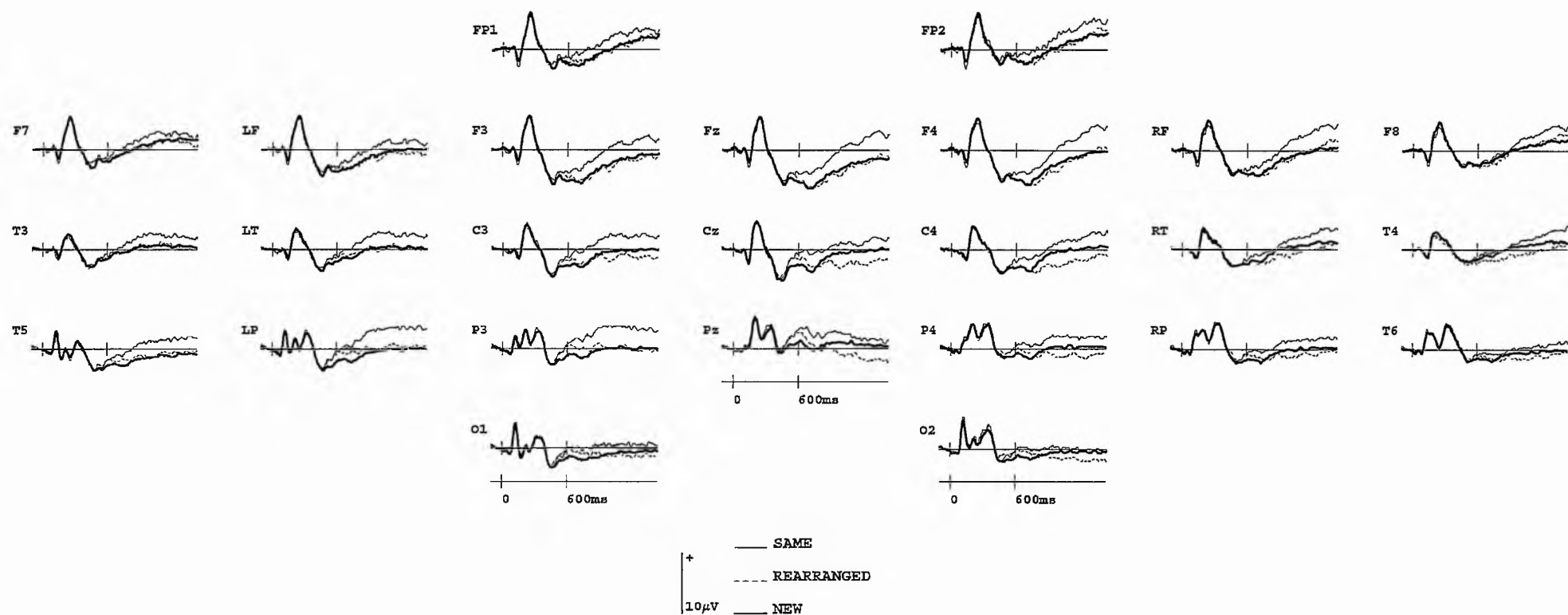
### **Topographic analyses**

The scalp topographies of the old/new effects for the same and rearranged pairs are shown for each latency region in figure 10. In each case, the effects begin with left temporo-parietal and bilateral frontal maximum, whereas by the latest of the three regions, they exhibit left temporo-parietal and right frontal maxima. The global ANOVA comparing the topographies of the two effects across latency regions revealed a single effect, an interaction between latency region and electrode site ( $F_{4.8,72.7} = 5.91$ ,  $p < 0.001$ ), and also gave rise to a marginally significant interaction between response category and electrode ( $F_{3.1,46.1} = 2.59$ ,  $p < .07$ ).

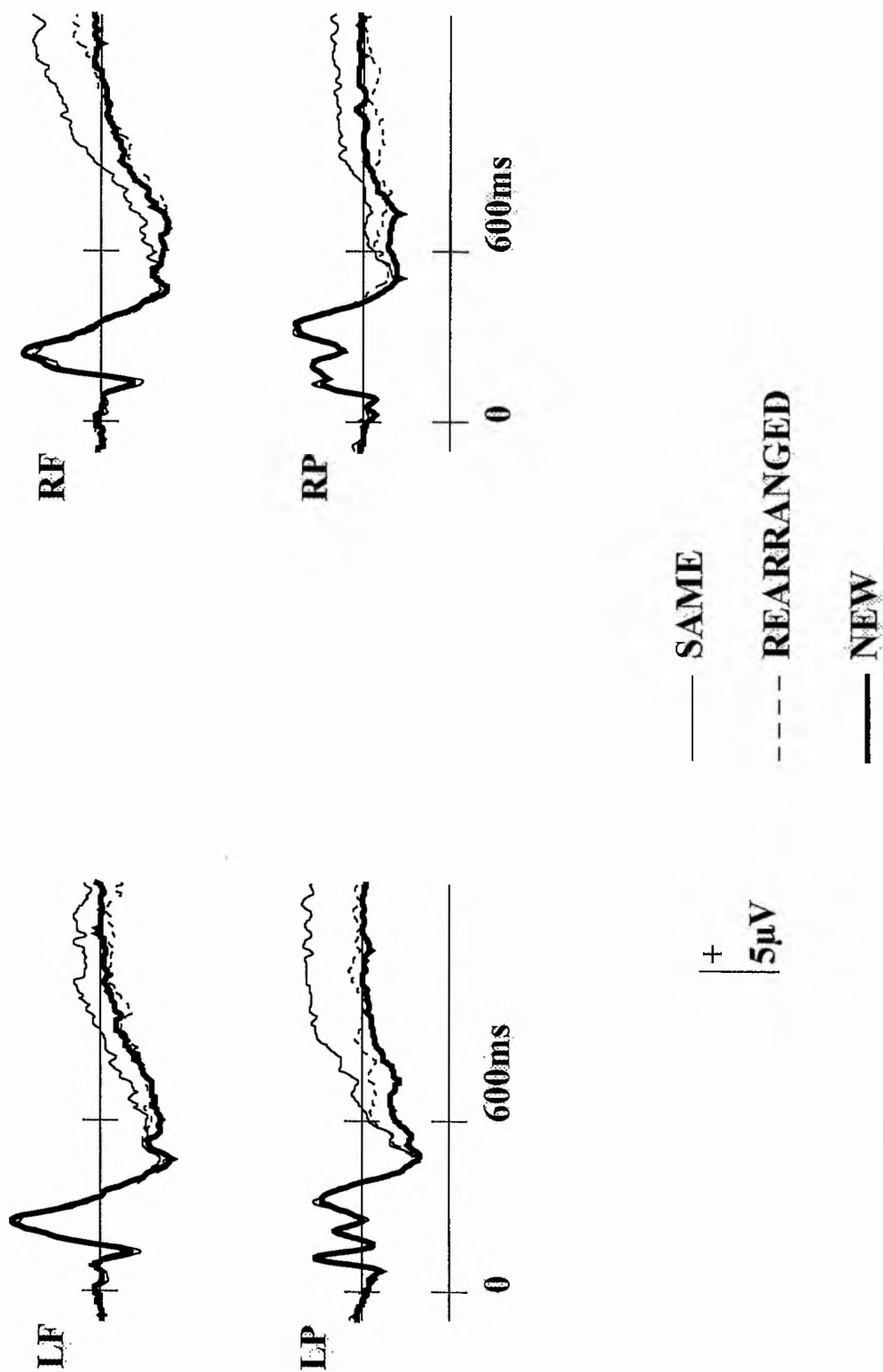
The subsidiary ANOVA revealed interactions between latency region and hemisphere, latency region and location, and latency region and site ( $F_{1.6,24.4} = 3.92$ ,  $p < 0.05$ ,  $F_{1.7,25.6} = 4.91$ ,  $p < 0.05$ , and  $F_{1.7, 25.1} = 3.78$ ,  $p < 0.05$  respectively), along with three-way interactions between latency region, hemisphere and location, and between latency region, location and site ( $F_{1.4,20.9} = 13.85$ ,  $p < 0.001$ , and  $F_{2.1,31.2} = 10.43$ ,  $p < 0.001$  respectively). These results reflect a change in the topography of the old/new effects with time. As can be seen in figure 10, for both response categories, the effects at temporo-parietal electrodes maintain a strong left hemisphere maximum throughout the recording epoch, whereas those at frontal electrodes become more asymmetric over time. In addition, there was a significant interaction between response category and site ( $F_{1.2,18.5} = 17.77$ ,  $p < 0.001$ ). Figure 10 shows that this effect reflects a tendency for the old/new effects for the rearranged pairs to be distributed somewhat more laterally than those for the same pairs.

### **Summary of results**

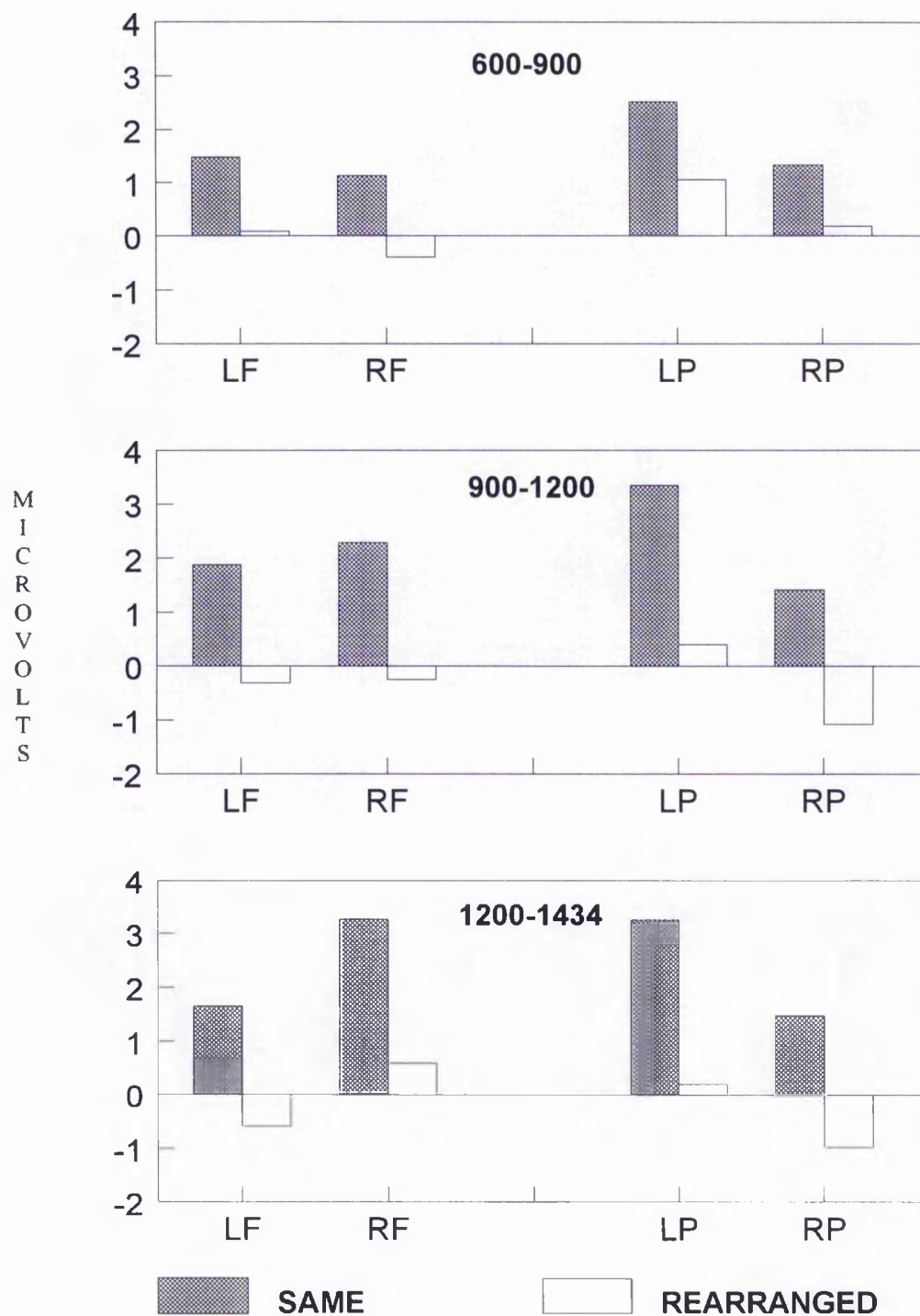
The analyses indicate that the ERPs for same and rearranged pairs were associated with old/new effects which, while exhibiting similar topographies, differed markedly in magnitude, with the effects for the same pairs exceeding those for the rearranged items. For both same and rearranged pairs the distribution of the old/new effects changed over time. In the earliest latency region analysed, they exhibited left parietal and bilateral frontal maxima, whereas by the end of the recording epoch the left parietal effect was accompanied by a distinct right frontal maximum.



**Figure 7.** Experiment 1: Grand average ERP waveforms elicited by correctly classified same, rearranged and new pairs. Plotted as in figure 1. Electrode locations are described in chapter 4, and are shown as in figure 6.



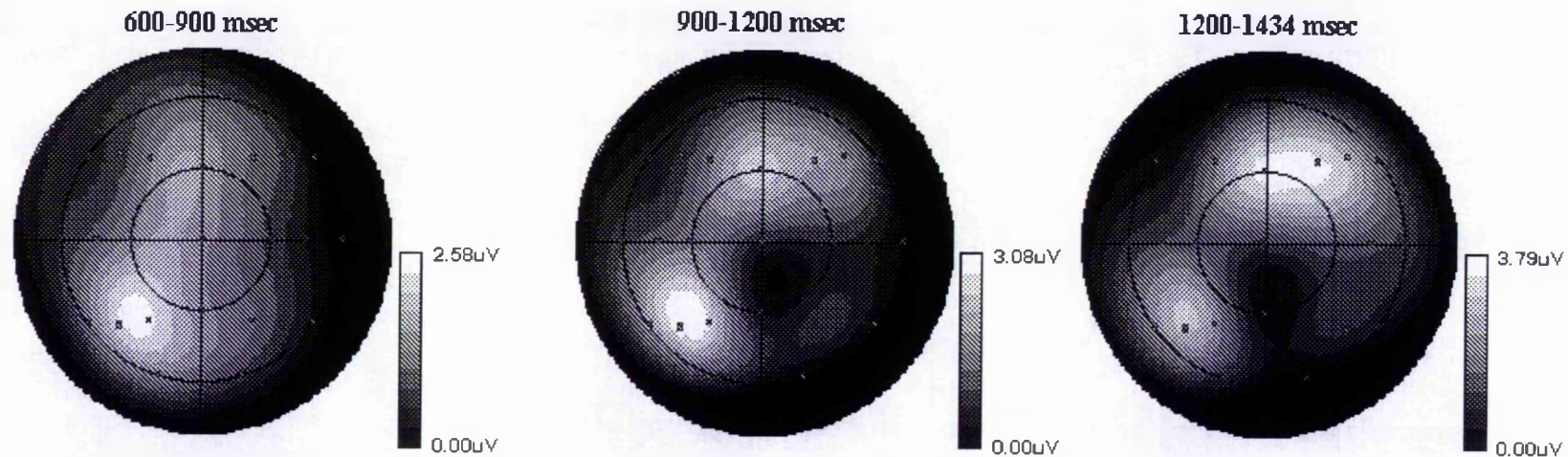
**Figure 8.** Experiment 1: Grand average ERP waveforms for same, rearranged and new response categories from left and right lateral frontal (LF, RF) and lateral parietal (LP, RP) electrode sites. Plotted as in figure 1.



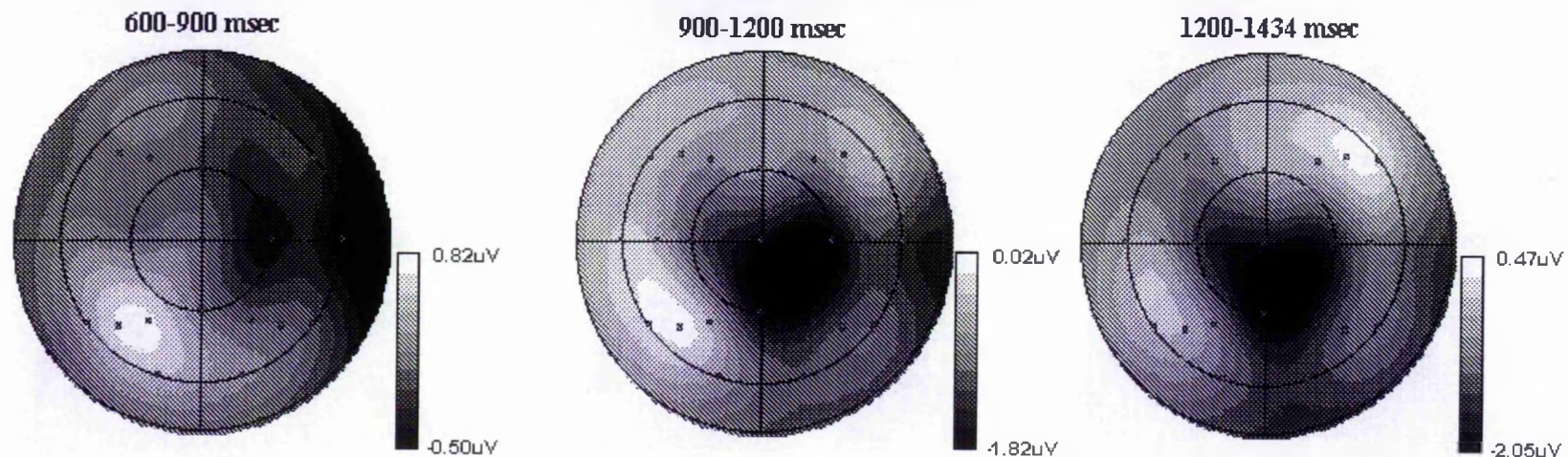
**Figure 9.** Experiment 1: Differences in mean ERP amplitude for same minus new pairs, and correct minus new pairs, for the 600-900 msec, 900-1200 msec, and 1200-1434 msec, latency regions. Amplitude measures are averaged over the electrode site indicated and the sites immediately inferior and superior to it (cf. Figure 6, chapter 4).



### SAME PAIRS



### REARRANGED PAIRS



**Figure 10.** Experiment 1: Topographic maps illustrating the distribution of the differences between ERPs to correctly classified same and new pairs (upper row), and between ERPs to correctly classified rearranged and new pairs (lower row), for the 600-900 msec, 900-1200 msec, and 1200-1434 msec, latency regions. The scale bar to the right of each map indicates the maximum and minimum of the voltage range. Electrodes shown as in figure 6.

## DISCUSSION

In agreement with previous findings (cf. Underwood, 1974) recognition memory was better for same than for rearranged pairs. The dual-process model of Yonelinas (1997) easily accommodates these results. According to this model, the probability of familiarity-based recognition should have been equivalent for both types of pair, whereas the probability of recollection would be greater for same than for rearranged pairs. Consequently, recognition memory for same pairs should exceed that for rearranged pairs.

The finding that rearranged pairs were more likely to receive a correct associative recognition judgement than were same pairs may appear paradoxical in light of the foregoing argument. However, the advantage for the rearranged pairs is only an apparent one. The asymmetry in the associative recognition judgements made to false alarms (new pairs falsely judged old) indicates that a strong bias operated in favour of the 'rearranged' response option. Subjects were highly successful in opposing this bias when making associative judgements to same pairs, as would be expected if 'same' responses are made whenever a word pair engenders strong recollection of the prior study episode. By contrast, the finding that similar proportions of 'rearranged' judgements were made to false alarms and to rearranged pairs is consistent with the proposal that such judgements usually reflect a 'default' decision made in the absence of recollection.

As expected (see Introduction to experiment 1), same pairs elicited sizeable, robust old/new effects very similar in character to those elicited by 'recollected' items in previous studies of source memory (Wilding, et al., 1995; Wilding and Rugg, 1996, 1997a). The ERPs elicited by rearranged pairs elicited qualitatively similar, but markedly smaller effects. The effects for the rearranged pairs were relatively short-lived however, especially at left posterior electrodes, where they reversed in polarity from 900 msec onwards.

The findings for the rearranged pairs most likely reflect the summation of small positive-going old/new effects with another, temporally overlapping component that also distinguishes recognised from new pairs. This component is a slow, posteriorly distributed negative wave that was also evident in several previous studies (Rugg et al.

1996; Wilding and Rugg, 1996, 1997a,b). The functional significance of this component is unknown, but the available evidence suggests that it reflects processes more closely associated with response-related factors than with memory for the eliciting items (Wilding and Rugg, 1997b). As evidenced by the similarity of the scalp distributions of the old/new effects for the same and rearranged pairs, the influence of this component differed little according to pair type. Thus, its relative prominence in the ERPs to rearranged pairs most probably reflects the fact that the small positive-going old/new effects elicited by these pairs exerted less of an offsetting influence than did the much larger effects associated with same pairs.

As noted in the previous paragraph, the scalp distributions of the old/new effects for the two classes of old pairs were similar to one another, in each case being characterised by a left parietal maximum that was maintained throughout the recording epoch, and a frontal effect that became progressively more right-sided with time. The topographies of the two effects were not entirely equivalent however, the rearranged pairs exhibiting effects that were distributed more laterally and diffusely than those for the same pairs. In light of the relatively small size of the effects for the rearranged pairs, this result should be treated with caution, as it may reflect little more than the fact that the distribution of these effects was more susceptible to the distorting influence of noise.

The existence of left parietal and right frontal old/new effects for both the same and the rearranged pairs suggests that, so far as can be judged from scalp recorded neural activity (cf. Rugg and Coles, 1995), successful recognition of these items was accompanied by activation of the same, or at least strongly overlapping, neural populations<sup>6</sup>. The old/new effects for each type of word pair did however differ in their magnitudes, those for the same pairs greatly exceeding those elicited by the rearranged pairs. On the assumption that these effects are indeed markers for recollection (see Introduction to experiment 1), this finding converges with the behavioural results to suggest that same pairs are more likely to engender recollection during tests of item or associative recognition than are rearranged pairs.

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<sup>6</sup> Despite the need for caution in its interpretation, the finding of a response category by site interaction in the topographic analyses means that there is a possibility that the two classes of old/new effect reflect the activity of at least partially distinct neural generators. In light of the fact that both effects exhibited similar left posterior and right frontal maxima, it is assumed that if this is the case, the generators of the effects for the two classes of word pair are nonetheless likely to be related to one another both anatomically and functionally (cf. Chapter 2).

The finding that the old/new effects for same pairs exceeded those for rearranged pairs is reminiscent of the difference between ERPs elicited by words attracting correct or incorrect source judgements reported by Wilding and Rugg (1996). Wilding and Rugg interpreted their findings in light of the proposal that the magnitude of old/new ERP effects might be proportional to the amount of information retrieved from memory (Rugg et al., 1995). They suggested that the larger old/new effects for items correctly assigned to source reflected the greater amount of information retrieved about such items relative to those for which the source could not be recollected.

Viewing recollection as a graded rather than an all or none process suggests one possible explanation of the differences between the old/new effects elicited by same and rearranged word pairs in the present experiment. By this argument, rearranged pairs were associated with partial or weak recollection on many trials. For instance, the presentation of a rearranged pair may elicit recollection about the prior occurrence of an individual word, but not about the item with which it was associated.

An alternative, and arguably more parsimonious, explanation of the differences in the magnitudes of the old/new effects for the two classes of word pair is also possible. This account is motivated by the proposal that associative judgements to same pairs are based almost exclusively on recollection, whereas those to rearranged pairs are made largely by 'default', due to the failure to recollect (Yonelinas, 1997). According to this proposal, the ERPs to rearranged pairs would have been formed from a mixture of the few trials on which recollection did occur and the great majority of trials on which it did not. By this argument, therefore, the attenuated old/new effects seen for rearranged pairs do not reflect the occurrence of a small effect on most trials, but result instead from the dilution of an infrequent 'full-blown' effect by trials on which there was no effect at all.

These two accounts are not mutually exclusive however; both of the proposed mechanisms may contribute to the differences in the magnitude of the old/new effects for same and rearranged pairs. Although it is impossible to determine the relative contributions of the two mechanisms, both accounts imply that recollection is, on average, stronger or more complete for same than for rearranged pairs.



The present findings provide additional information about the frontally distributed old/new effect first described by Wilding and Rugg (1996), in that they suggest that the effect comprises at least two temporally and topographically dissociable components. This dissociation is seen most clearly in the ERPs elicited by the same pairs, where old/new effects were at their largest. As is evident from figures 7 and 10, the frontal effects initially exhibited a bilateral distribution, which only shifted to a right hemisphere maximum after approximately 1200 msec post-stimulus. A similar pattern of effects is evident in the data of Wilding and Rugg (1996), although those authors did not comment on it. However, in a further study of source memory (Wilding and Rugg 1997b) the same authors demonstrated that the dissociation between these two frontal effects was statistically reliable.

The interpretation of the data from Wilding and Rugg's studies (1996, 1997b) is complicated by the fact that the shift in the distribution of the frontal effect coincided with the decline of the left parietal effect. Thus, the shift may merely have reflected a reduction in the contribution of the left parietal effect to anterior electrodes over the left hemisphere, rather than changes in the activity of the generators responsible for the frontal effects. In the present experiment the left parietal effect onset around 600 msec and persisted until the end of the recording epoch. During the same interval, the frontal old/new effect nonetheless shifted from a bilateral to a right-sided distribution. This shift cannot therefore be due to a decline with time in the influence of the left parietal effect.

The functional significance of these frontal old/new effects is unclear. Wilding and Rugg (1996) argued that the effects (they did not discriminate between the bilateral and asymmetric components discussed above) reflect 'post-retrieval' processes that operate on the products of retrieval to generate an episodic representation capable of supporting accurate source discrimination. On the basis of a study (Wilding and Rugg, 1997a) in which the right frontal effect was found partially to dissociate from source recollection, Wilding and Rugg further proposed that recollection may not be a sufficient condition for the emergence of the effect. They suggested that, in contrast to the processes reflected by the left parietal old/new effect, those reflected by the right frontal effect may be under a degree of strategic control.

The characterisation of frontal old/new effects as reflections of strategic post-retrieval processing has not been directly tested. The present findings are consistent with this characterisation, in that the imposition of the associative recognition judgement forced subjects to retrieve and make use of contextual (associative) information. Similarly, in the experiments of Wilding and Rugg, the imposition of a source judgement required explicit, task-related post-retrieval processing. If the prominent frontal effects observed in experiment 1 are indeed a consequence of task demands that emphasise the explicit processing of contextual information, then the effects should be attenuated or absent when there is no explicit requirement to make associative recognition judgements.

Before testing Wilding and Rugg's account of the frontal old/new effects (see experiment 3), a more pressing issue must be addressed. There is an important caveat to the preceding discussion, by virtue of the fact that there is a plausible alternative account of the findings from experiment 1. Whilst subjects may have discriminated between same and rearranged pairs (the associative judgement) on the basis of recollecting associative information, the experimental paradigm does not necessitate that this be the case. Because same and rearranged pairs were compared to new pairs, it is possible that subjects were able to accurately perform the initial old/new recognition judgement by recognising just one word from each pair. If this were the case, the ERP trials contributing to the averaged ERPs to the same and rearranged response categories would differ in terms of the quantity of information retrieved, regardless of how subjects performed the associative judgement. Thus, the ERP findings from experiment 1 need not necessarily reflect the neural correlates of the recollection of associative information.

If performance in experiment 1 was based on the recognition of one versus two words, the interpretation of the ERP effects discussed above would be seriously undermined. Rather than reflecting the recollection of associative information, the difference between the ERPs to same and rearranged pairs could simply reflect the difference between recognising one or two items. That is, the difference might reflect variation in the quantity of information retrieved from memory, based upon a simple familiarity or strength process, rather than in the probability of recollection. However, if the effects observed in experiment 1 are a consequence of the use of a 'one vs. two words' strategy, then the effects should be absent when this strategy is no longer available.

Experiment 2 was performed to test this prediction, prior to the further investigation of the functional significance of the old/new effects in experiment 3.

## **Chapter 6.**

### **EXPERIMENT 2**

#### **INTRODUCTION**

As discussed previously, it is important to demonstrate that the findings from experiment 1 did not simply reflect the fact that subjects employed a 'one vs. two words' strategy. To prevent this possibility, the new pairs used in experiment 1 can be exchanged for pairs consisting of one old and one new word (henceforth old-new pairs). This means that the initial old/new judgement can be made only on the basis of recognising both words in an old pair, and thus the subsequent associative judgement (discriminating between the same and rearranged pairs) can only be made on the basis of the recollection of associative information. Merely knowing that both words were old would not allow subjects to accurately discriminate between the two types of old pair. Experiment 2 therefore provides a test of the claim that the ERP effects seen in experiment 1 do not reflect the differential recollection of associative information.



## METHOD

### Subjects

18 subjects were employed. Data from 2 subjects was discarded due to insufficient artifact-free trials in the critical response categories. The remaining subjects had a mean age of 21.8 years (range 18 to 28 years), and 4 of them were female.

### Experimental materials

The experimental design, examples of stimuli and correct responses are shown in table 6. 640 randomly selected words (from the word pool in appendix A) were used to form 300 critical word pairs and 20 filler word pairs. Each subject was presented with 150 critical word pairs at study and 300 pairs at test. At test a third of the studied pairs maintained their pairing between study and test ('same' pairs), a third were randomly re-paired ('rearranged' pairs), and a third were re-paired with new items ('old-new' pairs). To generate 'old-new' test pairs, studied pairs were separated, and each word was re-paired with an unstudied word. The position of the old and new item in 'old-new' pairs was counterbalanced (half old-new, half new-old) to prevent subjects from anticipating the location of the old item.

**Table 6.** Experimental design, showing the different classes of stimuli, and associated correct responses.

<u>Phase</u>	<u>Class of Item</u>	<u>Example</u>	<u>Response</u>
Study List	150 word pairs:	doll-bush	
		charm-glue	
		paint-ride	
		green-honey	
Test List	75 same pairs:	doll-bush	Old: Same
	75 rearranged pairs:	charm-ride	Old: Rearranged
	150 old-new pairs:	green-steam	New

Eight study-test lists were formed, each presented to 2 subjects. The lists were formed such that, across lists, each word pair was used equally frequently as an old and new item (i.e., the unstudied items that were used to form 'old-new' pairs in one test list were study items on another, and vice-versa). Similarly, the use of word pairs as

'same' or 'rearranged' was also counterbalanced across lists (i.e., studied items that acted as rearranged pairs in one test lists were employed as same pairs in another, and vice-versa). Item order within each list was also randomised.

The resulting study-test lists were padded with additional filler items (20 pairs), generated according to the same procedure as for the critical items. A sequence of 10 filler pairs was located before every 150 critical items (10 at study and 20 at test).

### **Experimental task, procedures and ERP recording**

The study phase was identical to that in experiment 1 (cf. Chapter 4), other than for the number of items presented. The sequence of events on each test trial was also identical to that in experiment 1, other than for the number of items presented and the task instructions on the initial old/new recognition judgement. Subjects were instructed to make a speeded old/new judgement to each test pair, responding 'old' to pairs that contained two studied words, and 'new' to pairs containing one old studied and one unstudied item. They were instructed to make this judgement as quickly and as accurately as possible, then to wait for a cue to make a second response for any pairs judged to contain two old items. As in experiment 1, the second judgement required subjects to judge whether the words were in the same or a rearranged pairing compared to their pairing at study. The test list was administered in two blocks of 160 pairs, with a short rest break intervening between each block.

The procedure for recording the ERPs was the same as in experiment 1, other than for the lengthening of the post-stimulus recording epoch to 1944 msec, see chapter 4). This modification was motivated by the fact that in the previous experiment neither the parietal nor the frontal old/new effects had declined to baseline by the end of the 1434 msec post-stimulus recording epoch.

## RESULTS

### Behavioural data

Table 7 shows the mean probability of an old judgement to same, rearranged and old-new pairs. A one way ANOVA comparing these probabilities revealed a significant effect ( $F_{2,30} = 118.71$ ,  $p < 0.001$ ). Post hoc tests revealed significant differences between each pair of means. Subjects were able to discriminate both classes of old pair from the old-new pairs, and did so more accurately for same than for rearranged pairs.

**Table 7.** Mean probability (standard deviations) of an old response for the old/new judgement, and the subsequent probability of a correct associative judgement, for same, rearranged and old-new pairs. For old-new pairs, the associative score shows the probability of a 'rearranged' response to false alarms.

<u>Judgement</u>	<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>Old-New</u>
OLD/NEW	Old:	0.85 (0.08)	0.66 (0.11)	0.38 (0.15)
ASSOCIATIVE	Correct:	0.71 (0.16)	0.81 (0.16)	0.93 (0.07)

Table 7 also shows the probabilities of a correct response on the associative recognition judgement (conditionalised on initial recognition performance), as well as the proportion of false alarms (to old-new pairs) that received a 'rearranged' response. Analysis of the associative recognition judgements compared the probability of a correct response (averaged across same and rearranged pairs) against chance (i.e., 0.5). As in experiment 1 this comparison revealed that subjects were able to discriminate same from rearranged pairs ( $t(15) = 7.32$ ,  $p < 0.001$ ). As was also the case in experiment 1, analysis of the responses to false alarms showed a strong (0.93) bias towards judging such pairs as being 'rearranged' ( $t(15) = 24.31$ ,  $p < 0.001$ ). Following the analysis of experiment 1 the probability of correct associative recognition responses for each class of pair was contrasted with the probability of making the same response to a false alarm, elucidating any differences in responses to same and rearranged pairs. This analysis revealed that same pairs received significantly more 'same' responses than did false alarms (0.71 vs. 0.07,  $t(15) = 12.33$ ,  $p < 0.001$ ),

whereas rearranged pairs significantly fewer 'rearranged' responses than false alarms (0.81 vs. 0.93,  $t(15) = 3.37$ ,  $p < 0.005$ ).

Table 8 shows the mean RTs for responses on the initial recognition judgement, shown according to the accuracy of that judgement, and also according to the accuracy of the subsequent associative judgement. A two-way ANOVA on the data separated according to the initial old/new judgement revealed main effects of word pair type and accuracy ( $F_{2,30} = 19.74$ ,  $p = 0.005$ ; and  $F_{1,15} = 23.28$ ,  $p < 0.001$ , respectively) and an interaction between the two ( $F_{2,30} = 8.03$ ,  $p < 0.005$ ). Post hoc tests revealed that, for both the same and rearranged pairs, RTs to correct responses were significantly faster than those to incorrect responses, but no such difference was present in the RTs for responses to old-new pairs.

**Table 8.** Mean reaction times (msec) separated according both to the accuracy of the initial old/new recognition judgement and the subsequent associative recognition judgement.

<u>Judgement</u>	<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>Old-New</u>
OLD/NEW	Correct:	1801	2083	2120
	Incorrect:	2247	2269	2114
ASSOCIATIVE	Correct:	1669	2002	
	Incorrect:	1978	1865	

Table 8 also shows the RTs conditionalised according to the accuracy of the associative judgement. ANOVA revealed no significant main effects, but did reveal a significant interaction between pair type and accuracy ( $F_{1,15} = 9.07$ ,  $p < 0.01$ ). Post hoc tests revealed that correct responses were associated with significantly faster RTs for same than rearranged pairs, whereas no such difference was found for incorrect responses, and that whilst the RTs for same pairs were faster for correct than incorrect responses this was not the case for rearranged pairs.

### ERP data

ERPs were formed for 3 critical response categories: correctly classified old-new pairs (henceforth *old-new pairs*); same pairs correctly classified as old and same (*same pairs*); and rearranged pairs correctly recognised as old and rearranged (*rearranged*

*pairs*). The mean numbers of trials contributing to each category of ERPs were 80, 40, and 36 respectively.

Figure 11 shows the grand average ERP waveforms for all 25 recording sites, and figure 12 shows the ERPs from the left and right frontal and parietal sites only. The figures show that the ERPs for same pairs become more positive than those for both the old-new and rearranged pairs from approximately 600 msec post stimulus onset. This effect is small in size, and appears to be largest over fronto-polar electrodes initially. However, over time the effect develops a clear left hemisphere maximum over posterior sites and the opposite right hemisphere maximum over anterior sites. By contrast, the ERPs to rearranged pairs show little sign of a positive shift relative to the old-new pairs, rather, they exhibit a negative going shift that is largest over right centro-parietal electrodes.

As in experiment 1, the magnitude of ERP effects was quantified by calculating the mean amplitude (relative to the 102 msec pre-stimulus baseline) of the waveforms over successive latency regions. These regions were 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec, the final region covering the extension to the recording epoch employed in experiment 1. As was discussed in the introduction to experiment 2, analysis of these data aimed to demonstrate that the differences seen between the ERPs to same and rearranged pairs in experiment 1 were not simply a function of subjects employing a 'one vs. two words' strategy. Consequently, the amplitude analyses involved a series of planned ANOVAs, comparing the same vs. old-new and same vs. rearranged response categories, to demonstrate whether the pattern of effects seen for the same pairs remained when this strategy was not available. Topographic analyses were also performed, investigating possible changes in the distribution of effects for the same pairs over time.

#### **Amplitude analyses**

Initial global ANOVA of the 600-900 msec latency region revealed an interaction between response category and site ( $F_{5.1,76.9} = 2.40$ ,  $p < 0.05$ ). For each of the remaining regions the global ANOVA revealed a main effect of response category, and an interaction between response category and site (900-1200 msec:  $F_{1.9,28.7} = 7.90$ ,  $p < 0.005$  and  $F_{5.7, 86.0} = 3.64$ ,  $p < 0.005$ ; 1200-1500 msec:  $F_{1.6,24.5} = 6.82$ ,  $p < 0.01$  and  $F_{5.9,88.8} = 3.39$ ,  $p = 0.005$ ; 1500-1944 msec:  $F_{1.8,26.3} = 4.14$ ,  $p < 0.05$ , and

F5.1,76.3 = 3.21,  $p < 0.05$  respectively). The results of the subsidiary ANOVAs between the same vs. old-new, and same vs. rearranged response categories can be seen in table 9, and are elucidated below. The differences in the mean amplitude of the ERPs between are shown in figure 13, over each latency region, for lateral frontal and temporo-parietal electrodes.

**Table 9.** Results of the amplitude analyses, over each latency region. Only significant effects involving the factor of response category (RC) are reported. HM = Hemisphere, L = Location (Anterior vs. Posterior), ST = Electrode site (Inferior vs. Mid-Lateral vs. Superior).

<u>LATENCY REGION</u>	<u>PAIRWISE COMPARISON</u>	
	<u>Same v Old-New</u>	<u>Same v Rearranged</u>
<u>600-900 msec</u>		
RC x ST	-	F1.3,19.9 = 4.74, $p < 0.05$
RC x HM	-	-
RC x HM x L	F1,15=7.13, $p < 0.05$	F1,15 = 8.32, $p < 0.05$
<u>900-1200 msec</u>		
RC	-	F1,15 = 17.04, $p = 0.001$
RC x ST	-	F1.2,18.7 = 19.76, $p < 0.001$
RC x HM	-	-
RC x HM x L	F1,15=18.48, $p = 0.001$	F1,15 = 23.85, $p < 0.001$
<u>1200-1500 msec</u>		
RC	-	F1,15 = 24.31, $p < 0.001$
RC x ST	-	F1.4,20.3 = 14.98, $p < 0.001$
RC x HM	-	F1,15 = 9.22, $p < 0.01$
RC x HM x L	F1,15=20.70, $p < 0.001$	F1,15 = 12.50, $p < 0.005$
<u>1500-1900 msec</u>		
RC	-	F1,15 = 10.54, $p < 0.005$
RC x ST	-	F1.6,23.7 = 15.61, $p < 0.001$
RC x L	-	F1,15 = 6.26, $p < 0.05$
RC x HM	F1,15 = 13.72, $p < 0.005$	-
RC x HM x L	F1,15 = 29.43, $p < 0.001$	F1,15 = 5.64, $p < 0.05$
RC x L x ST	F1.6,23.3 = 4.87, $p < 0.05$	-

Same versus Old-New: Table 9 shows that for each latency region the analysis revealed an interaction between category, hemisphere, and location. This reflects the same pattern of effects in each latency region; compared to the ERPs to old-new pairs, the ERPs to same pairs exhibit a left greater than right asymmetry at temporo-parietal sites, and the opposite asymmetry in favour of the right hemisphere at frontal sites. As figure 13 shows, the effects are very small in size during the initial 600-900 msec epoch, but are considerably larger during each of the subsequent latency regions. Table 9 also shows that the ANOVA for the 1500-1900 msec latency region revealed an

additional significant three way interaction, between category, location and site. As can be seen in figure 11, this reflects the greater positivity in the ERPs for same pairs compared to those for old-new pairs, a difference which increases in size as electrodes get closer to the midline at anterior, but not posterior, scalp sites.

Same versus Rearranged: For each latency region the ANOVAs contrasting the ERPs for rearranged and same pairs revealed a significant interaction between response category and site, along with a significant three-way interaction between category, hemisphere and location (see table 9). These effects reflect greater positivity in the ERPs to same pairs compared to those for the rearranged pairs. As can be seen in figure 13, for each latency region the three-way interaction reflects that fact that this difference is larger over the right than the left hemisphere at anterior electrodes, whereas the positive shift is bilaterally distributed at posterior electrodes. By the 1500-1900 msec latency region however, the effect is larger over the left than right hemisphere at posterior electrode sites. In addition, for each latency region the interaction between category and site reflects the fact that the difference between the ERPs is larger nearer to the midline (see figure 11).

#### **Topographic analysis**

As discussed above, the primary aim of this experiment was to investigate whether the effects seen for the same pairs in experiment 1 were due to subjects discriminating between these two classes of stimuli simply on the basis of recognising two versus one words. Consequently, the topographic analysis was aimed at elucidating the pattern of effects seen for the same pairs. The effects in the 600-900 msec latency region were small in size however, reducing the validity of any topographic analysis that could be performed upon these data. Hence, the topographic analyses were restricted to the larger and more reliable effects found in the remaining three latency regions. Topographic maps illustrating the distribution of the effects over successive latency regions (the differences in amplitude between the ERPs to same and old-new pairs) can be seen in figure 14. In each latency region the figure clearly indicates the presence of left parietal and right frontal maxima over left temporo-parietal and right frontal scalp sites respectively.

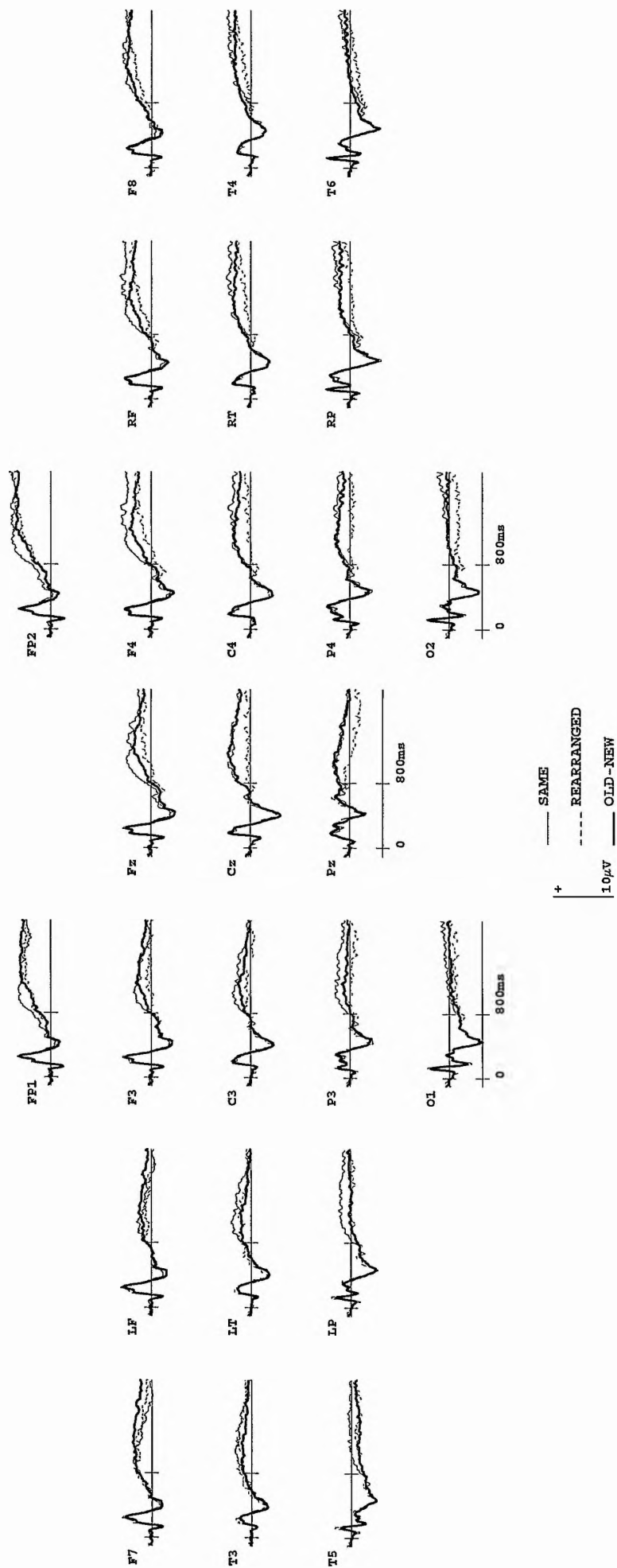
To investigate whether the topography of the effects changed over the course of the recording epoch, the topographies of the effects in each latency region were compared

using ANOVA, employing the data from all 25 sites. This ANOVA revealed no significant interaction between epoch and site, suggesting that the distribution of effects did not differ over time. Subsidiary ANOVA, employing the factors of category, hemisphere, location (frontal vs. temporo-parietal), and site (inferior vs. mid-lateral vs. superior) also revealed no significant effects involving epoch, supporting the conclusion that the scalp distributions were not significantly different over time. This analysis did give rise to one significant interaction however, between hemisphere and location ( $F_{1,15} = 5.14, p < 0.05$ ). This interaction confirms the presence of left parietal and right frontal effects, but the findings suggest that unlike in experiment 1, the scalp distribution of these effects did not change over time.

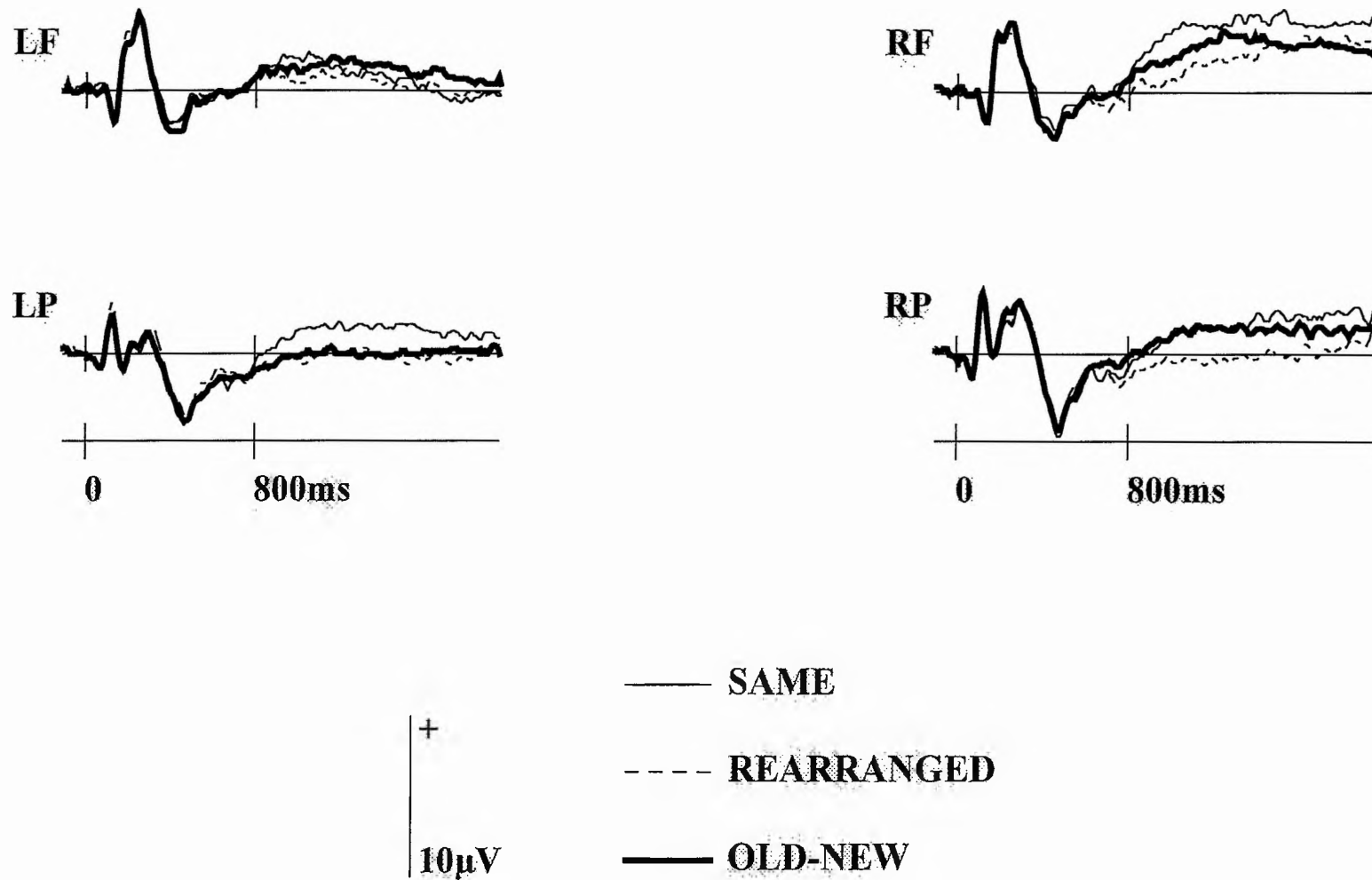
### **Summary of results**

As in experiment 1, relative to the ERPs to old-new and rearranged pairs, those to the same pairs were associated with positive going old/new effects that were larger over the left than right hemisphere at posterior electrodes but larger over the right than left hemisphere at anterior electrodes. In contrast to the findings of experiment 1 these effects were small in size during the initial 600-900 msec latency region, becoming more sizeable and robust during the remainder of the recording epoch. In accordance with the findings of experiment 1, same pairs were associated with topographically dissociable left temporo-parietal and right frontal old/new effects, but, unlike in the first experiment, there was no evidence of a change in the lateral distribution of the frontal effects over time.

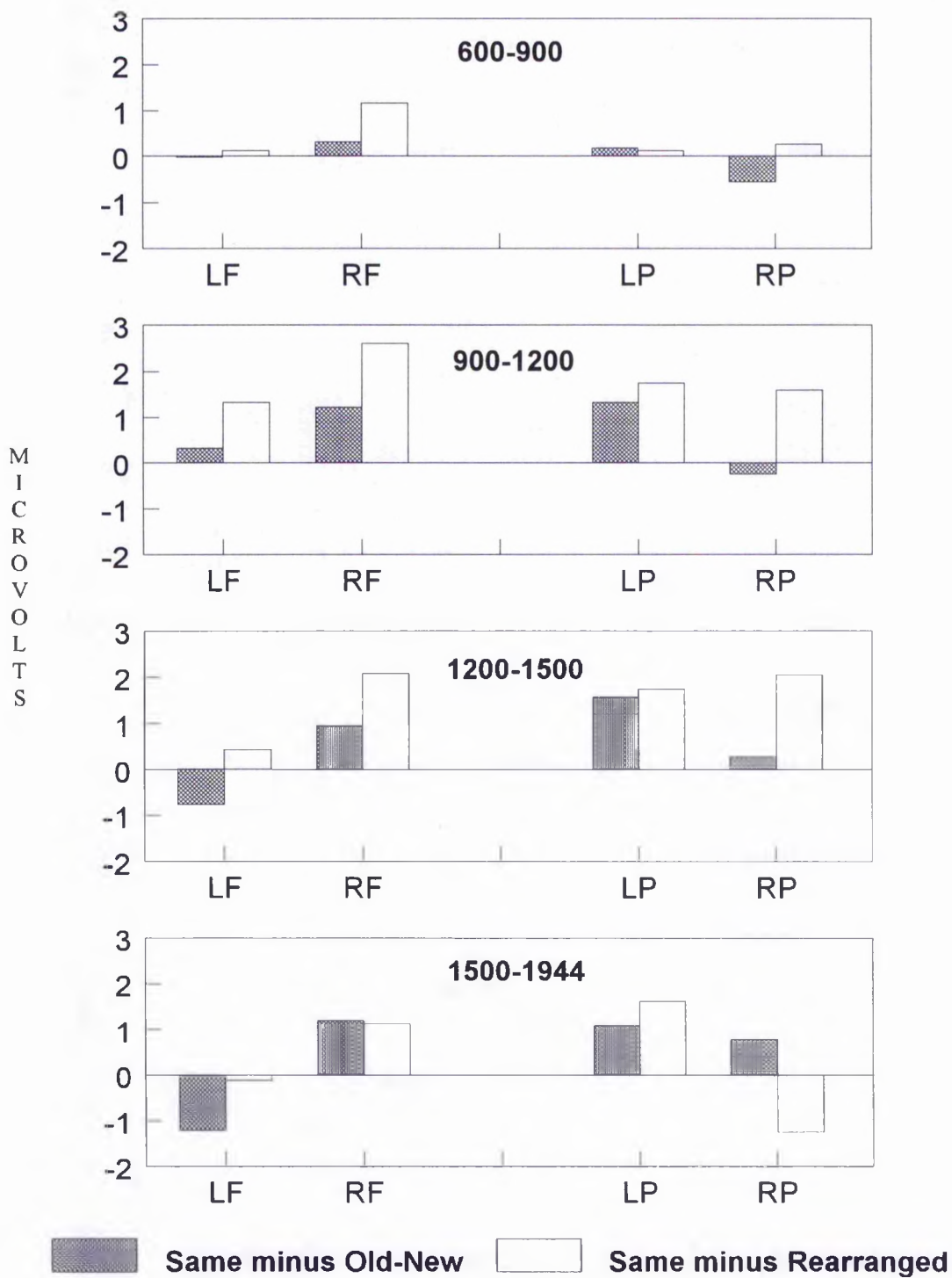




**Figure 11.** Experiment 2: Grand average ERP waveforms elicited by correctly classified same, rearranged and old-new pairs. Scale bar and electrodes are shown as in figure 7.

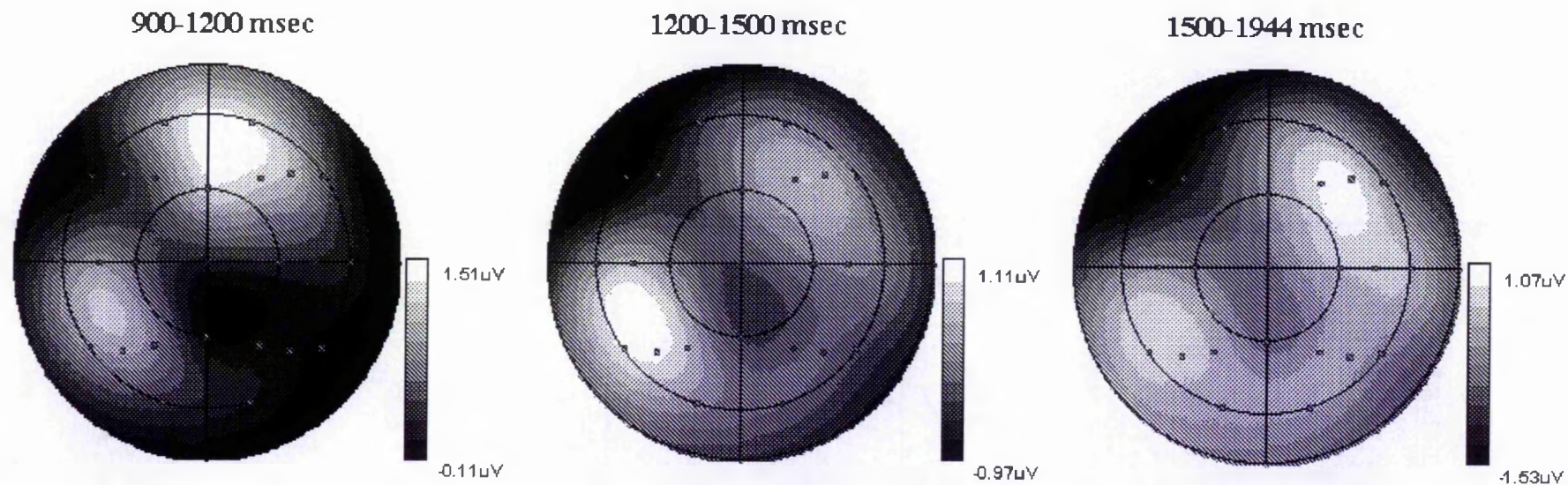


**Figure 12.** Experiment 2: Grand average ERP waveforms for same, rearranged and old-new response categories from left and right lateral frontal (LF, RF) and lateral parietal (LP, RP) electrode sites.



**Figure 13.** Experiment 2: Differences in mean ERP amplitude for same minus new pairs, and correct minus old-new pairs, for the 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec latency regions. Amplitude measures are averaged over the electrode site indicated and the sites immediately lateral and superior to it.

## SAME PAIRS



**Figure 14.** Experiment 2: Topographic map illustrating the distribution of the differences between ERPs to correctly classified same and old-new pairs for the 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec latency regions. Scale bars and electrodes are shown as in figure 10.

## DISCUSSION

As in experiment 1, recognition memory performance was superior for same than rearranged pairs, consistent with a dual process model of performance (e.g., Yonelinas, 1997). Performance on the old/new recognition judgement was not identical to that in experiment 1 however. Notably, the old/new recognition advantage for 'same pairs' was larger (primarily due to a lower hit rate to the rearranged pairs), and the false alarm rate to 'new pairs' was substantially larger (38% compared to 18%). Neither of these findings is surprising, given the particular experimental manipulation employed in experiment 2. Replacing the new pairs with old-new pairs is likely to induce a higher level of false alarms in and of itself, because subjects would inevitably recognise some of these items as being old. As discussed previously, the initial old/new recognition response to rearranged pairs in experiment 1 may have depended, to some extent, upon the recognition of just a single member of each pair. To the degree that this was no longer a viable basis upon which to respond in experiment 2, recognition of the rearranged pairs would be expected to be lower than in experiment 1.

Behavioural performance on the associative judgement was very similar to that in experiment 1. Subjects were clearly able to perform the associative judgement accurately, despite the fact that it was no longer possible for them to employ a 'one vs. two word' strategy (cf. Introduction to experiment 2). As in experiment 1, despite the presence of an old/new recognition memory advantage for the same pairs, the rearranged pairs were more likely to receive a correct associative response. Again, this can be accounted for by the strong bias towards responding 'rearranged' to false alarms. Consistent with the interpretation of performance in experiment 1, subjects appear to accurately recognise same pairs whenever a word pair engenders the recollection of a prior study episode, sufficient to overcome the response bias towards responding 'rearranged'. Moreover, although subjects must have been able to recognise both members of a rearranged pairs as being old, as in experiment 1 the associative judgements to these pairs appears to reflect a 'default' decision made largely in the absence of recollection.

In sum, the behavioural results are consistent with the suggestion that, in experiment 1, subjects may have recognised some proportion of the rearranged pairs as being old on the basis of recognising just one item from each pair (as evidenced by the changes in performance on the initial old/new judgement). Nonetheless, performance on the associative judgement appears to have depended upon the veridical recollection of associative information (as evidenced by the accurate discrimination of same from rearranged pairs on the associative judgement). Thus, it seems unlikely that the findings of experiment 1 can be explained by a 'one vs. two words' account of performance (cf. Discussion of experiment 1, and Introduction of experiment 2).

Looking at the ERP data, the critical question addressed by the present experiment was whether the ERP effects seen in experiment 1 would remain when the possibility of subjects relying on a 'one vs. two word' strategy had been ruled out. In light of the behavioural findings discussed above it would be expected that the ERP data should reveal a similar pattern of results to those found in experiment 1. The effects would not be expected to be entirely equivalent however, because the ERP baseline consisted of correctly rejected old-new pairs (rather than the correctly rejected new pairs employed in experiment 1). When interpreting the ERP data this change in baseline must be taken into account; to the degree that subjects recollected the old item contained within each old-new pair, the pattern of old/new effects would be attenuated (as explained below).

Relative to the ERPs to correctly rejected old-new pairs, the ERPs to same pairs gave rise to statistically reliable old/new effects in each latency region. As figure 14 shows, these effects are similar to those found in experiment 1, exhibiting left parietal and right frontal maxima. The effects are not identical to those seen in experiment 1 however; the effects were small in size during the initial 600-900 msec latency period, and the distribution of the old/new effects did not change with time. These differences can be accounted for in terms of the change in the ERP baseline noted above. If some proportion of trials contributing to the ERP baseline were associated with the recollection of old items, then some signs of the ERP old/new effects would likely have been present in the ERP correct rejection baseline. This is perhaps best thought of as a 'raised' baseline, resulting in the observed attenuation of the old/new effects during the 600-900 msec latency region.



The fact that the distribution of the old/new effects did not change over time is a consequence of the attenuation of the effects during the 600-900 msec latency region. In experiment 1 the frontal old/new effects were bilaterally distributed during the initial 600-900 msec latency period, becoming asymmetric from 900 msec onwards. Thus, the absence of a change in distribution over time in experiment 2 is not surprising, given that the topographic analyses were restricted to the data from 900 msec onwards (due to the small size of the effects in the 600-900 msec latency region).

Finally, comparison of the ERPs to the same and rearranged response categories also suggests that the results of experiment 1 were not just a reflection of subjects remembering one versus two words. The findings were similar to those in experiment 1, the ERPs to same pairs being more positive going than those to the rearranged pairs. This finding is important; if the difference between the ERPs to same and rearranged pairs found in experiment 1 simply reflected memory for two versus one items, then the difference would have been absent in experiment 2. The difference was not identical to that found in experiment 1 however. First, the difference between the ERPs to the same and rearranged pairs was smaller in experiment 2 than 1, particularly during the initial 600-900 msec latency region. Like the attenuation of the old/new effects found for the same pairs, this is not surprising in itself. As discussed above, the behavioural results suggest that a small proportion of rearranged pairs were recognised on the basis of one item in experiment 1. The removal of these trials from the averaged ERP for the rearranged pairs in experiment 2 would likely result in the observed attenuation of the difference between the same and rearranged pairs.

More puzzling than the reduction in the size of the difference between the ERPs to same and rearranged pairs however is a change in the asymmetry of the difference. Consistent with the results of experiment 1, the difference between the ERPs is larger over the right than left hemisphere at frontal electrodes. By contrast to the results of experiment 1 however, the difference is bilaterally distributed at temporo-parietal electrode sites. The reason for this change in the asymmetry at parietal sites is unclear. One possible explanation is that the effects are slightly delayed and more jittered in time. Support for this account can be found in the RT data; mean response times were somewhat longer in experiment 2 than in experiment 1. Moreover, the difference between the ERPs to same and rearranged pairs was asymmetrically larger over the left

than right hemisphere at parietal electrodes during the final 1500-1944 msec latency region (a region that was not present in the data from experiment 1).

In sum, both the behavioural and ERP findings from experiment 2 suggest that the findings of experiment 1 cannot simply be accounted for in terms of subjects employing a 'one vs. two word' strategy. Rather, the results are consistent with the alternative interpretation, i.e., that the ERP old/new effects are a reflection of processes contributing to, or contingent upon, the recollection of associative information. Experiment 2 also makes a further contribution, in that it highlights one of the difficulties inherent to the use of the subtraction procedure (that is, in contrasting pairs of ERPs). As was discussed above, because of the experiment manipulation employed in experiment 2, the ERP baseline was not equivalent to that employed in experiment 1. In the present case the consequence of changing the ERP baseline was relatively straightforward to interpret. However, this example illustrates how important it is to take such differences into account when making comparisons of data across different studies.



## **Chapter 7.**

### **EXPERIMENT 3**

#### **INTRODUCTION**

Having demonstrated that the findings of experiment 1 reflect memory processes associated with the recollection of associative information, rather than the recognition of one versus two words, it is possible to further investigate the functional significance of the ERP old/new effects. As noted in the Discussion of experiment 1, the functional significance of the right frontal old/new effect is unclear. To recap briefly, Wilding and Rugg (1996) argued that the effect reflects strategic 'post-retrieval' processes that operate on the products of retrieval. The findings of experiments 1 and 2 are consistent with this characterisation, in that the imposition of the associative recognition judgement forced subjects to retrieve and make use of contextual (associative) information. However, Wilding and Rugg did not directly test this characterisation of the frontal old/new effects.

The aim of experiment 3 was to investigate whether the requirement to engage in explicit, task related, 'post-retrieval' processing of associative information is a necessary condition for the emergence of the frontal old/new effects found in experiments 1 and 2. This was achieved by modifying the design employed in

experiment 1<sup>7</sup>, such that subjects made only a single old/new judgement to each pair. The removal of the associative judgement eliminates the requirement to use associative information to meet the demands of the task. It therefore provides a test of the proposal that the frontal old/new effects observed in the previous experiments are a reflection of this strategic task requirement.

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<sup>7</sup> The return to the use of entirely 'new pairs' (as in experiment 1) was motivated by the fact that when 'old-new' pairs were employed (in experiment 2) behavioural performance levels were poorer, and the size of the old/new effects was somewhat smaller.

## **METHOD**

### **Subjects**

18 subjects were employed. Data from 2 subjects was discarded due to insufficient artifact-free trials in the critical response categories. The remaining subjects had a mean age of 24.6 years (range 17 to 34 years), and 5 of them were female.

### **Experimental materials**

Experimental lists were generated in exactly the same way as in experiment 1, but the number of critical items employed at study and test was halved. Thus, the lists were constructed from 400 words, which had been selected randomly from the pool of 800 words used in the first experiment. Each study list contained a total of 110 word pairs (100 critical pairs and 10 fillers), whereas each test list totalled 220 pairs (100 new, 50 same and 50 rearranged and 20 fillers).

### **Experimental procedure and ERP recording**

Details of the study procedure are provided in chapter 4. The sequence of events on each test trial was identical to that employed in experiment 1, with one exception. The '?' character that served as cue for the second response in experiment 1 was replaced by the '!' fixation character. The '!' was, therefore, displayed on each trial for 4.9 rather than 2.4 sec. Subjects were instructed to respond to each test pair, depressing one response button for pairs judged to be old pairs, and the other button for those judged as new.

See chapter 4 for details of the procedures used for recording the ERPs.

## RESULTS

### Behavioural data

Table 10 shows the mean probability of an old judgement to same, rearranged and new pairs. An ANOVA comparing these probabilities revealed a significant effect ( $F_{2,30} = 421.39$ ,  $p < 0.001$ ). Post hoc tests revealed significant differences between each pair of means. Thus subjects were able to discriminate both classes of old pair from new pairs, and did so more accurately for same than for rearranged pairs.

**Table 10.** Mean probability (standard deviations) of an old response for the old/new judgement, shown for same, rearranged and new pairs.

<u>Judgement</u>	<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>New</u>
OLD/NEW	Old:	0.87 (0.09)	0.69 (0.13)	0.22 (0.12)

Table 11 shows the mean RTs for same, rearranged and new pairs, separated according to the accuracy of the recognition response. ANOVA revealed a significant effect of accuracy ( $F_{1,15} = 56.33$ ,  $p < 0.001$ ), and an interaction between word pair type and accuracy ( $F_{2,30} = 11.61$ ,  $p < 0.001$ ). Post hoc tests revealed that correct responses were faster than incorrect responses for same and rearranged pairs, but not for new pairs. In addition, the RTs for correctly classified pairs differed from one another, same pairs attracting the fastest responses, and new pairs the slowest.

**Table 11.** Mean reaction times (msec) on the old/new recognition judgement, separated according to accuracy of response.

<u>Response</u>	<u>Same</u>	<u>Rearranged</u>	<u>Old-New</u>
Correct:	1308	1522	1608
Incorrect:	1954	1746	1603

### ERP data

ERPs were formed for three response categories: correctly classified new pairs, same pairs correctly identified as old (same pairs), and rearranged pairs correctly identified

as old (rearranged pairs). The mean numbers of trials contributing to each category of ERPs were 67, 37, and 30 respectively. Figure 15 shows these grand average ERP waveforms for all 25 recording sites, and figure 16 shows the ERPs from the left and right frontal and parietal sites only. The figures show that the ERPs for same pairs become more positive than those for new and rearranged pairs from approximately 600 msec post stimulus onset. This effect exhibits a left hemisphere maximum at posterior sites, and a later-onsetting right hemisphere maximum anteriorly. The ERPs to rearranged pairs show little sign of an equivalent effect, but become more negative than the new pairs from around 900 msec onwards.

As in experiment 2, the magnitude of ERP effects was quantified over 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec latency regions. Analysis of these data followed the same rationale and procedures as in experiments 1 and 2, and the results of these analyses are reported in table 12. The scalp topographies of the old/new effects were also analysed. These analyses, conducted on the differences in amplitude between the ERPs to old and new pairs, were employed to test whether the topography of the old/new effects changed over time.

#### **Amplitude analyses**

The global ANOVAs of the 600-900, 900-1200 and 1200-1500 msec latency regions each revealed a main effect of response category ( $F_{1.7,26.1} = 10.16$ ,  $p < 0.01$ ;  $F_{2,30} = 10.96$ ,  $p < 0.001$ ; and  $F_{1.9,29.2} = 15.04$ ,  $p < 0.001$  respectively). For the final 1500-1944 msec region, the ANOVA revealed a main effect of response category, and an interaction between response category and site ( $F_{1.9,29} = 17.63$ ,  $p < 0.001$ , and  $F_{5.8,86.8} = 3.61$ ,  $p < 0.01$ , respectively). The results of the subsidiary ANOVAs comparing each pair of response categories can be seen in table 12, and are elucidated below.

Same versus New: The ANOVA for the 600-900 msec latency region revealed several significant effects, including an interaction between category, hemisphere, location, and site. These effects reflect the greater positivity of the ERPs to same pairs (see figure 17). The involvement of hemisphere and location in the four way interaction reflect the fact that this positive shift exhibits a left hemisphere asymmetry at temporo-parietal sites, and a smaller asymmetry in favour of the right hemisphere at frontal

sites. The reason for the involvement of site in the four way interaction is that these effects are larger at electrodes positioned nearer to the midline than they are laterally.

Table 12 shows that, in each case, the ANOVAs for the remaining latency regions revealed a significant interaction between category, hemisphere and location. As figure 17 shows, this pattern of effects reflects the greater positivity in the ERPs for same pairs compared to those for correct new pairs, a difference which is larger over the left hemisphere at temporo-parietal sites, but which predominates over the right hemisphere at frontal sites.

**Table 12.** Results of the amplitude analyses, comparing each pair of response categories, over each latency region. Only significant effects involving the factor of response category (RC) are reported. HM = Hemisphere, L = Location (Anterior vs. Posterior), ST = Electrode site (Inferior vs. Mid-Lateral vs. Superior).

<u>LATENCY REGION</u>	<u>PAIRWISE COMPARISON</u>		
	<u>Same v New</u>	<u>Rearranged v New</u>	<u>Same v Rearranged</u>
<b><u>600-900</u></b>			
RC	F1,15 = 24.62, p < 0.001	-	F1,15 = 11.96, p < 0.005
RC x ST	F1.2,18.6 = 10.90, p < 0.005	-	F1.6,24.6 = 12.87, p < 0.001
RC x HM x L	-	F1,15 = 4.28, p = 0.056	-
RC x L x ST	-	F1.3,20.2 = 3.73, p = 0.057	-
RC x HM x L x ST	F1.7,25.1 = 6.07, p < 0.01	-	-
<b><u>900-1200</u></b>			
RC	F1,15 = 17.81, p < 0.001	-	F1,15 = 20.12, p < 0.001
RC x ST	F1.2,18.1 = 7.34, p < 0.05	-	F1.5,21.8 = 16.71, p < 0.001
RC x HM x L	F1,15 = 7.71, p < 0.005	F1,15 = 7.10, p < 0.05	-
<b><u>1200-1500</u></b>			
RC	F1,15 = 19.40, p < 0.001	-	F1,15 = 25.36, p < 0.001
RC x ST	F1.2,17.4 = 6.17, p < 0.05	-	F1.7,25.6 = 22.91, p < 0.001
RC x HM x L	F1,15 = 7.80, p < 0.05	F1,15 = 10.05, p < 0.005	-
<b><u>1500-1944</u></b>			
RC	F1,15 = 16.92, p < 0.001	-	F1,15 = 27.31, p < 0.001
RC x ST	F1.2,17.4 = 7.63, p < 0.05	-	F1.7,25.7 = 39.30, p < 0.001
RC x L	-	F1,15 = 5.14, p < 0.05	-
RC x HM x L	F1.2,17.4 = 11.82, p < 0.005	F1,15 = 20.09, p < 0.001	-

Rearranged versus New: The ANOVA for the 600-900 msec revealed only marginally significant effects. The analyses of the 900-1200 and 1200-1500 msec latency regions revealed a significant interaction between category, hemisphere and location. The reasons for this interaction can be seen in figure 17, which shows that at right temporo-parietal sites the ERPs for rearranged pairs are more negative-going than those for new pairs, whereas at right frontal sites the rearranged pairs are more positive-going. The

ANOVA for the final latency region revealed significant interactions between category and location, and between category, hemisphere and location. These findings reflect the fact that over temporo-parietal sites the ERPs for the rearranged pairs exhibit a negative shift, maximal over the right hemisphere, whereas little difference between the response categories is evident at frontal sites.

Same versus Rearranged: For all four latency regions, the ANOVAs contrasting the ERPs for rearranged and same pairs revealed a significant effect of response category, and an interaction between response category and site (see table 12). In each case these effects reflect the facts that the ERPs to the same pairs are more positive-going, and that this difference is larger nearer to the midline (see figure 15).

#### **Topographic analysis**

Because of their small size, and their marginal reliability in the 600-900 msec latency region, the results of a topographic analysis of the old/new effects associated with the rearranged pairs were considered to be of questionable worth. The analysis of scalp topography was therefore confined to the larger and more robust effects associated with the same pairs. Figure 18 illustrates the scalp topography of these effects over successive latency regions. The figure indicates that the old/new effects for same pairs are remarkably similar across all four latency regions, consisting of two topographically distinct maxima, over left temporo-parietal and right frontal scalp sites respectively.

To investigate whether the topography of the old/new effects evolved over the course of the recording epoch, the topographies of the effects in each latency region were contrasted by ANOVA, employing the data from all 25 sites. This revealed a marginally significant effect of electrode site ( $F_{3.9,58.1} = 2.32, p < .07$ ), but no sign of a site by epoch interaction. A follow-up ANOVA was conducted employing the factors of latency region, hemisphere, location (frontal vs. temporo-parietal), and site (inferior, mid-lateral, superior). This ANOVA gave rise to a main effect of site ( $F_{1.8,27.5} = 7.59, p < 0.005$ ), along with interactions between hemisphere and location ( $F_{1,15} = 13.97, p < 0.005$ ), and hemisphere and site ( $F_{1.7,26.2} = 6.43, p < 0.01$ ), but to no effects of latency region (maximum  $F = 1.89$ ). These findings confirm the coexistence of left parietal and right frontal effects in these data, but suggest that, unlike in experiment 1, these effects did not change over time.

### **Summary of results**

As in experiment 1, the same pairs were associated with sizeable and robust old/new effects. The old/new effects associated with rearranged pairs were, however, small in magnitude, unreliable over the earliest latency region, and supplanted at many electrode sites by a negative-going effect. Again in accordance with the findings of experiment 1, same pairs were associated with two topographically dissociable old/new effects, a left temporo-parietal maximum and a right frontal maximum. Unlike in experiment 1, however, there was no evidence of a change in the lateral distribution of the frontal old/new effects with time.



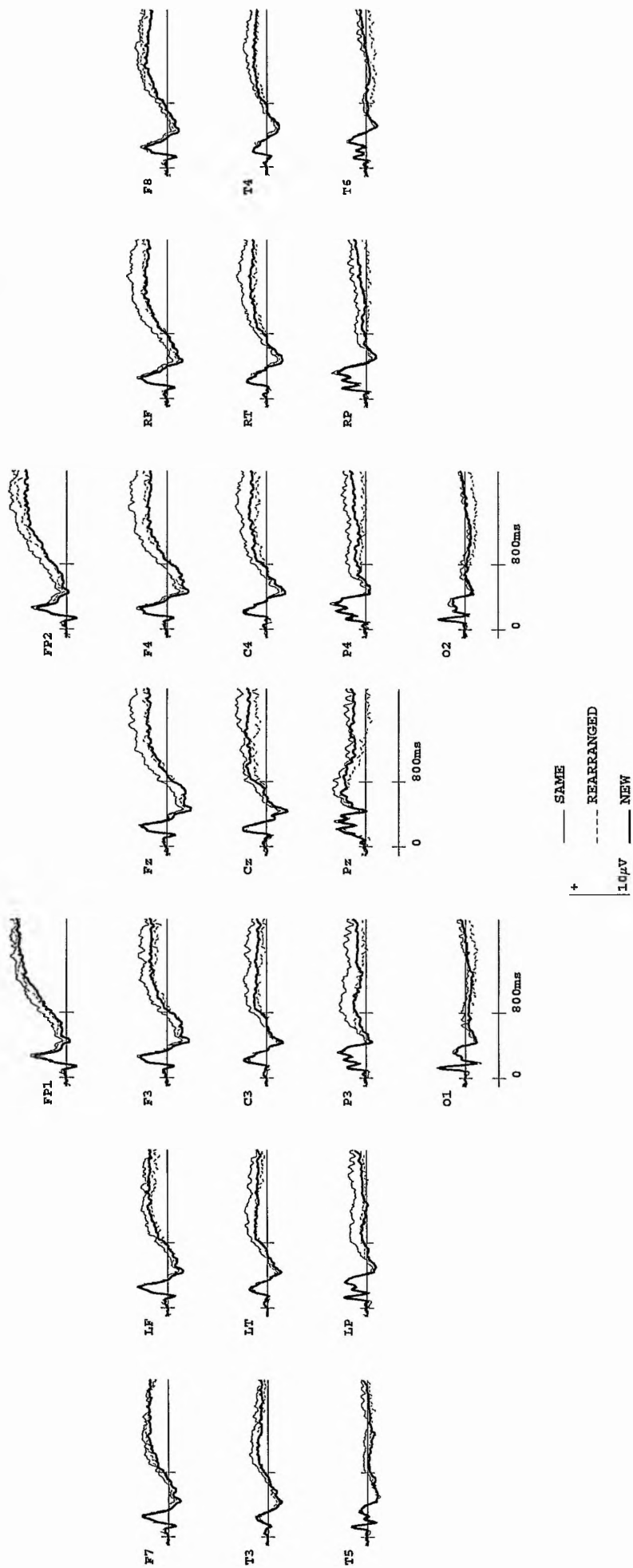
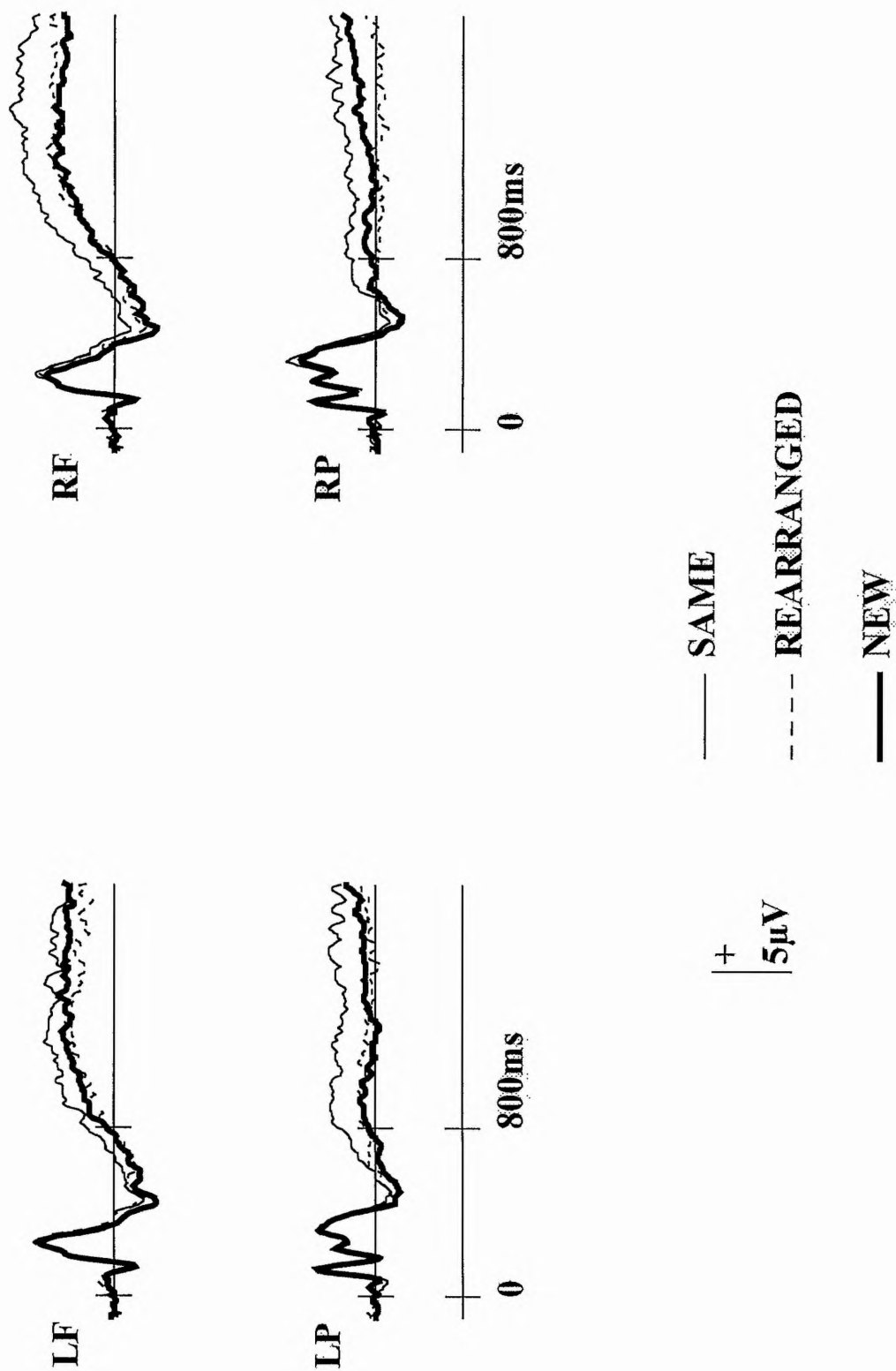
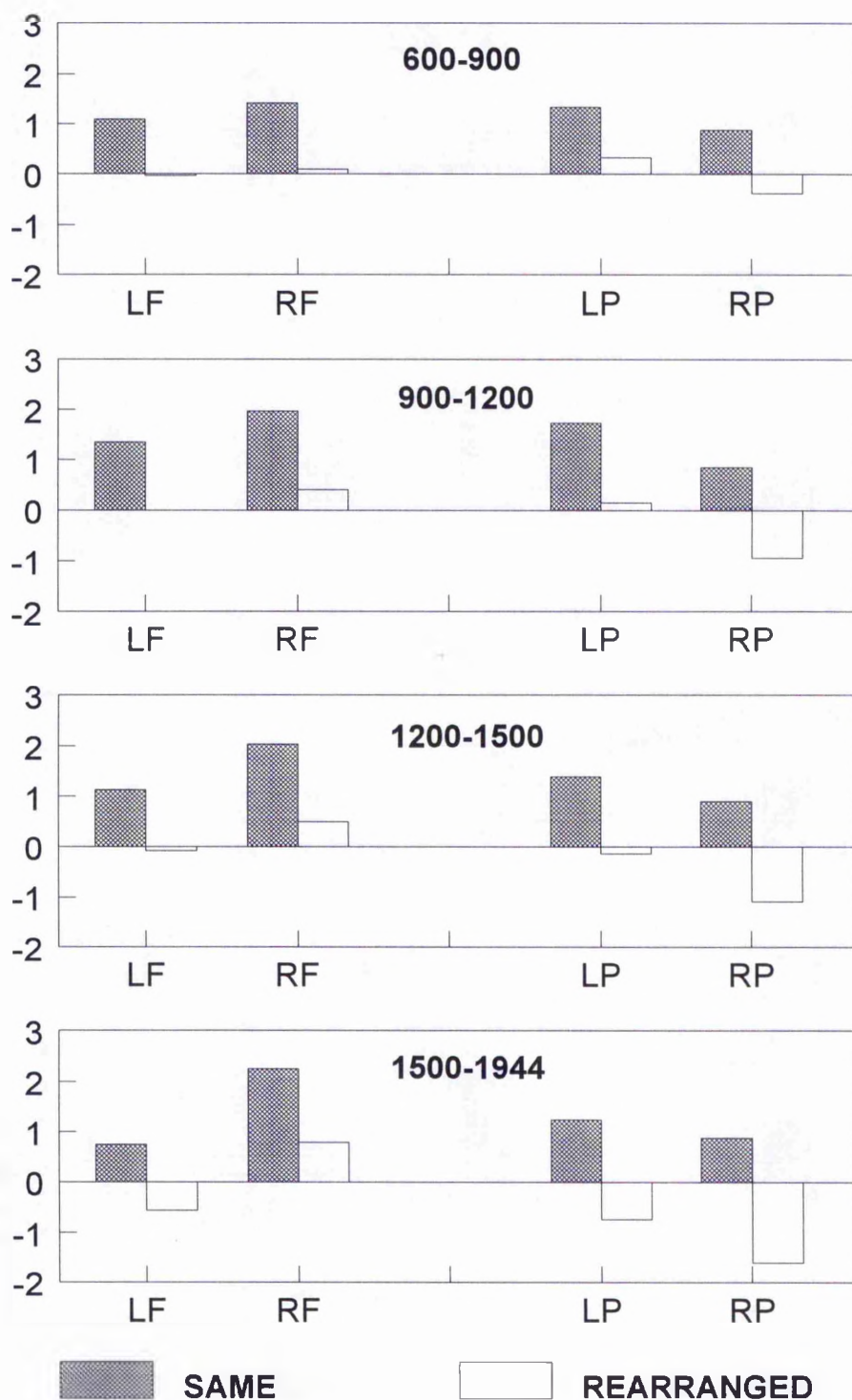


Figure 15. Experiment 3: Grand average ERP waveforms elicited by correctly classified same, rearranged and new pairs. Scale bar and electrodes are shown as in figure 7.

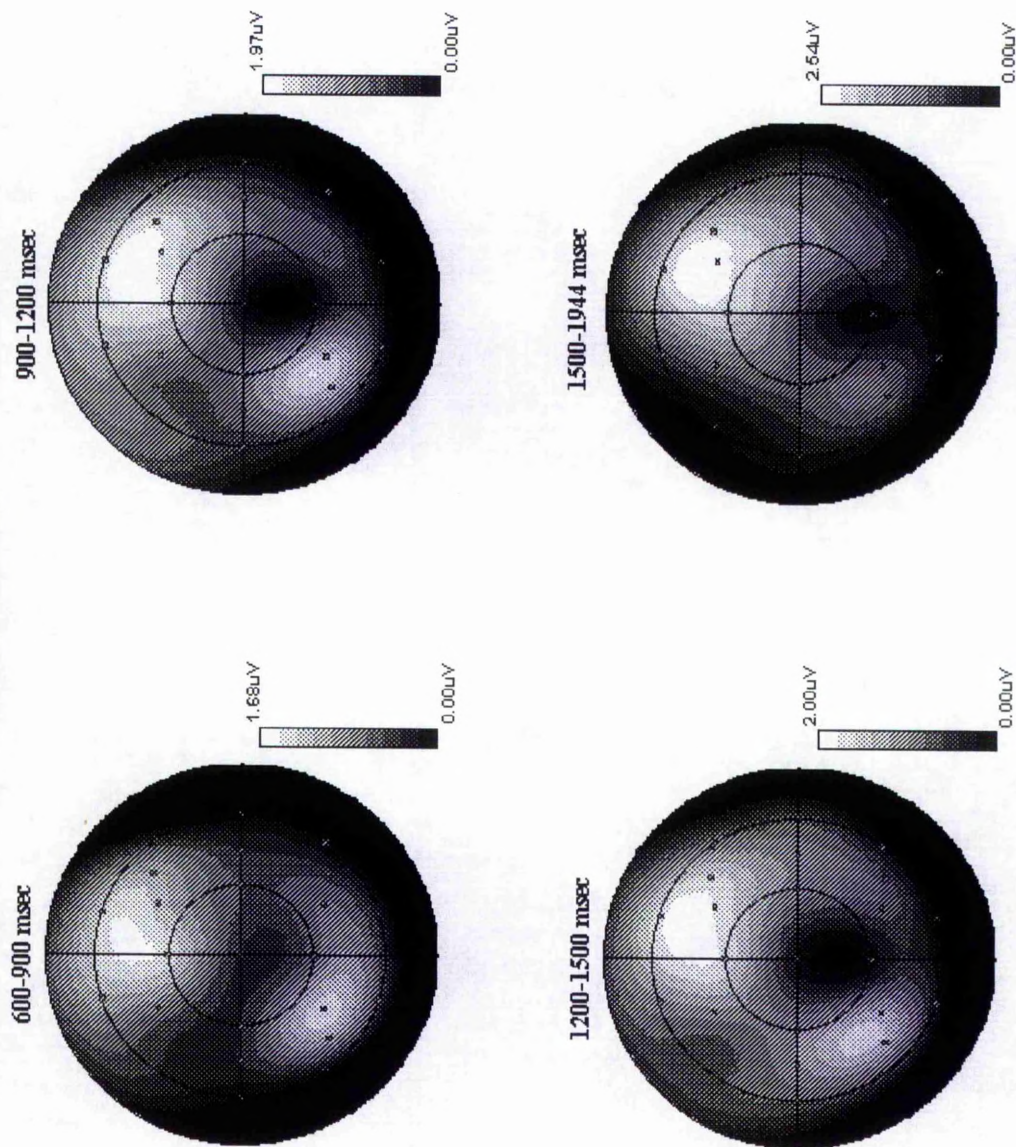


**Figure 16.** Experiment 3: Grand average ERP waveforms elicited by the same, rearranged and new response categories, for left and right lateral frontal (LF, RF) and lateral parietal (LP, RP) electrode sites.



**Figure 17.** Experiment 3: Differences in mean ERP amplitude for same minus new pairs, and rearranged minus new pairs, over the 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec latency regions. Amplitude measures are averaged over the electrode site indicated and the sites immediately lateral and superior to it.

# SAME PAIRS



**Figure 18.** Experiment 3: Topographic maps illustrating the distribution of the differences between ERPs to correctly classified same and new pairs over the 600-900 msec, 900-1200 msec, 1200-1500 msec and 1500-1944 msec latency regions. Scale bars and electrodes are shown as in figure 10.

## DISCUSSION

As in experiments 1 and 2, there was a significant advantage in recognition memory performance for same pairs, despite the fact that the task no longer required memory for associations established at study to be retrieved explicitly. This finding can be interpreted as further evidence for the proposal that same pairs benefit from recollection to a greater extent than do rearranged pairs. The magnitude of the recognition advantage for the same pairs was somewhat larger in the present experiment than in experiment 1, indicating that the absence of the associative recognition requirement did not cause subjects to reduce their dependence on recollection as a basis for responding to the old/new recognition judgement.

In light of these behavioural findings, it would be expected that the ERPs elicited by same and rearranged words pairs would, as in experiment 1, differ with respect to the magnitude of any ERP correlates of recollection. As a result of the removal of the associative recognition judgement, however, the magnitude of these recollection-related ERP effects would likely be smaller than those identified in the first experiment, since it is no longer possible to separate recognised same pairs according to whether or not their study episode was accurately recollected (as was the case in experiment 1). Thus, the ERPs elicited by such pairs in the present experiment include a higher proportion of trials on which recollection failed than was the case in experiment 1, leading to a relative 'dilution' of the ERP correlates of recollection.

Turning to the ERP data, the critical question posed by the experiment was whether the right frontal old/new effect found in experiments 1 and 2 would remain, despite the removal of the explicit requirement to make an associative recognition judgement. The ERPs to recognised same pairs exhibited statistically reliable right frontal old/new effects similar in character to the right frontal effects found in the previous experiments. Thus, the findings of experiment 3 suggest that the explicit requirement to discriminate between different classes of recognised item is not a necessary condition for the emergence of this frontally distributed old/new effect. Rather, in the context of the recognition of arbitrarily associated word pairs, the engagement of the cognitive operations reflected by the right frontal effect appears to be relatively obligatory in nature.

Unlike in experiment 1 however there was no evidence to suggest that the right frontal effect became more asymmetric over time. The reason for this difference between the findings of the two experiments is unclear. One possibility is that it reflects the change from a test procedure requiring serial responses to one in which only a single response must be made. A similar suggestion was made by Wilding and Rugg (1997b), who noted that the bilateral effect evident in their data was absent in an earlier study of source memory in which only a single response was required to each test item (Wilding and Rugg 1997a). This account does nothing however to elucidate the functional significance of the bilaterally distributed frontal effect. Moreover, the frontal effect did not become more asymmetric over time in experiment 2, where a serial rather than single response was required. Subsequent discussion of the functional and neurological significance of the frontal old/new effects will therefore be confined to the asymmetric component (the right frontal effect), which was equally evident in all 3 experiments.

Finally, as expected, both left parietal and right frontal old/new effects were greater in magnitude in the ERPs to same than to rearranged pairs. As in experiment 1, at temporo-parietal sites the old/new effect for rearranged pairs became increasingly negative-going over time, reflecting the contribution of the posteriorly distributed negative component discussed earlier (see Discussion of experiment 1). Unfortunately the small and unreliable old/new effects for the rearranged items precluded the comparison of their topography with the topography of the effects for same pairs.



## Chapter 8.

### INTERIM DISCUSSION 1

In all 3 experiments old/new recognition was better for same than for rearranged pairs. In addition, for the associative recognition judgement in experiments 1 and 2, subjects were able to overcome a strong bias towards responding 'rearranged' and classify the great majority of the same pairs correctly. As already discussed, these findings are consistent with the proposal that same and rearranged pairs are equally likely to be recognised on the basis of familiarity, but that same pairs are more likely to engender recollection.

It is important to acknowledge however that while the behavioural findings are consistent with a dual-process account, they do not in themselves necessitate such an account. The findings are equally compatible with a single process model in which words in same pairs engender stronger and more complete recollection of their encoding episodes than do words in rearranged pairs, as might be expected on the basis of general principles of memory function such as 'encoding specificity' (Tulving and Thomson, 1973) and 'transfer appropriate processing' (Morris, Bransford, and Franks, 1977).

Likewise, the ERP findings are consistent with both dual- and single-process accounts of recognition. Notably, as was the case in the studies of Wilding and Rugg (1996,

1997b), there was no evidence for an ERP correlate of familiarity based recognition. Such evidence would have taken the form of ERP old/new effects that were either of equivalent magnitude in the ERPs to same and rearranged pairs, or were larger in the ERPs to the rearranged pairs. Although it should be stressed that the absence of such findings cannot be taken as evidence against the proposal that recognition can be based on processes other than recollection, it is evident that the present results provide no support in favour of such a proposal.

Nonetheless, the present findings clearly demonstrate that the electrophysiological correlates of recognition memory for word pairs differ markedly according to whether associations formed at study are maintained or are broken at test. These differences are found in the magnitudes of two topographically dissociable old/new effects. In respect of their scalp distributions and functional properties, these effects closely resemble two previously identified correlates of successful memory retrieval: the left parietal and right frontal old/new effects (e.g., see Allan et al., *in press*). Thus, the present findings lend support to previous proposals (cf. Allan et al. *in press*, Wilding and Rugg, 1996, 1997a,b) that these ERP effects reflect functional distinct processes engaged during the recollection of prior episodes.

Neuropsychological evidence (e.g., see Mayes, 1988) indicates that recollection depends critically upon the hippocampal formation and associated medial temporal and diencephalic structures (the medial temporal lobe memory system). It has been proposed that the role of this system is to bind or link together in memory the various features of an event at the time it is experienced, allowing its reinstatement in response to an appropriate retrieval cue (e.g., Cohen and Eichenbaum, 1993; Gaffan, 1994; Kroll et al., 1996; McClelland et al., 1995). In light of such proposals, the present findings, which indicate that the left parietal effect is sensitive not so much to whether test items are old or new, but whether they preserve information about associations formed during a single prior study episode, add weight to the suggestion that this effect reflects retrieval mediated by the medial temporal memory system (cf. Rugg et al., 1996; Wilding and Rugg, 1996).

The present findings also provide new information about the right frontal old/new effect. As discussed previously, Wilding and Rugg (1996, 1997a,b) proposed that this effect reflects processing supported by the prefrontal cortex; specifically, task related



post-retrieval processing performed on the products of successful recollection. This proposal is consistent with neuropsychological evidence which suggests that the prefrontal cortex contributes to performance on memory tasks that require the evaluation and employment of remembered information in a strategic, goal directed manner (e.g., Moscovitch, 1992, 1995).

The findings are consistent with the idea that the right frontal old/new effect reflects successful recollection, in that the magnitude of the effect was markedly larger for the ERPs to same pairs than it was for rearranged pairs. Contrary to what might have been expected on the basis of the proposals of Wilding and Rugg, however, the effect was found not only in experiments 1 and 2, but also in experiment 3, when the explicit requirement to evaluate and employ recollected information in a goal directed manner was reduced considerably. This finding demonstrates that the right frontal effect is not restricted to memory tasks, such as source memory, in which the correct response is dictated by the content of the recollected information.

Although the right frontal effect appears to be an obligatory correlate of the recollection of associative information, it has not been reported in numerous previous studies of recognition memory for isolated words (for review see Rugg, 1995). Recent evidence suggests, however, that the effect can be found in standard old/new recognition tests under certain circumstances. For example, Allan and Rugg (1997) found a small right frontal old/new effect in the ERPs to correctly identified old words in a recognition memory task in which accuracy was very high. Similarly, Schloerscheidt and Rugg (1997) reported that successful recognition of pictures of objects was associated with a right frontal old/new effect, again in the context of high levels of recognition accuracy.

Why should right frontal effects be present in these but not in earlier studies of old/new recognition memory? One possible explanation is that the emergence of the right frontal effect is related to the richness or amount of information that is retrieved in response to the test cue. By this argument, the post-retrieval processes reflected by this effect are obligatorily engaged whenever the amount of information retrieved from episodic memory exceeds some threshold, and such post-retrieval processes may sometimes be engaged regardless of task demands. This threshold is less likely to be exceeded when the experimental task requires simple recognition memory of words,

than when the encoded information is particularly rich (as in the present experiments), or when a relatively large amount of information must be retrieved in order to satisfy task demands (as in tests of source memory).

That said, previous evidence also suggests that the right frontal old/new effect is not a necessary consequence of the recollection of a prior study episode, even under circumstances similar to those in the present experiments. Rugg et al. (1996, and see Tendolkar et al., 1997, for similar findings) employed a study task very similar to the one used here, but at test presented only one member of each study pair. For each item judged old, subjects were required to recall the word with which it had been associated at study. As would be expected on the basis of the present findings, Rugg et al. (1996) found that the left parietal old/new effect elicited by recognised words for which associative recall was successful was larger than the effect elicited by recognised words for which the associate could not be recalled. By contrast, there was no sign of a right frontal effect in the ERPs to the 'recollected' items.

Thus, although associative recognition and associative recall might seem to rely upon the recollection of similar information, the two tasks are associated with different electrophysiological 'signatures', with only recognition giving rise to the right frontal old/new effect. Clearly, it is of interest to determine whether associative recognition and associative recall employ qualitatively different retrieval processes, or whether instead they differ with respect to processes that act upon retrieved information. According to current proposals about the functional significance of the right frontal effect - that it reflects processes that act upon the products of retrieval - the latter is the more likely possibility. By this account, additional post-retrieval processes appear to be engaged by associative recognition but not associative recall.

An alternative account of the relationship between associative recognition and recall can be found in the proposals of Koriat and Goldsmith (1996). They investigated differences in the role of monitoring and control process across memory tasks, and argued that differences in a subject's 'freedom to respond' have a critical influence upon memory performance. For example, in a typical cued recall task subjects have no control over what a specific retrieval cue causes them to remember, but they can control what they choose to report. Thus, the ability to monitor the contents of retrieval allows a trade off between the frequency and accuracy of responding. In contrast, in a

typical recognition memory task subjects are tested under forced choice conditions where monitoring and control processes cannot play as critical a role. Thus, within the framework provided by Koriat and Goldsmith, associative recall would be expected to be at least as dependent as associative recognition upon post-retrieval monitoring and control processes. In sum, it remains to be seen whether associative recognition and associative recall employ fundamentally different retrieval processes, or if they simply differ with respect to the post-retrieval processes that are performed upon retrieved information. Experiments 4 and 5 were designed to investigate this question.

## **Chapter 9.**

### **EXPERIMENT 4**

#### **INTRODUCTION**

There is converging evidence that performance on episodic memory tasks depends upon a network of brain regions. Among the most important of these regions are the hippocampus and adjacent medial temporal structures (the 'medial temporal memory system'; e.g., Cohen and Eichenbaum, 1993; Gaffan, 1994; Squire and Zola-Morgan, 1991), and the prefrontal cortex (e.g., Wheeler, Stuss and Tulving, 1995; Stuss and Benson, 1983; Stuss, Eskes and Foster, 1994). The medial temporal system is thought to play an obligatory role in the retrieval of recently acquired episodic information. By contrast, the role of the prefrontal cortex is generally regarded as more flexible, supporting a range of processes that are called into play to differing extents by different retrieval tasks (e.g., Squire, Knowlton and Musen, 1993; Moscovitch, 1992).

As discussed in chapter 3, the findings from recent ERP studies of episodic memory retrieval are consistent with the foregoing framework. One ERP correlate of episodic memory - the 'left parietal old/new effect' - is characterised by a positive shift in ERPs to words correctly recognised as old relative to ERPs to new words. The effect onsets around 400 msec post-stimulus and is maximal over the left temporo-parietal scalp.

The findings from a variety of studies suggest that the left parietal effect is elicited selectively by test items that engender retrieval of their encoding episode (recollection; cf. Wilding, Doyle and Rugg 1995; Wilding and Rugg 1996; Paller and Kutas, 1992; Smith, 1993; for a recent review see Allan, Wilding and Rugg, in press). Moreover, it has been proposed (Wilding and Rugg, 1996) that the effect reflects retrieval processes associated with recollection, and that it is an indirect reflection of the contribution of the medial temporal lobe memory system to episodic retrieval (cf. Cohen and Eichenbaum, 1993; Squire and Zola-Morgan, 1991).

A second ERP correlate of episodic memory has also been found; the 'right frontal old/new effect'. To recap briefly, this effect was first demonstrated in a study of source memory (Wilding and Rugg, 1996), and consists of a positive shift that is maximal over right frontal electrodes. In that study, the effect onset at about the same time as the left parietal old/new effect, but showed a markedly more sustained time course. Because the right frontal effect was larger in ERPs elicited by items that received correct rather than incorrect source judgements, Wilding and Rugg (1996) proposed that it reflected processes associated with the successful recollection of prior episodes.

As discussed in chapter 3, although there seems to be a strong link between recollection and the left parietal effect, this link appears to be weaker in the case of the right frontal effect. For example, the right frontal effect is seldom prominent in ERPs elicited in simple recognition memory tasks (Allan et al. in press), and Wilding and Rugg (1997b) identified a situation in which even successful source memory was not accompanied by the effect. Consequently, Wilding and Rugg (1997a,b) suggested that the right frontal effect reflects 'post-retrieval' processes that are recruited in certain circumstances to operate on the products of episodic retrieval.

Like source memory, the ability to retrieve recently learnt associations between two items is heavily dependent upon episodic memory. In both cases, memory for the familiarity of the test items *per se* is not sufficient to support accurate performance. Whereas successful source memory depends on the ability to recollect the association between a study item and its encoding context, associative memory requires recollection of information about the specific relationship between a pair of study items. Notably, two different tasks can be employed to tap memory for recently acquired associations. Associative *recall* requires subjects to retrieve the associate of a

recently studied test item presented in isolation. By contrast, associative *recognition* requires subjects to discriminate between pairs of old items that maintain their pairing between study and test, and pairs that have been recombined between study and test phases.

The relationship between the ERP old/new effects and episodic recollection has been investigated using both associative recall (Rugg, Schloerscheidt, Doyle, Cox and Patching, 1996) and associative recognition (experiments 1-3). As was described in chapter 3, in the study of Rugg et al. (1996) subjects first learned a series of novel word pairs. At test one member of each study pair was presented, intermixed with new words. Subjects were required to judge whether each test item was old or new, and for each word judged old, to report its study partner. In keeping with the proposal that it indexes episodic retrieval, a significant left parietal effect was elicited only by those recognised old words for which associative recall was successful. There was, however, no sign of a right frontal old/new effect.

Whilst there have been several previous studies of associative recognition (experiments 1-3), for present purposes the first of these is most relevant here. To recap briefly, the study phase of that experiment was identical to that of Rugg et al. At test however, new pairs of items were intermixed with old items, which were presented in either the 'same' pairing as at study or in a 'rearranged' pairing. The task was to discriminate between old and new pairs, and for pairs judged old, to discriminate between same and rearranged pairs. Relative to the ERPs elicited by both new and rearranged pairs, the ERPs elicited by correctly classified same pairs exhibited left parietal *and* right frontal old/new effects, along with an earlier, bilateral frontally distributed old/new effect.

Taken together, the findings from the studies described above suggest that associative recall and associative recognition have different electrophysiological correlates. Whereas in both tasks recollected items give rise to a left parietal old/new effect, frontally distributed old/new effects were only elicited by recollected items in the associative recognition task.

These findings appear to be at odds with the functional account of the right frontal old/new effect proposed by Wilding and Rugg (1996; see above). One might take the view that the information retrieved on tests of associative recall and source memory is

so disparate that the differential engagement of post-retrieval processes is to be expected (the argument put forward by Rugg et al. (1996) to account for their lack of a right frontal effect; cf. Chapter 3). It is difficult however to see how this argument can be extended to the comparison between associative recall and associative recognition. On the face of it, the two tasks require retrieval of the same kind of information (novel associations), and there is no principled reason for supposing that recognition places greater demands on post-retrieval processing than does recall.

The conclusion that there is an inconsistency between the findings from the ERP studies of associative recognition and recall is however, based upon a comparison made between two studies that differed in many respects other than their task demands. Thus, experiment 4 was designed to allow the ERP correlates of associative recognition and recall to be compared in the same subjects when extraneous procedural differences between the tasks were kept to a minimum. The two tasks were compared directly, employing a randomised experimental design. ERPs were recorded from considerably more electrodes (25 vs. 13), and for a longer recording epoch (1944 msec vs. 1436 msec) than those employed by Rugg et al. (1996). At issue is the question of whether, under these conditions, the ERP correlates of successful associative recognition and associative recall differ.

## METHOD

### Subjects

20 students participated in the experiment. Data from 3 subjects was discarded due to insufficient artifact-free trials in the critical response categories. An additional subject was discarded due to a technical failure. The mean age of the remaining subjects was 20.9 years (range 18 to 31 years), 10 of whom were female.

### Experimental stimuli

The 880 words were chosen from those in appendix A, and used to form 440 semantically and associatively unrelated word pairs. Of these 400 were used as critical items, and the remaining 40 for training. The experimental design is shown in table 13, along with examples of each class of item.

**Table 13.** Experimental design for a single study-test block, showing the different classes of stimuli and the correct responses, for both associative recognition and recall.

<u>Phase</u>	<u>Class of Item</u>	<u>Example</u>	<u>Response</u>
Study List	40 word pairs:	doll-bush charm-glue paint-ride green-honey	
Test List			
Associative Recognition	10 same pairs:	doll-bush	Old: Same
	10 rearranged pairs:	charm-ride	Old: Rearranged
	20 new pairs:	rock-steam	New
Associative Recall	20 old items:	green-xxx	Old: Honey
	20 new items:	creep-xxxx	New

For associative recognition half of the old items maintained their pairing between study and test ('same' pairs), whereas the remaining half were randomly re-paired ('rearranged' pairs). For associative recall, test items comprised the first word of a study pair and a row of Xs. The position of the word and Xs was counterbalanced and the number of Xs (ranging from 4 to 8) did not correspond to the length of the words' original partners.



The 400 critical word pairs were used to generate 8 study-test lists (each of which was presented to 2 subjects) such that across lists, each word pair was employed equally frequently for each task. The use of word pairs as study items was also counterbalanced across lists, such that each pair served equally often as an 'old' or 'new' test item. The items used to form 'same' or 'rearranged' pairs for the associative recognition task were also counterbalanced across lists. Item order within each list was also randomised. Finally, each of the resulting study-test lists was separated into 5 blocks, such that each study block contained 40 word pairs, and each test block contained 80 pairs of stimuli: 20 'old' items and 20 'new' items for each task.

In addition to the critical experimental lists, a training list was also generated, according to the same procedure as for the critical items, but containing only 20 study pairs and 40 test items.

### **Experimental tasks, procedures and ERP recording**

The experiment was run over five study-test blocks, preceded by the initial training session. Details of the study phase procedure are provided in chapter 4. Each test phase followed immediately after the study phase. Subjects were told that they would have to perform two tasks, each task being cued with a different fixation character. The '\*' character signalled an associative recognition trial, and the '#' character signalled a trial requiring associative recall. Each trial began with the presentation of one of these fixation characters, displayed for 800 msec. Following a 124 msec period during which the screen was blank, the test items were presented for a duration of 300 msec. The screen then remained blank for a further 3 seconds, at which time another fixation character '?' was presented for 4 seconds, which signalled that the subject should respond. The next trial then began. During the test phase the interval between the onset of successive test items was 10 sec.

By contrast with the procedure employed in experiments 1-3, at test subjects were required to make verbal responses, which were monitored and recorded by the experimenter. Examples of the correct response for each type of test stimuli are shown in table 13. For the associative recognition task subjects were instructed to make an initial old/new judgement for each pair, responding 'old' to pairs judged as studied, and 'new' to pairs judged as unstudied. For pairs judged as being old an additional

response was required, 'same' for words judged as having maintained their study pairing, 'rearranged' for words judged as being from separate study pairs, and 'don't know' when uncertain. An initial old/new judgement was also required for the associative recall task. Again, for any word judged to be old an additional response was required, either to report the word's original study partner, or if unable to do so, to respond 'don't know'.

Details of the ERP recording procedures are provided in chapter 4.

## RESULTS

### Behavioural data

Table 14 shows the probability of an 'old' response to old and new items on the initial old/new judgement, for both associative recognition and associative recall. A t-test was performed to compare recognition accuracy (measured as  $[p(\text{hit}) - p(\text{false alarm})]$ ) across task revealed a significant effect ( $t_{15} = 11.33$ ,  $p < 0.001$ ), indicating that performance was superior in the associative recognition task.

The hit rates on the associative recognition task were 97% and 93% for same and rearranged pairs respectively. A t-test comparing these hit rates revealed a significant effect ( $t_{15} = 4.24$ ,  $p = 0.001$ ), confirming that performance was better for same than for rearranged pairs.

**Table 14.** Mean percentage (standard deviations) of an old response on the initial old/new judgement for both associative recognition and associative recall. The subsequent probability of a correct associative recognition response is also shown for same and rearranged pairs (contingent upon a correct old/new recognition response)

<u>Judgement</u>	<u>Class of item</u>	
	<u>Old</u>	<u>New</u>
<u>Old/new recognition</u>		
% 'OLD': Recognition	94.9 (3.2)	2.3 (2.5)
% 'OLD': Recall	80.4 (8.1)	4.4 (3.2)
<hr/>		
<u>Associative recognition</u>	<u>Same</u>	<u>Rearranged</u>
% 'CORRECT'	90.0 (5.8)	90.1 (5.5)

Table 14 also shows the proportion of correct associative recognition responses made to pairs that were judged old (although an option, no subjects responded 'don't know' to these items). Not surprisingly, a t-test comparing the proportion of correct judgements for same and rearranged pairs revealed that these proportions did not differ. Subjects made too few false alarms to permit an analysis of their associative judgements to these items.

Of those old words that were correctly recognised in the associative recall task, 49% were associated with correct recall of their study partner, 43% elicited a 'don't know' response, and the remaining 8% elicited an incorrect response.

### ERP data

As the focus of interest is in the contrast between the neural correlates of successful associative memory on each task, analysis of the ERP data was restricted to only two response categories<sup>8</sup>. For associative recognition these categories were correctly classified new pairs (henceforth 'new pairs'), and same pairs that were both recognised as old and correctly classified as 'same' ('recognised' pairs). For associative recall the categories were correctly classified new words ('new words'), and recognised old words for which the studied associate was correctly recalled ('recalled' words). The mean number of trials contributing to the ERPs for associative recognition was 81 and 38 for the 'new' and 'recognised' response categories respectively. For associative recall the mean number of trials was 79 and 35 for the 'new' and 'recalled' response categories respectively.

Figure 19 shows the grand average ERP waveforms for the associative recognition task from all 25 electrode sites. The waveforms diverge from approximately 600 msec post-stimulus onset, with the ERPs for the recognised pairs becoming more positive than those for new pairs. This positive shift is larger over the left than the right hemisphere at temporo-parietal electrodes, but is more bilaterally distributed at frontal electrodes. The left hemisphere temporo-parietal positivity remains present (but decreases in size) throughout the recording epoch. From approximately 1400 msec post-stimulus the bilateral frontal positivity is replaced by a right-sided effect.

Figure 20 shows the grand average ERP waveforms for associative recall, again from all 25 electrode sites. As was the case for the recognition data, the waveforms begin to diverge from approximately 600 msec post-stimulus onset, with the ERPs for recalled pairs becoming more positive than those to new items, and exhibiting a left greater

---

<sup>8</sup> Sufficient trials were available for the formation of two additional ERP waveforms, one for each task. For associative recognition ERPs were formed for 'rearranged' responses (i.e., to rearranged pairs that were both recognised and correctly classified as being rearranged), and for recall ERPs were formed for 'don't know' responses (i.e., old words for which the studied associate could not be correctly recalled). The ERPs to these response categories does not bear directly on the issue that this study was designed to address, thus these ERPs are not considered in detail. For completeness however, the ERP waveforms are shown in appendix B, shown for all 25 recording sites.

than right asymmetry at both frontal and temporo-parietal electrodes. At temporo-parietal sites this positivity is replaced from approximately 900 msec by a right-sided negative-going effect, which continues until the end of the recording epoch. At frontal sites a right-sided effect is evident from approximately 1400 msec post-stimulus.

#### **Rationale for the ERP analyses**

As noted, the principal aim of experiment 4 is to investigate whether frontally distributed old/new effects are present in the ERPs for each task, and if so, to characterise and compare them. Consequently, the analysis of the magnitude of effects focused upon lateral frontal electrodes (F7/F8, LF/RF, and F3/F4; the same frontal sites that were analysed in experiments 1-3). The ERPs were analysed by measuring the mean amplitudes of the waveform (relative to the 102 msec pre-stimulus baseline) over three latency regions; 600-900 msec, 900-1400 msec and 1400-1900 msec. These latency regions were chosen on the basis of visual inspection of the waveforms, as those that best captured the pattern of old/new effects as they evolved over time. Notably, the 1400-1900 msec epoch covers a latency region that was absent in the original Rugg et al. (1996) study.

Analysis was initially performed separately for each task, investigating the magnitude and distribution of the frontally distributed old/new effects within each epoch. These analyses employed ANOVA with factors of response category (old vs. new), hemisphere (left vs. right), and site (inferior vs. mid-lateral vs. superior). The results of these analyses are shown in table 15. Results of the analysis of the data from analogous temporo-parietal sites (T5/T6, LP/RP, and P3/P4) are also shown in the table. These analyses are not commented upon in detail, but serve to demonstrate the presence of statistically significant old/new effects over temporo-parietal electrodes, and permit a comparison with the findings with the previous studies of associative recognition and recall (experiments 1-3 in this thesis, and Rugg et al., 1996, respectively). Only significant F values are reported, and as interest lies solely in differences between the ERPs associated with each response category, significant effects that do not involve the factor of response category are not reported. Figure 17 illustrates, for each task and latency region, the mean amplitude difference between the ERPs for old and new response categories.

## Magnitude analyses

Associative Recognition: As can be seen in table 15, analysis of the data from the 600-900 msec latency region established the presence of significant differences between the ERPs to the recognised and new response categories over frontal scalp sites, in the form of a significant interaction between response category and site. Figure 21 shows that this interaction reflects the fact that the ERPs for recognised pairs are more positive going than those to the new pairs, and that this positivity increases as electrodes get nearer to the midline. There was however no evidence of any significant effects involving hemisphere during the 600-900 msec latency region.

**Table 15.** Results of the ANOVAs of the amplitude analyses, for each task, over each latency region. Only significant effects involving the factor of response category are reported. RC = Response Category (Old vs. New), HM = Hemisphere, ST = Electrode Site (Inferior vs. Mid-Lateral vs. Superior).

	<u>ASSOCIATIVE RECOGNITION</u>		
	<u>600-900 msec</u>	<u>900-1400 msec</u>	<u>1400-1900 msec</u>
<u>FRONTAL</u>			
RC	F1,15 = 12.63, p < 0.005	F1,15 = 10.71, p = 0.005	-
RC x HM	-	-	F1,15 = 6.80, p < 0.05
RC x ST	F1.1,17.0 = 6.06, p < 0.05	F1.2,18.4 = 11.12, p < 0.05	F1.2,17.4 = 5.29, p < 0.05
RC x HM x ST	-	F1.3,19.8 = 4.03, p < 0.05	F1.5,22.4 = 4.34, p < 0.05
<u>PARIETAL</u>			
RC	F1,15 = 9.96, p < 0.01	F1,15 = 7.21, p < 0.05	-
RC x HM	F1,15 = 7.33, p < 0.05	F1,15 = 8.42, p < 0.05	F1,15 = 4.84, p < 0.05
RC x ST	F1.1,16.2 = 12.66, p < 0.005	F1.2,18.5 = 7.06, p < 0.05	-
	<u>ASSOCIATIVE RECALL</u>		
	<u>600-900 msec</u>	<u>900-1400 msec</u>	<u>1400-1900 msec</u>
<u>FRONTAL</u>			
RC	F1,15 = 7.29, p < 0.05	-	-
RC x HM	-	-	F1,15 = 17.84, p = 0.001
RC x HM x ST	F1.6,23.9 = 5.68, p < 0.05	F1.4,21.6 = 7.47, p < 0.01	F1.4,20.6 = 5.68, p < 0.05
<u>PARIETAL</u>			
RC	-	F1,15 = 7.79, p < 0.05	-
RC x HM	F1,15 = 17.39, p = 0.001	F1,15 = 19.53, p < 0.001	F1,15 = 14.15, p < 0.005
RC x ST	-	F1.3,18.9 = 11.99, p < 0.005	-
RC x HM x ST	-	F1.2,17.5 = 13.19, p = 0.001	F1.5,23.2 = 12.99, p < 0.001

Table 15 also shows that significant old/new effects were present for the 900-1400 and 1400-1900 msec latency regions. In both cases, the ANOVAs giving rise to three way interactions between category, hemisphere and site. Figure 21 shows that for the 900-1400 msec epoch this interaction reflects a positive going shift in the ERPs to recognised pairs. This effect is larger at sites near to the midline, and falls off more

rapidly over the right than left hemisphere. For the 1400-1900 msec epoch the interaction reflects a positive going shift that once again increases in size as electrodes get closer to the midline. In contrast to the pattern found in the earlier epochs however, the effect is largely restricted to electrodes over the right hemisphere.

Associative Recall: Table 15 also shows the results of the ANOVAs comparing the ERPs for recalled and new pairs. As figure 21 shows, the significant three way interaction for the 600-900 msec data between category, hemisphere and site reflects the presence of a frontal old/new which is larger over the left than the right hemisphere. The involvement of site in the interaction reflects the fact that the positive shift is diffusely distributed across electrode sites over the left hemisphere, but is focused towards the midline over the right hemisphere. A similar pattern of effects can be seen for the 900-1400 msec region, for which there is a significant interaction between category, hemisphere and site. Again this reflects a positive shift in the ERPs to recalled items that is diffusely distributed over left hemisphere electrodes, and more focused towards the midline over the right hemisphere.

The results of the ANOVA for the final 1400-1900 msec region also revealed a significant three way interaction between category, hemisphere and site (see table 15). Once again, this reflects the presence of a positive going old/new effect in the ERPs for the recalled items. Figure 21 shows that the pattern of effects differs from that found in the earlier epochs. During the 1400-1900 msec epoch the positive going old/new effect is restricted to the right hemisphere, an effect that increases in size as electrodes get closer to the midline.

#### **Topographic Analyses**

Since there were statistically significant frontal old/new effects for both tasks in all three latency regions, it was possible to compare the scalp distributions of the effects in each region as a function of task. These topographic analysis was conducted on the differences in amplitude between the ERPs to the old and new response categories (see figure 22). The analyses were conducted initially on the data from all 25 sites (employing the factors of task and site), followed by planned ANOVAs of the data from lateral frontal electrodes (factors of task, hemisphere and site).

600-900 msec: The initial ANOVA comparing the distributions of the effects across all 25 sites failed to reveal a significant task by site interaction ( $F < 1$ ). Similarly, the planned ANOVA restricted to lateral frontal electrodes revealed no effects that involved the factor of task (max  $F = 1.22$ ). Thus, there was no evidence that the scalp distribution of the old/new effects for recognition and recall differed during this epoch.

900-1400 msec: The initial ANOVA revealed a significant interaction between task and site ( $F_{3.4,51.3} = 4.46$ ,  $p = 0.005$ ), indicating that the distribution of old/new effects varied according to task. The ANOVA restricted to data from lateral frontal electrodes also revealed a significant interaction between task and site ( $F_{1.3,19.2} = 7.14$ ,  $p < 0.025$ ). As can be seen from figure 22, this interaction reflects the fact that for recall the frontal old/new effect are diffusely distributed across frontal electrodes, whereas for recognition the effects are more sharply focused towards the midline.

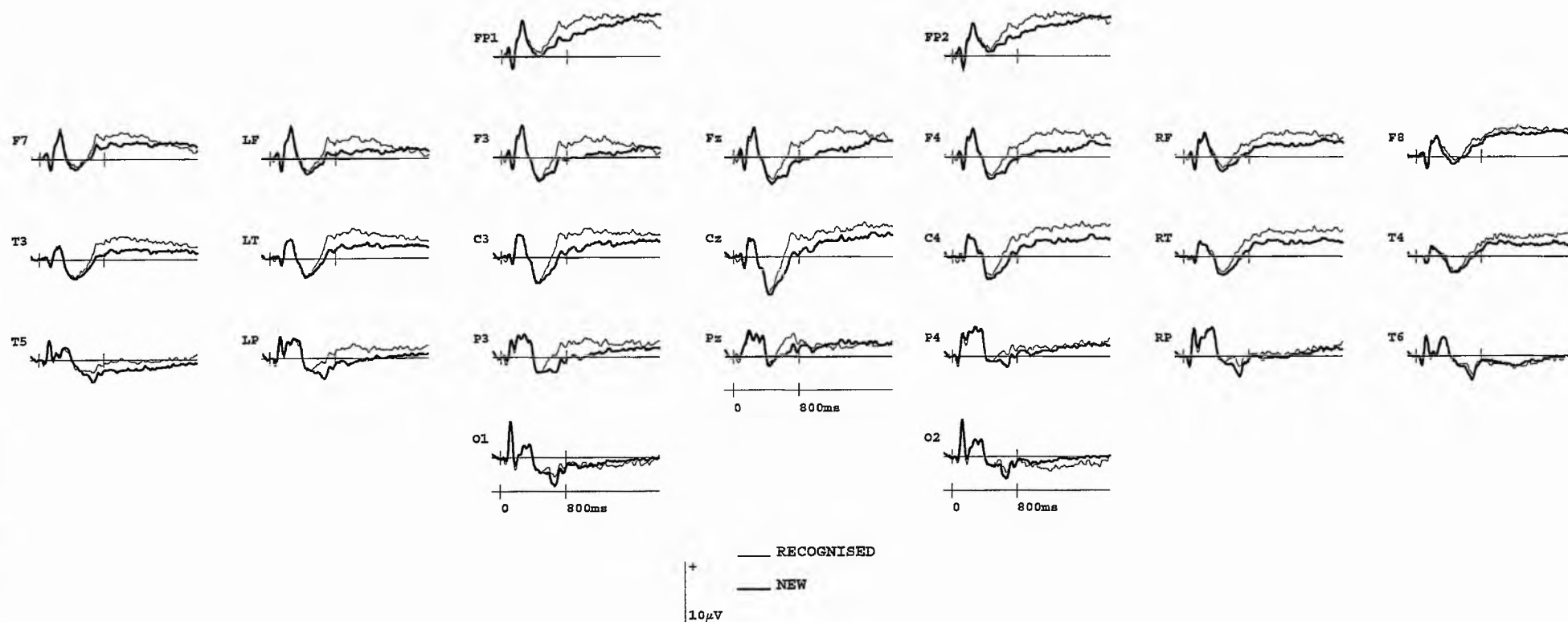
1400-1900 msec epoch: Neither the initial nor the planned ANOVA revealed any effects involving the factor of task during this epoch ( $F = 2.20$ ), indicating that the scalp distributions of the old/new effects were statistically equivalent across the two tasks (see figure 22). Importantly, the planned ANOVA did reveal a significant effect of hemisphere, along with an interaction between hemisphere and site ( $F_{1,15} = 18.56$ ,  $p = 0.001$ , and  $F_{1.4,21.3} = 18.28$ ,  $p < 0.001$  respectively). In demonstrating that the old/new effects in this latency region were larger over the right than left frontal scalp these findings echo the results of the magnitude analyses described previously. They also indicate that these asymmetries, and their relative magnitudes across the homotopic electrode pairs, were statistically equivalent across the two tasks (compare figures 21 and 22).

### **Summary of results**

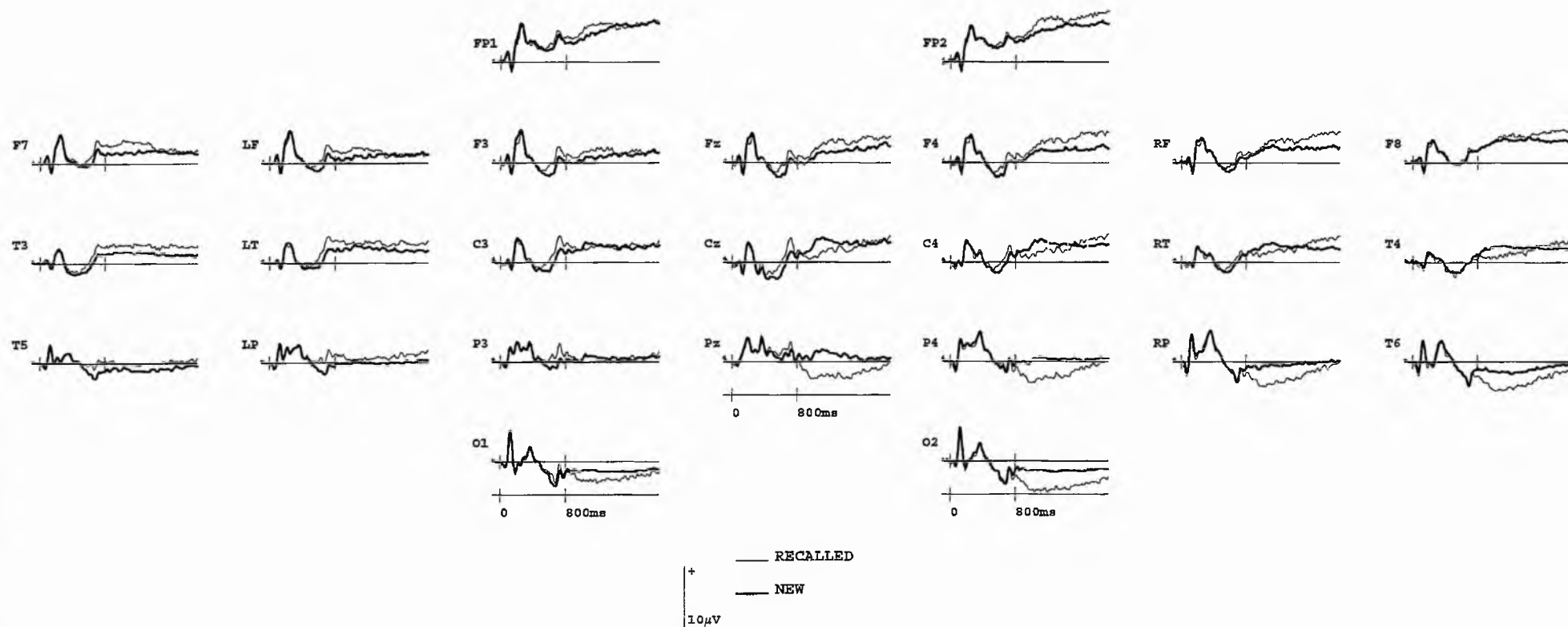
Analysis of the ERP data revealed that there were statistically significant frontally distributed old/new effects for both tasks. The topographic analyses revealed no evidence that the distribution of these old/new effects differed across task during the early 600-900 and late 1400-1900 msec latency regions. Critically, the analyses confirmed the presence of right frontal old/new effects for both tasks during the 1400-1900 msec latency region. The effects were not entirely equivalent for both tasks however. During the 900-1400 msec epoch the old/new effects were diffusely



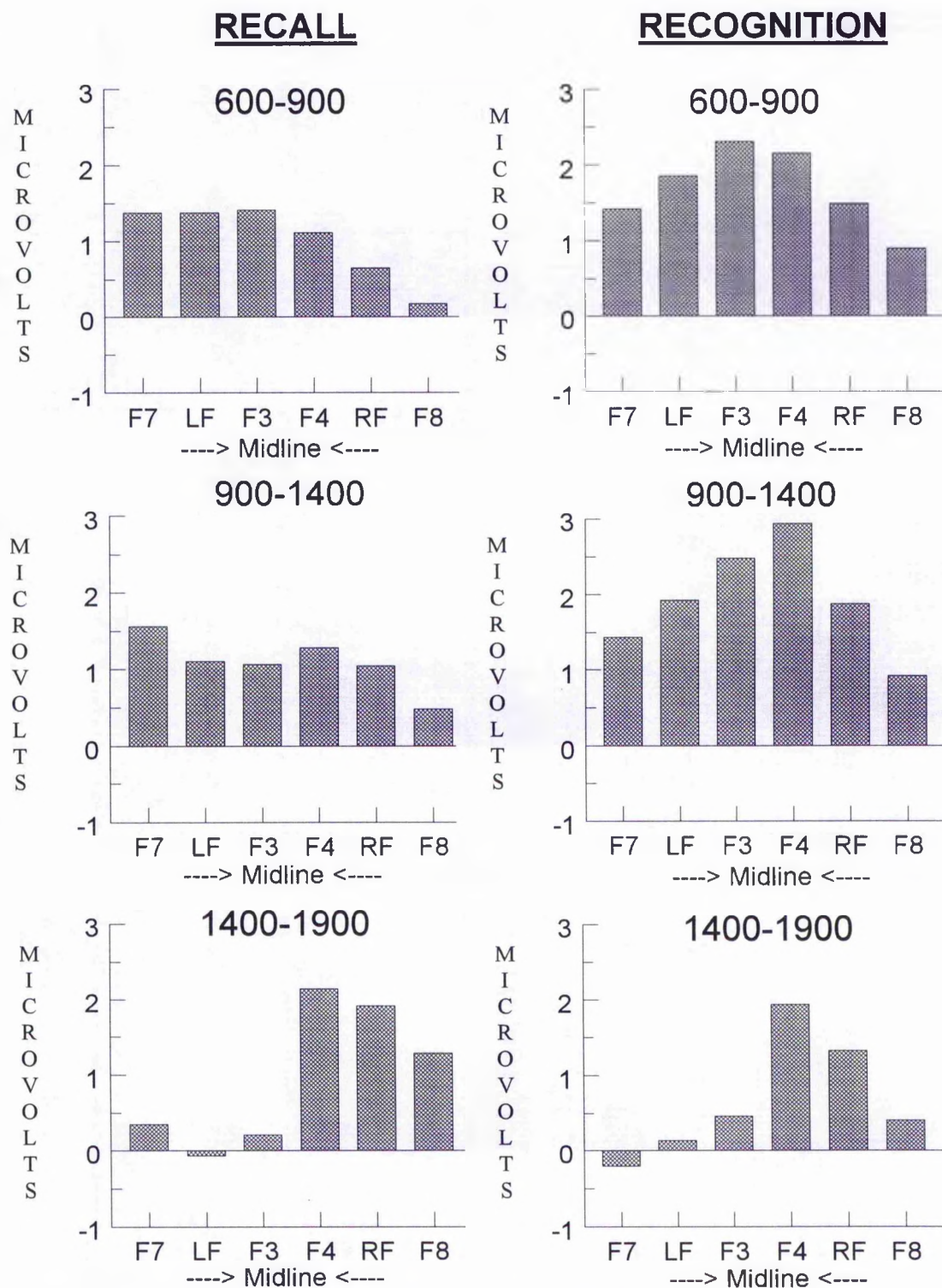
distributed across frontal electrodes for recall, but more sharply focused towards the midline for recognition.



**Figures 19.** Experiment 4: Grand average ERPs for the recognised and new response categories for associative recognition. Scale bar and electrodes are shown as in figure 7.



**Figure 20.** Experiment 4: Grand average ERPs for the recalled and new response categories for associative recall. Scale bar and electrodes are shown as in figure 7.

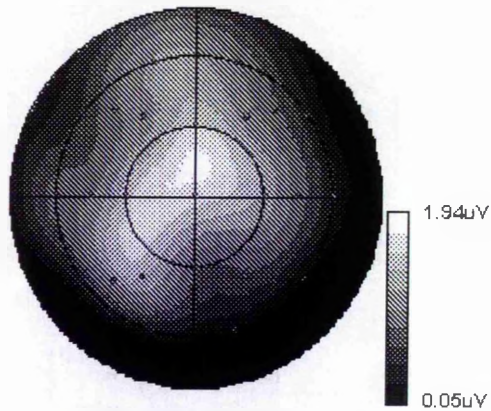


**Figure 21.** Experiment 4: Mean amplitudes of the difference between the ERPs for correct old and new responses, shown separately for recall (left) and recognition (right) during the 600-900 (top), 900-1400 (middle) and 1400-1900 (bottom) msec latency regions. Values are shown for the lateral frontal electrodes employed in the magnitude analyses. The data are shown for the left and right hemispheres, with sites arranged as on the head (inferior-to-superior on the left, superior-to-inferior on the right).

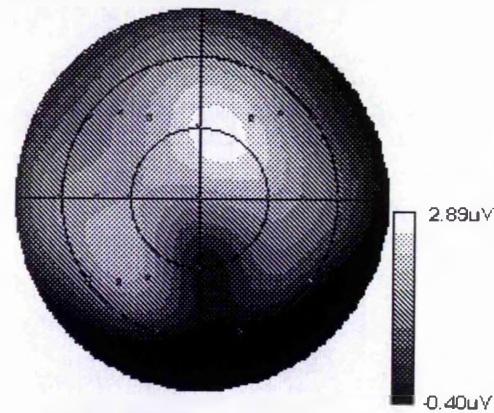


## RECOGNISED

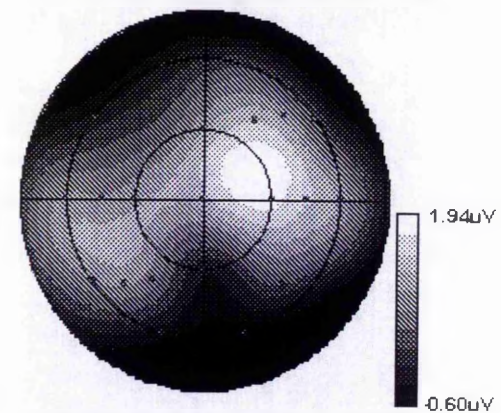
600-900 msec



900-1400 msec

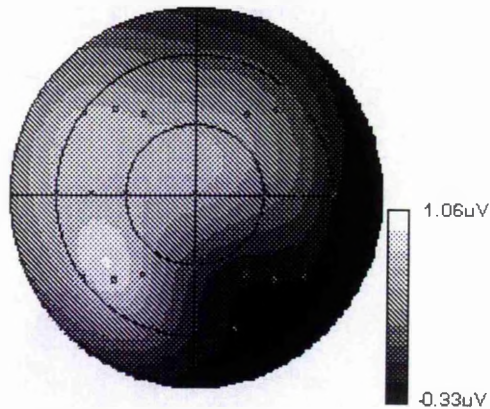


1400-1900 msec

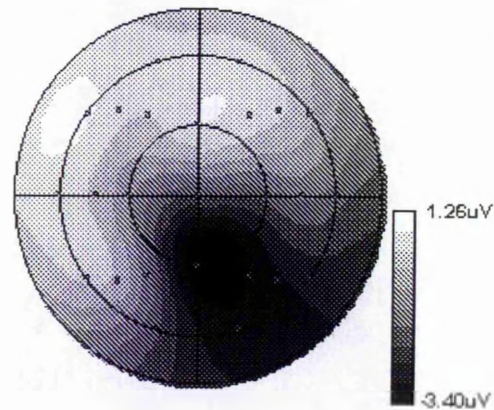


## RECALLED

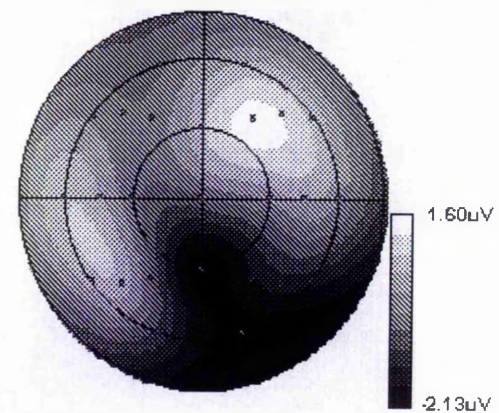
600-900 msec



900-1400 msec



1400-1900 msec



**Figure 22.** Experiment 4: Topographic maps illustrating the scalp distribution of the old/new effects for associative recognition (top row) and associative recall (bottom row), over the 600-900, 900-1400 and 1400-1900 msec latency regions. Scale bars and electrodes are shown as in figure 10.

## DISCUSSION

As indexed by the initial old/new recognition judgement, item recognition was highly accurate for both tasks. Performance was better in the recognition than recall task however. The fact that two words were presented as retrieval cues during each recognition test trial (and hence two opportunities to recognise a study item), compared to one word for each recall trial, provides an obvious explanation for the observed difference in performance on the initial recognition decision.

On both components of the associative recognition task performance was substantially better than in the previous experiment employing this task (cf. Experiment 1). This difference between the previous and the present study is almost certainly a reflection of the fact that fewer study items were employed in the present experiment (200 vs. 100 pairs). Performance on the first component of the associative recall task was similar to that reported by Rugg et al. (1996), but the proportion of recognised words associated with correct recall was somewhat higher (49% vs. 36%). This difference too may reflect the employment in the present study of shorter study lists than were employed previously (128 pairs in Rugg et al.).

Performance on the second component of each task indicated that, in both cases, subjects were able to accurately recollect a substantial proportion of the study episodes. In the case of associative recall the probability of reporting a study associate correctly by chance is vanishingly small; thus, it can be assumed that episodic recollection was the basis for performance on essentially every trial on which recall was successful. Of course, for the associative recognition task chance responding would give rise to correct associative judgements on 50% of trials. Given that subjects' judgements were accurate on some 90% of trials, however, it is safe to assume that guessing played only a small role in these judgements. Following Yonelinas (1997), it seems likely that on the great majority of trials on which subjects correctly endorsed recognised words pairs as 'same', this judgement was based on the recollection of the association formed at study.

The ERPs obtained during the associative recognition task resemble those described in experiment 1 quite closely. Recognised pairs elicited a sustained left parietal effect, the onset of which was roughly concurrent with a bilaterally distributed frontal positivity

which, from approximately 1200 msec post-stimulus, evolved into a right frontal effect that persisted until the end of the recording epoch. Similarly, in the case of the associative recall task, the ERPs from the posterior scalp resemble those from the initial study employing that task, in that they exhibited an initial left parietal effect followed by a sustained, right-sided negativity.

The key question is whether, in the associative recall task, the ERPs from frontal electrodes resemble more closely those found previously for associative recall (cf. Rugg et al., 1996) or those found for associative recognition (cf. experiment 1). The answer is clear: the pattern of old/new effects obtained from the frontal electrodes in the recall task was very similar to that found for recognition, and not at all like that reported by Rugg et al. (1996). Frontal effects were evident from approximately 600 msec post-stimulus, becoming increasingly right-sided with time, so as to exhibit a strongly right-sided asymmetry. Thus, at least in the experimental context employed here, successful associative recall does differentially engage the generators of frontal old/new effects.

How can these findings be reconciled with those of Rugg et al.? In the case of the late-onsetting right frontal effect observed here for associative recall, there may be nothing to reconcile. Rugg et al. employed a sampling epoch that terminated 1434 msec post-stimulus, and would therefore have been unable to observe a right frontal effect onsetting as late (ca. 1400 msec) as the one evident in the present experiment.

By contrast to the case of the right frontal effect however, there is a clear conflict between the findings of the present study and those of Rugg et al. with regard to 'early', bilateral frontal old/new effects. In the present study these effects onset around 600 msec, well within the recording epoch employed by Rugg et al. There was however, no sign of such effects in the data from that study (see figure 5, chapter 3). Clearly, the present findings are inconsistent with those of Rugg et al (1996), and indicate that, at least in the experimental context employed here, successful associative recall does differentially engage the generators of the frontal old/new effects.

Finally, it should be noted that whereas the scalp distributions of the old/new effects in each task were statistically equivalent for the 600-900 msec and 1400-1900 msec latency regions, this was not the case for the intervening region, where, among other

distributional differences, frontal effects were distributed more diffusely across the scalp in the recall task than they were in the recognition task. This finding suggests that, for this latency region at least, the patterns of neural activity (and, presumably, the cognitive operations) engaged by the two tasks differed, at least in part. This is unsurprising, given the quite different retrieval cues and demands of the two tasks. What is more surprising, perhaps, is the finding that, in the latency regions preceding and following this one, the patterns of neural activity associated with successful recollection in each task were so similar. Despite their procedural differences, it would appear that the two tasks engage many of the same cognitive operations.

Why should the present findings be so different from those of Rugg et al. (1996)? One possible reason for the presence of the frontally distributed effects in the present study is that the effects are sensitive to the overall 'context' in which the associative recall task was performed. In the experiment of Rugg et al. (1996) all test trials belonged to the same task. In the present experiment, however, subjects were required to switch between tasks on a trial-by-trial basis. It is possible that the requirement to constantly switch tasks was in some way responsible for the presence of the early frontal effects in the present associative recall task (cf. Johnson et al., 1997; Shallice, 1988). By this account, the frontal old/new effects found for associative recall should not be present if the two tasks are compared under conditions where subjects are not required to switch between tasks on a trial-by-trial basis. Experiment 5 was designed to investigate this possibility, prior to any further discussion of the present findings.



## **Chapter 10.**

### **EXPERIMENT 5**

#### **INTRODUCTION**

Experiment 5 was designed to investigate whether the presence of frontally distributed old/new effects in the ERPs for successful associative recall in experiment 4 was a result of the requirement to switch between tasks on a trial by trial basis. To remove this requirement the experimental design was modified so that task was now a blocked rather than a randomised variable. If the frontal old/new effects observed for the associative recall task in experiment 4 were a consequence of the requirement to switch between this task and associative recognition, they should be absent in experiment 5.

## **METHOD**

### **Subjects**

21 subjects participated in the experiment, none of whom had taken part in experiment 4. Two subjects failed to complete the experiment due to technical failure, and the data from 3 other subjects were discarded due to a lack of artifact free trials. The remaining 16 subjects (5 female, 11 male) had a mean age of 22.8 years (range 17 to 31 years).

### **Experimental stimuli**

The experimental stimuli comprised the same 440 word pairs that were employed in experiment 4 (400 critical pairs, and 40 practice pairs). The experimental procedure for each task was the same as those used in experiment 4, as was the method for generating and counterbalancing the study-test lists.

The critical difference between the present and previous experiment was in the separation of the recognition and recall trials into different blocks. Each subject was presented with 4 study-test blocks, 2 for associative recognition, and 2 for associative recall. Each study block contained 50 word pairs, and each test block contained 100 pairs. An AABB design was employed, such that half of the subjects performed the two associative recognition blocks first, whereas the remaining subjects performed the associative recall blocks first. The AABB design was chosen (rather than ABBA or ABAB designs) to minimise the switches between tasks.

A training block was also generated for each task, which was presented immediately before the administration of the first experimental block of the appropriate task.

### **Experimental procedure and ERP recording**

The study and test phases procedures were identical to those employed in experiment 4, except for the blocking of trials. Prior to the first training block subjects were provided with instructions for the first task, and were not informed of the second task until immediately before the training block for that task. In all other respects the experimental procedures, instructions and response requirements were maintained from experiment 4, as were the EEG recording and analysis procedures (see chapter 8).

## RESULTS

### Behavioural data

Table 16 shows the probability of an 'old' response to test items on the initial old/new judgement for each task. A t-test comparing recognition accuracy (measured as  $[p(\text{hit}) - p(\text{false alarm})]$ ) across task revealed a significant effect ( $t_{15} = 5.41$ ,  $p < 0.001$ ), confirming that performance was superior in the associative recognition task. The hit rates for the associative recognition task were 94% and 86% for same and rearranged pairs respectively. These rates were found to differ significantly ( $t_{15} = 5.33$ ,  $p < 0.001$ ), confirming the superior hit rate for same pairs.

**Table 16.** Mean percentage (standard deviations) of an old response on the initial old/new judgement for both associative recognition and associative recall. The subsequent probability of a correct associative recognition response is also shown for same and rearranged pairs (contingent upon a correct old/new recognition response).

<u>Judgement</u>	<u>Class of item</u>	
<u>Old/new recognition</u>	<u>Old</u>	<u>New</u>
% 'OLD': Recognition	89.7 (5.1)	2.9 (4.2)
% 'OLD': Recall	82.3 (7.2)	6.2 (5.8)
<u>Associative recognition</u>	<u>Same</u>	<u>Rearranged</u>
% 'CORRECT'	90.5 (6.8)	97.8 (8.1)

Table 16 also shows the probability of a correct associative recognition response for pairs judged old. A t-test comparing these probabilities revealed no significant difference. As in experiment 4 the 'don't know' response option was not used by any subject, and too few false alarms were made to allow an analysis of the associative judgements for these items. For the associative recall task, 48% of correctly recognised old words were associated with correct recall of their study partner, 44% elicited a 'don't know' response, and the remaining 8% elicited an incorrect response.

## ERP data

ERPs were formed for the same response categories as in experiment 4<sup>9</sup>. For associative recognition the mean number of trials contributing to the ERPs for each response category was 80 and 35 for new and recognised pairs respectively. For associative recall the mean number of trials were 79 and 34 for new and recalled pairs respectively.

Figure 23 shows the grand average waveforms obtained for the associative recognition task from all 25 electrode sites. The pattern of effects is similar to that found in experiment 4 (cf. figure 19), with the ERPs for recognised pairs more positive going than those for the new pairs. The positive shift is larger over the left than the right hemisphere at temporo-parietal electrodes, but initially exhibits a bilateral distribution at frontal electrodes. The left greater than right asymmetry over temporo-parietal sites remains present throughout the remainder of the recording epoch, whereas at frontal sites a right sided positivity can be seen from approximately 1400 msec post-stimulus onwards.

Figure 24 shows the equivalent grand average waveforms for associative recall. As was the case for the recognition data, over temporo-parietal electrodes the ERPs for the recalled items exhibit a positive going shift, with a left greater than right asymmetry. As in experiment 4, from approximately 900 msec this effect is replaced by a right-sided negative going effect, which continues until the remainder of the recording epoch. The pattern of effects found over frontal electrodes differs somewhat from that found in experiment 4 (cf. figure 20), in that there is little sign of the early frontal old/new effects. By contrast however, a late-onsetting, right frontal effect is clearly evident from approximately 1400 msec post-stimulus.

The magnitudes of the ERP old/new effects were analysed in the same way as those in experiment 4, employing the same electrode sites and latency regions as in that experiment (see table 17). Close examination of the old/new effects reveals that they appear to onset slightly earlier in experiment 5 than in experiment 4. Consequently, additional analyses were performed on the data from an earlier 400-600 msec latency

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<sup>9</sup> As in experiment 4, sufficient trials were available for the formation of ERP waveforms for 'rearranged' and 'don't know' responses. Again, these ERPs do not bear directly on the issue that this study was designed to address, and although the ERPs are not considered in detail, they are shown in appendix C.

region. The results of these analyses were consistent with those found for the subsequent 600-900 msec latency region and, because they do not alter the interpretation of the data, they are not reported in detail. Figure 25 illustrates the mean amplitude differences between the ERPs for old and new response categories, shown separately for each task and latency region.

**Table 17.** Results of the ANOVAs of the amplitude analyses, for each task, over each latency region. Only significant effects involving the factor of response category are reported. RC = Response Category (Old vs. New), HM = Hemisphere, ST = Electrode Site (Inferior vs. Mid-Lateral vs. Superior).

	<u>ASSOCIATIVE RECOGNITION</u>		
	<u>600-900 msec</u>	<u>900-1400 msec</u>	<u>1400-1900 msec</u>
<u>FRONTAL</u>			
RC	$F_{1,15} = 10.39, p < 0.01$	$F_{1,15} = 16.49, p = 0.001$	$F_{1,15} = 4.69, p < 0.05$
RC x HM	-	-	$F_{1,15} = 11.49, p < 0.005$
RC x ST	$F_{1,1,16.9} = 5.73, p < 0.05$	-	-
<u>PARIETAL</u>			
RC	$F_{1,15} = 14.93, p < 0.005$	-	-
RC x HM	$F_{1,15} = 10.14, p < 0.01$	$F_{1,15} = 9.96, p < 0.01$	-
RC x ST	$F_{1,1,16.6} = 18.59, p < 0.001$	-	-
	<u>ASSOCIATIVE RECALL</u>		
	<u>600-900 msec</u>	<u>900-1400 msec</u>	<u>1400-1900 msec</u>
<u>FRONTAL</u>			
RC x HM	-	-	$F_{1,15} = 20.23, p < 0.001$
<u>PARIETAL</u>			
RC x HM	$F_{1,15} = 26.81, p < 0.001$	$F_{1,15} = 33.02, p < 0.001$	$F_{1,15} = 6.48, p < 0.05$

#### Magnitude analyses

Associative Recognition: Table 17 shows the results of the ANOVA for associative recognition, revealing that significant frontal old/new effects were present for all three latency regions. Analysis of the data for the 600-900 msec latency region revealed a significant effect of response category and an interaction between category and site. As figure 25 shows, these effects reflect the presence of a bilaterally distributed old/new effect that increases in size as electrodes get closer to the midline. For the 900-1400 msec region the analysis produced a single significant effect, that of response category. Again, examination of figure 25 reveals the presence of an old/new effect that is bilaterally distributed across frontal scalp sites. Finally, the ANOVA for the 1400-1900 msec epoch revealed a significant interaction between response category and hemisphere. In contrast to the previous latency regions however, figure 25 reveals that

the frontal old/new effect in this latency regions exhibits a right greater than left asymmetry.

**Associative Recall:** Table 17 also shows the results of the analysis comparing the ERPs for recalled and new pairs. As figure 25 shows, the results confirm the impression gained from figure 24 that there are no significant frontal old/new effects for the 600-900 and 900-1400 msec latency regions (max  $F_s = 1.62$  and  $0.34$  respectively)<sup>10</sup>. By contrast, table 17 shows that the ANOVA for the 1400-1900 msec region revealed a significant interaction between response category and hemisphere. As figures 25 and 24 both indicate, this interaction is due to the presence of a right frontal old/new effect in this latency region.

#### **Topographic Analyses**

The scalp distributions of the old/new effects in each task were compared, employing the same procedure as in experiment 4. Figure 26 shows the scalp distributions of the old/new effects for each task over successive latency regions. Comparison of figures 26 and 22 reveals that the pattern of old/new effects found for the recognised pairs is very similar across experiments 4 and 5. Moreover, the pattern of effects found for the recalled pairs also appears to be very similar across experiments 4 and 5, despite the fact that the magnitude analyses revealed no evidence for reliable frontal old/new effects during the 600-900 and 900-1400 msec latency regions in experiment 5.

For the 600-900 and 900-1400 msec latency regions, comparisons of the old/new effects for recognition and recall failed to reveal any evidence of an interaction involving task and site in either the 25 site ANOVA or the planned ANOVA of the data from frontal electrodes ( $F_s < 1$ ). Thus, despite the absence of statistically significant frontal old/new effects in the ERPs for associative recall, there is no evidence that the distribution of effects differed across task. Similarly, for the 1400-1900 msec latency region, the analyses revealed no significant effects involving task and site ( $F_s < 2$ ). Importantly, the planned ANOVA of the data from frontal electrodes did reveal a significant main effect of hemisphere ( $F_{1,15} = 20.05$ ,  $p < 0.001$ ),

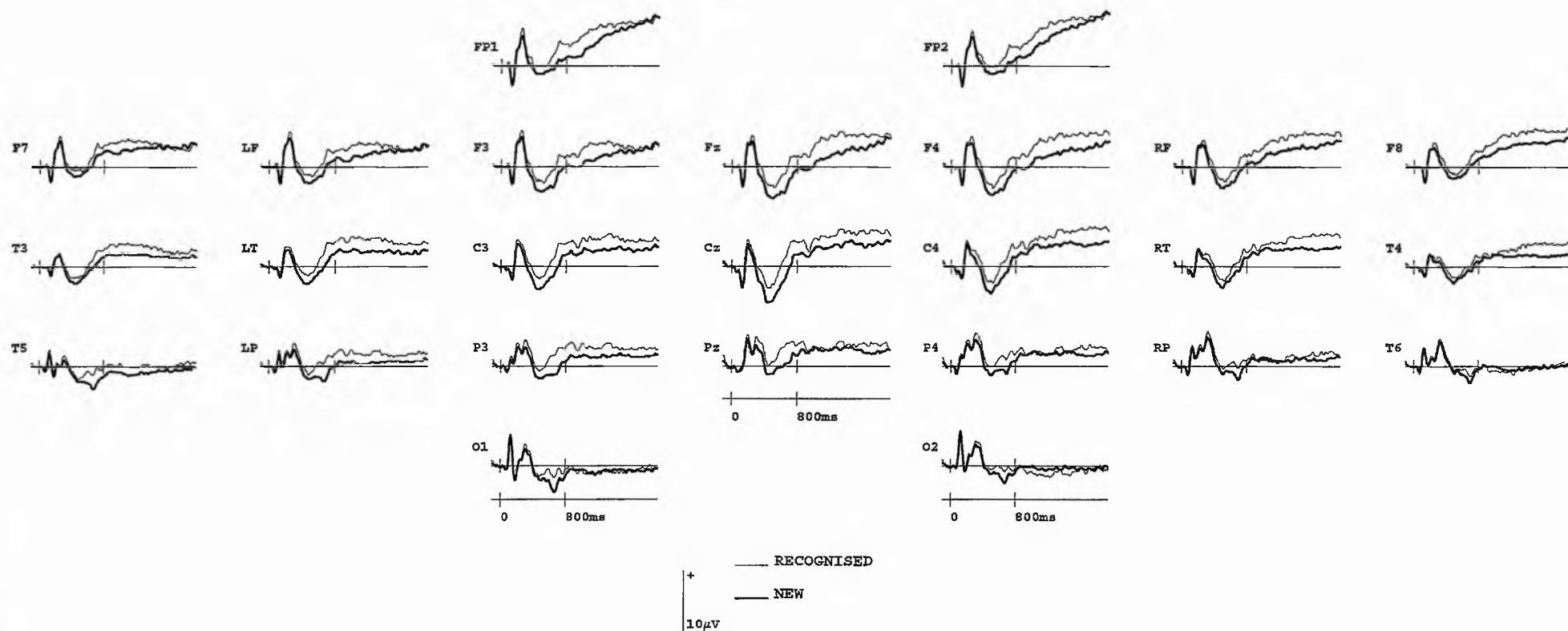
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<sup>10</sup> Examination of the ERPs for associative recall reveals a small and temporally restricted positive shift in the recalled waveform, an effect that is largest over Fz, and restricted to sites closest to the midline. Close examination of the data from Rugg et al. (1996) reveals a similar (in size, duration, and distribution) effect. However, as was the case in the data of Rugg et al., and the analyses reported in the results section here, targeted analyses (i.e., restricted to appropriate sites and time periods) failed to reveal evidence for a statistically significant frontal old/new effect.

reflecting the presence of a significant right frontal old/new effect for both tasks during this epoch (cf. Figure 26).

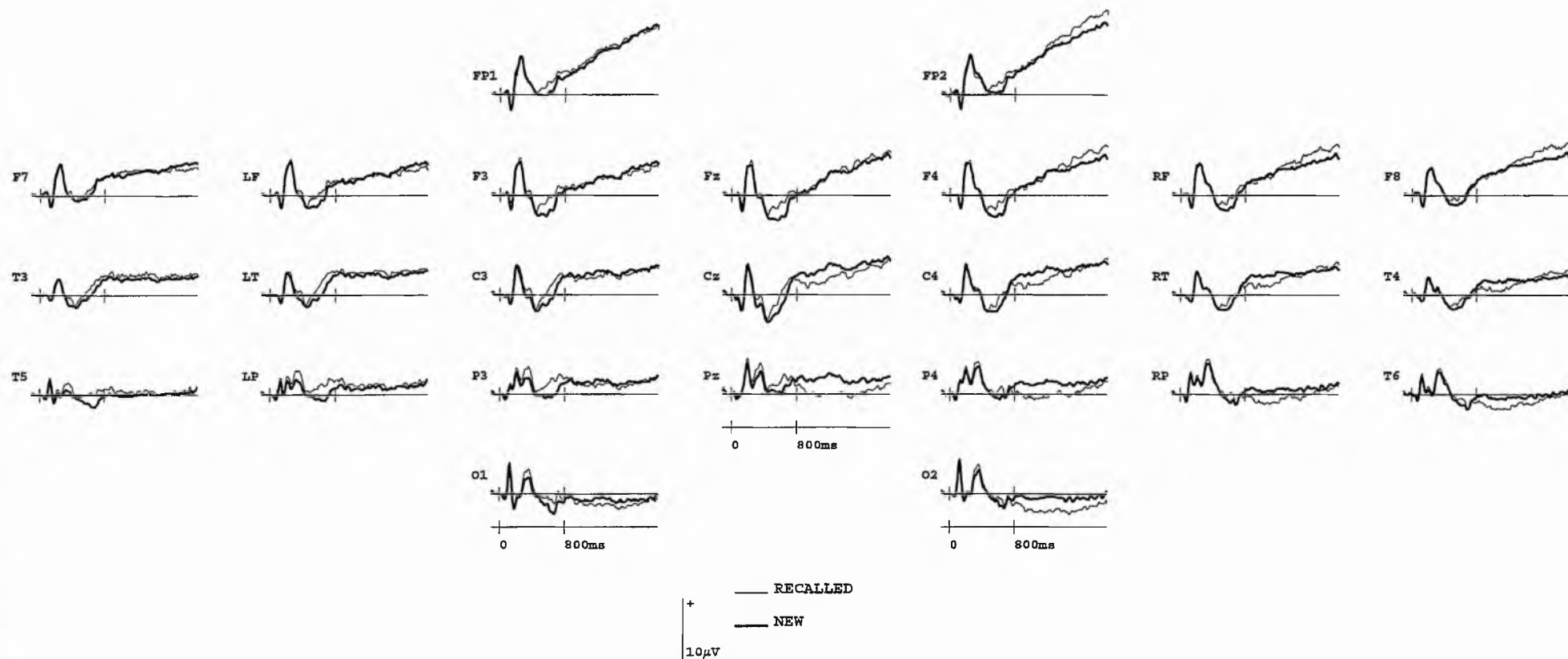
### **Summary of results**

Significant frontally distributed old/new effects were found in the ERPs for associative recognition during all 3 latency regions. The effect exhibited a bilateral distribution during the early 600-900 and 900-1400 msec epochs and a right-sided maximum during the later 1400-1900 msec epoch. By contrast, for associative recall significant frontal old/new effects were only found during the 1400-1900 msec epoch, exhibiting a right-sided maximum. Across task topographic analyses revealed no evidence that the scalp distribution of the old/new effects differed as a function of task in any latency region. These analyses did however confirm the presence of the right frontal old/new effect for both tasks during the 1400-1900 msec latency region.

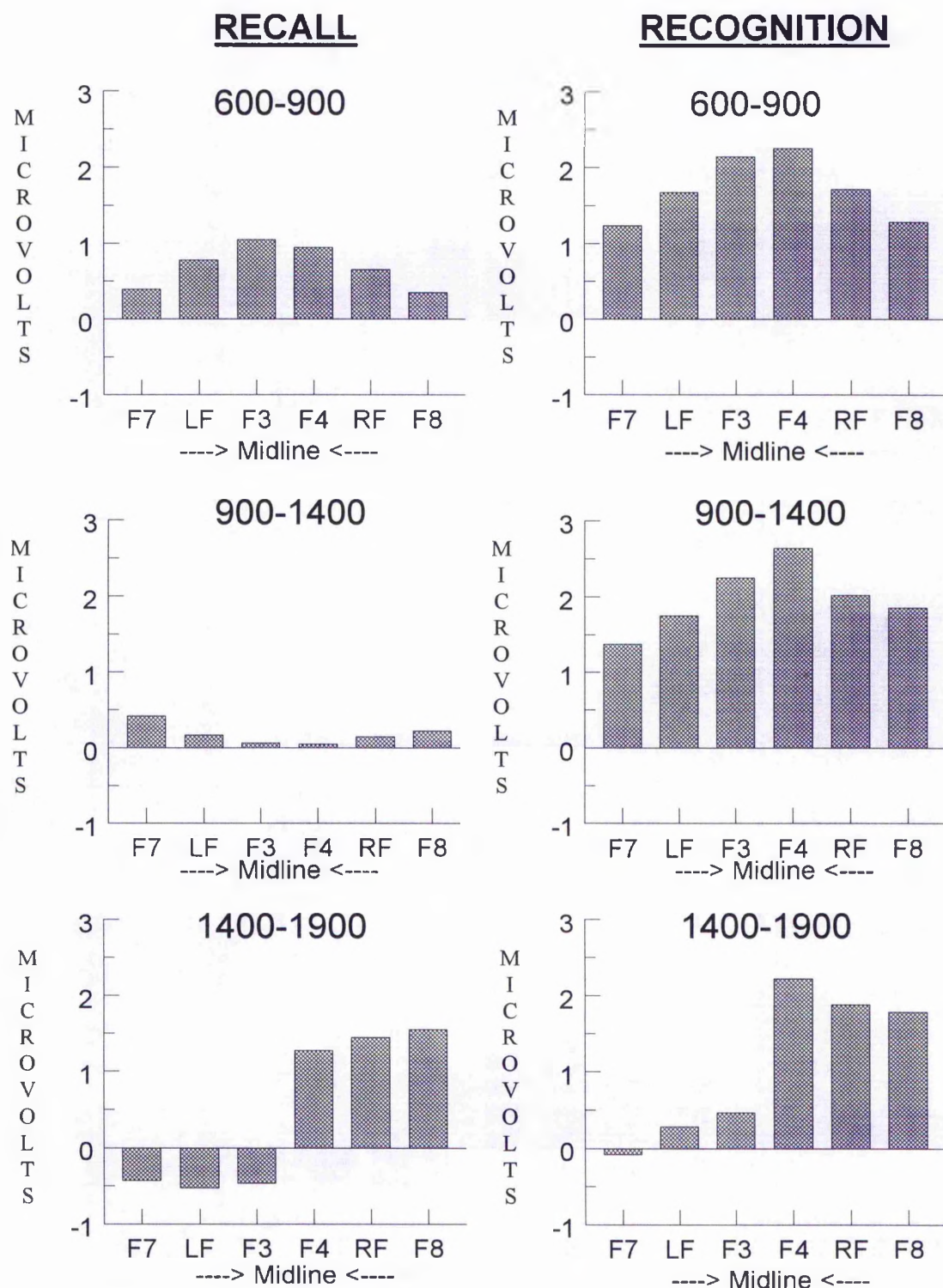


**Figures 23.** Experiment 5: Grand average ERPs for the recognised and new response categories for associative recognition. Scale bar and electrodes are shown as in figure 7.





**Figure 24.** Experiment 5: Grand average ERPs for the recalled and new response categories for associative recall. Scale bar and electrodes are shown as in figure 7.

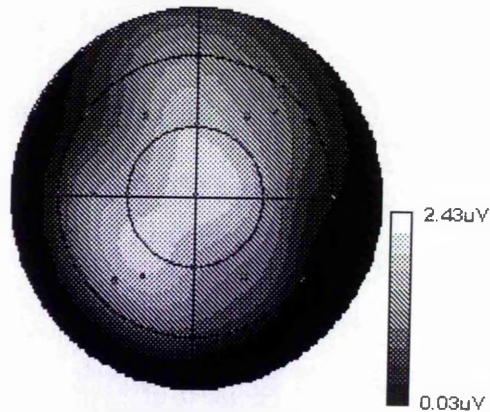


**Figure 25.** Experiment 5: Mean amplitudes of the difference between the ERPs for correct old and new responses, shown separately for recall (left column) and recognition (right column) during the 600-900 (top), 900-1400 (middle) and 1400-1900 (bottom) msec latency regions. Values are shown for the lateral frontal electrodes employed in the initial within task, within epoch, analyses. The data are shown for the left and right hemispheres, with sites arranged as on the head (inferior-to-superior on the left, superior-to-inferior on the right).

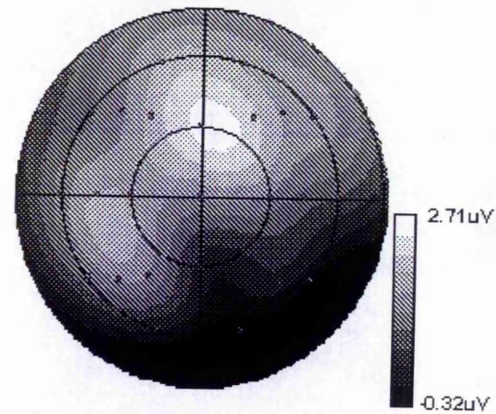


## RECOGNISED

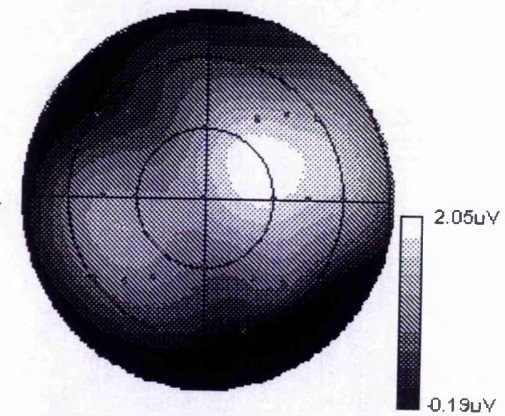
600-900 msec



900-1400 msec

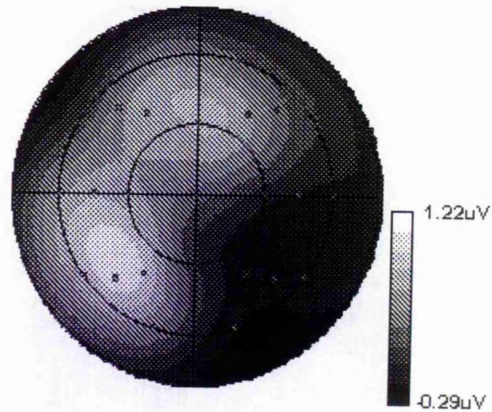


1400-1900 msec

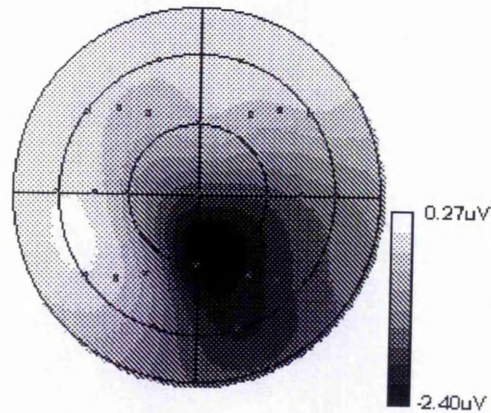


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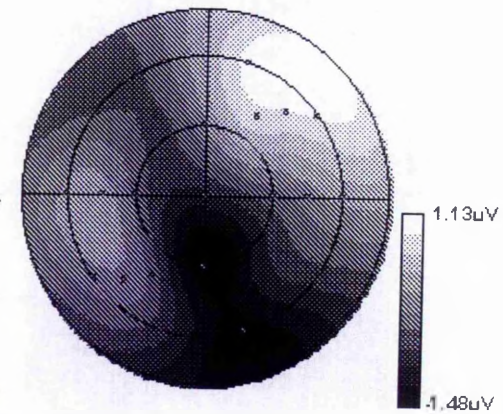
600-900 msec



900-1400 msec



1400-1900 msec



**Figure 26.** Experiment 5: Topographic maps of the scalp distribution of the old/new effects for associative recognition and associative recall, over the 600-900, 900-1400 and 1400-1900 msec latency regions. Scale bars and electrodes shown as in figure 10.

## DISCUSSION

Performance measures were similar to those found in experiment 4, both on the old/new recognition judgement and the subsequent associative recognition and recall components of each task. Looking first at the old/new judgement, performance was superior for the recognition task relative to the recall task. As was the case in experiment 4, this difference in recognition performance is likely due to the provision of two retrieval cues on each associative recognition trial, compared to the one cue on each associative recall trial. Performance levels on the second component of each task were virtually identical to those in experiment 4. For associative recognition, 90% of same pairs were recognised as such (compared to 91% in experiment 4). For associative recall, 48% of old items were correctly recalled (compared to 49% in experiment 4). It seems reasonable to assume therefore that the alteration from a randomised to blocked experimental design did not lead subjects to perform the tasks in a significantly different manner, and that, as in experiment 4, episodic recollection was the basis for performance on both tasks.

Turning to the ERP data, the pattern of old/new effects found for associative recognition closely resembled those found in experiment 4. Specifically, recognised pairs elicited sustained left parietal and frontal old/new effects, with the frontal effect developing from a bilateral to a right-sided distribution over the course of the recording epoch. As is clear from a comparison of figures 22 and 26, changing from a random to blocked design does not appear to have significantly influenced the ERP old/new effects correlated with successful associative recognition.

The critical question addressed by experiment 5 concerns the pattern of frontally distributed old/new effects for associative recall: were frontal old/new effects found in experiment 4 a result of the requirement to switch between tasks? With regard to the generators of the right frontal effect the answer is clear. As in experiment 4, a right frontal old/new effect was present in the ERPs from approximately 1400 msec post-stimulus (cf. Figure 24). Moreover, as in experiment 4, topographic analyses revealed no difference in the distribution of the effects for associative recognition and recall. Thus, the presence of the right frontal old/new effect in experiment 4 cannot be attributed to the use of a procedure that required subjects to switch between two tasks.

Rather, contrary to the conclusions of Rugg et al. (1996; and Allan et al., in press), but in support of the findings of experiment 4, successful associative recall does engage the generators of the right frontal old/new effect.

The present findings are less clear with regard to the generators of the earlier bilateral frontal effect however. Unlike in experiment 4, the right frontal old/new effect in successful recall was not preceded by a bilateral frontal old/new effect during the earlier 600-900 and 900-1400 msec latency regions (compare figures 20 and 24). However, whilst the present findings clearly differ from those of experiment 4, the data are remarkably similar to those from Rugg et al. (1996; see figure 5, chapter 3). In that study there was no evidence of significant frontal old/new effects, and because of the short recording epoch employed (terminating 1434 msec post-stimulus) the late right frontal old/new effect found in the present experiment would not have been seen by Rugg et al. Thus, the present findings are similar to those of Rugg et al. (1996), suggesting that, when associative recall is tested in isolation, successful performance does not elicit the early bilateral frontal old/new effect.

Rugg et al. (1996) interpreted the absence of a positive shift over frontal electrodes as evidence that the generators of the frontal old/new effect (they did not distinguish between bilateral and right-sided effects) were inactive in the case of associative recall. Whilst this explanation is attractive, not least because it is consistent with Rugg et al., it is difficult to draw this conclusion in the present case. If the generators of the early frontal old/new effect were selectively engaged by the recognition but not recall task, this would have been expected to result in a significant across-task difference in topography (cf. Chapter 4). However, there was no evidence that the scalp distribution of the old/new effects for recall and recognition differed during the 600-900 and 900-1400 msec latency regions. Notwithstanding the difficulties of drawing strong conclusions on the basis of the absence of a significant difference in topography (cf. Rugg and Coles, 1995), this finding is at least suggestive that the absence of the early frontal old/new effect reflects a quantitative rather than qualitative difference.

Tentative support for the above conclusion comes from several sources. First, the generators of the later right frontal old/new effect were clearly active in the present data, but the magnitude of this effect was smaller than in experiment 4 (compare figures 21 and 25). Thus, the absence of the early frontal effect may reflect little more

than the general attenuation of activity in experiment 5. Second, visual comparison of the topographic distribution of the old/new effects found in experiments 4 and 5 reveals similar frontally distributed maxima during the 600-900 and 900-1400 msec latency regions, despite the fact that significant positive going effects were only present in experiment 5 (compare figures 22 and 26). Finally, if the absence of the early bilateral frontal effect in the ERPs for recall does reflect a quantitative difference, this would suggest that the generators of the effect reflect processes that are selectively engaged by the requirement to switch between tasks on a trial by trial basis. However, it seems unlikely that such processes would be differentially sensitive to task switching in the case of recall but not recognition. In sum, although the present findings are somewhat ambiguous regarding the early bilateral frontal effect, the results confirm that the generators of the right frontal effect are engaged by successful associative recall, regardless of the requirement to switch between tasks.

## Chapter 11.

### INTERIM DISCUSSION 2

The ERP correlates of successful associative recognition and recall were compared under conditions where the factor of task was either a randomised or blocked variable (experiments 4 and 5 respectively). In both experiments item recognition (as indexed by accuracy on the initial old/new judgement) was superior for recognition than recall. As discussed previously this difference in performance can be accounted for in terms of the greater opportunity for retrieval that is provided by the provision of two words on every recognition trial, compared to one word on every recall trial (see Discussion to experiment 4).

In both experiments performance on the second component of each task was superior to that in previous studies, a difference that most likely reflects the use of shorter study lists in the present experiments (see the Discussion to experiment 4 for further details). More significantly, performance on each task was remarkably similar across experiments, suggesting that subjects were able to recollect a similar number of prior study episodes in each case (see Discussion of experiment 5).

The ERP findings for the associative recognition task were similar in experiments 4 and 5, and closely resembled those found previously (cf. experiment 1). Regardless of whether the recognition task was presented in isolation or randomly intermixed with

associative recall, successful associative recognition elicited sustained left parietal and frontally distributed old/new effects - the frontally distributed effect developing over time, from a bilateral to a right sided distribution (onsetting approximately 1400 msec post-stimulus). These findings provide further support for the results of experiments 1 to 3, confirming that successful associative recognition does engage the generators of the frontally distributed old/new effects.

Consistent with the findings of Rugg et al. (1996), in both experiments the ERPs for successful recall exhibited a small and temporally restricted left parietal old/new effect, developing into a right-sided negative going shift from approximately 900 msec post-stimulus. This slow negative going waveform has been seen in previous studies, most notably in a study of source memory by Wilding and Rugg (1997a), where the magnitude of the effect was found to increase with reaction time. The present findings do not elucidate the functional significance of this negative going effect per se. However, the absence of any topographic differences between the old/new effects in each task suggests that the generators of this negative going effect were equally active in both cases. Moreover, the relative prominence of the effect in the ERPs for successful recall is consistent with previous findings (cf. Rugg et al.; and experiment 1 in this thesis). Whilst reaction time data is not available in the present experiment, RTs would likely be longer for successful recall relative to those for recognition.

The central question addressed by experiments 4 and 5 was whether the generators of the right frontal old/new effect were active in the case of successful associative recall. In this respect the findings are clear; frontally distributed old/new effects were present in both experiments. In experiment 4 the frontal effects exhibited an initial bilateral distribution, becoming right-sided from approximately 1400 msec post-stimulus. A right-sided frontal old/new effect was also evident in experiment 5 from approximately 1400 msec post-stimulus, but the earlier bilaterally distributed positivity was not present.

The finding of a reliable right frontal effect for associative recall resolves the apparent inconsistency, noted in the Introduction to experiment 4, between the findings from experiments 1-3 of the present thesis, and those of Rugg et al. (1996). The present findings indicate that, contrary to the view of Rugg et al. (1996, see also Allan et al., in press), there is no reason to believe that associative recall fails to engage the processes



reflected by the right frontal old/new effect. Rather, as might be expected within the framework proposed by Koriat and Goldsmith (1996), associative recall, a task which would be expected to place a burden on post-retrieval processing at least as great as that of associative recognition, does indeed elicit the putative ERP index of such processing.

In both tasks, and in both experiments, the right frontal effect emerged somewhat later (at ca. 1300-1400 msec) than was observed in previous studies of either source memory (Wilding and Rugg, 1996; ca. 800-900 msec) or associative recognition (experiments 1-3; ca. 1000-1100 msec). There are several possible explanations for this delay. In the case of associative recall, the delay may simply be a consequence of the nature of the task, reflecting the additional time, relative to other kinds of task, required to retrieve episodic information. However, the finding that the right frontal effect was also relatively delayed in associative recognition suggests that this is not the whole story, and that other factors also played a role. One notable possibility comes from the fact that, unlike in the previous studies employing these tasks, responses to test items were withheld until 3 sec post stimulus offset. This delay between the presentation of the test item and response initiation may have resulted in the slower engagement of post-retrieval processing than when responding was speeded.

The findings from experiments 4 and 5 are less clear with regard to the early bilateral frontal old/new effect. When the two tasks were randomly intermixed the early bilateral effect was present in the ERPs for both tasks, but when the tasks were blocked the effect was present only for associative recognition. The present results are indeterminate, but suggest that the absence of the effect in experiment 5 reflects a quantitative rather than qualitative change across experiments (see discussion of experiment 5). This conclusion does not however address why the early bilateral frontal effect should be so sensitive to the manipulation of the experimental design, and moreover, why should it should be differentially affected in recall but not recognition? Unfortunately, limited progress has been made in understanding the functional significance of the early frontal activity. However, the present results suggest that the generators of this effect are especially sensitive to the context in which memory retrieval occurs.

The absence of the bilateral frontal effect in the ERPs for recall in experiment 5 does

not appear to be a reflection of differences in memory retrieval per se. As noted previously, the very similar levels of performance on the associative recall task in experiments 4 and 5 suggests that subjects were equally likely to recollect the prior study episode regardless of whether the design was randomised or blocked. Moreover, in both experiments a reliable left parietal old/new effect was present, evolving into a right-sided negativity from around 900 msec post-stimulus onset. Thus, as indexed both by the left parietal old/new effect (the putative index of recollection), and measures of behavioural performance, the likelihood of recollection appears to have been equivalent in experiments 4 and 5.

The foregoing discussion points towards a second possibility, that the magnitude of effects over frontal scalp simply reflects the influence of the posteriorly distributed response-related negativity (cf. Wilding and Rugg, 1997a). By this account, changes in the magnitude of the positive going shift over frontal scalp are attributable to the additive effect of changes in the magnitude of the negative going shift over temporo-parietal scalp. This explanation is unsatisfactory however, because the negative going wave is inversely related to response times. Although RT data are not available in the present experiment, it is reasonable to assume that response times would more likely decrease than increase as a result of the removal of the requirement to switch between task. Thus, any significant change in RT would be expected to reduce the size of the negative going wave, and thus lead to an increase (rather than decrease) in the size of the frontal effect. Consistent with the above account, comparison of the ERPs for recall in experiments 4 than 5 suggests that, if anything, the magnitude of the negative going component is somewhat smaller in the latter case.

Whatever the reason for the emergence of the early frontal effects in the present recall task, the findings add to the range of circumstances in which relatively early, bilateral or left-sided old/new effects have been observed over the frontal scalp (e.g., see experiments 1-3 in this thesis; Schloerscheidt and Rugg, 1997; Tendolkar, Doyle and Rugg, 1997; Wilding and Rugg, 1997a). To take just one example, Tendolkar et al. (1997) used the same associative recall task as was employed here, in an investigation of retroactive interference. Whilst they did not find any ERP effects associated with interference, successful recall was associated with the standard left parietal old/new effect, along with a positive going shift that was maximal over left-frontal electrodes.

Importantly, in this experiment the early frontal old/new effect onset prior to the left parietal effect, and moreover, was not accompanied by a later right frontal old/new effect.

It is presently unclear whether these early onsetting frontal effects reflect activity in the same neural generators that are responsible for the later right frontal effect, along with a contribution from additional (left-localised) generators, or whether instead the early effects reflect activity of an entirely separate generator population. Either way, given that the early effects have in two studies (Schloerscheidt and Rugg, 1997; Tendolkar, Doyle and Rugg, 1997) been found to onset earlier than the left parietal old/new effect (held to index the retrieval of episodic information), it seems unlikely that they can be encompassed by the 'post-retrieval' hypothesis put forward to account for the later-occurring, right frontal effect (e.g., Allan et al., in press; Rugg, Schloerscheidt and Mark, 1997; Wilding and Rugg, 1996). Rather, it would appear that these effects reflect processes that either initiate or support the process of episodic retrieval.

In summary, the present findings indicate that the recollection of associative information, whether in the context of associative recall or associative recognition, is accompanied by the right frontal ERP old/new effect, a putative index of 'post-retrieval' processing (Allan et al., in press; Wilding and Rugg, 1996). In demonstrating that the right frontal effect can be elicited during associative recall, the present studies extend the range of memory tasks in which this effect is observed. Moreover, in combination with recent findings (e.g., Tendolkar et al., 1997), the present data suggest that the frontally distributed old/new effect reflects neither a neurally nor a functionally homogeneous process, dissociating into two temporally and topographically distinct ERP components.

## **Chapter 12.**

### **GENERAL DISCUSSION**

Specific details of the behavioural and ERP findings from each experiment have been considered in the relevant discussion chapters. The present chapter provides a broader account, tying the results together, focusing on the significance of the findings for functional accounts of the ERP old/new effects, and highlighting important areas for future research. First, the empirical work will be briefly summarised, recapping the rationale for, and main results of each experiment. Second, each of the ERP old/new effects will be discussed, relating the present findings to previous work discussed in the earlier review chapters, and, where relevant, introducing more recent ERP findings. Finally, a more general proposal will be made concerning the functional significance of frontally distributed old/new effects, drawing on converging evidence from recent neuroimaging studies.

#### **Summary of experimental findings**

ERP studies of explicit memory retrieval suggest that successful recollection is associated with two temporally and topographically dissociable ERP old/new effects – the left parietal and right frontal effects, associated with retrieval and post-retrieval processes respectively. The experiments reported in the present thesis aimed to further

investigate the effects, by employing tests of associative memory (the retrieval of information about relations between study items) as a means of operationally defining recollection. In each experiment the encoding conditions were identical; subjects studied a series of novel word pairs. ERPs were recorded whilst subjects' memory for the word pairs was tested.

Experiment 1 employed an associative recognition test. Subjects were required to discriminate old from new word pairs, and for pairs judged old, to discriminate same from rearranged pairs. Relative to the ERPs for correctly rejected new pairs, the ERPs for successful recognised same pairs exhibited left parietal and right frontal old/new effects, similar to those seen in studies of source memory. The ERPs for the rearranged pairs exhibited smaller, but qualitatively similar, old/new effects, consistent with the suggestion that rearranged pairs are recollected less often than same pairs (cf. Yonelinas, 1997). Thus, in combination with previous behavioural studies of associative recognition, the findings of experiment 1 provided convergent evidence in support of the 'recollection' account of the ERP old/new effects. The findings suggested however, that the frontal old/new effect could be dissociated into two components, an early bilateral effect, and a later right-sided effect.

The results of experiment 1 suggest that successful associative recognition engages the generators of the left parietal and right frontal old/new effects. Experiment 2 was designed to remove a potentially serious confound (i.e., that it was possible that the ERP findings simply reflected the difference between recognising one versus two words) by replacing the new pairs with old-new pairs. The ERP findings from experiment 2 were similar to those from experiment 1 – successful associative recognition elicited left parietal and right frontal old/new effects. Although the findings were not identical to those from experiment 1 (primarily due to the use of a different ERP baseline), they were nonetheless consistent with the suggestion that the ERP effects reflected the successful retrieval of associative information.

Experiment 3 was designed to further investigate the functional characteristics of the right frontal old/new effect. Drawing on the fact that the right frontal effect is not seen in studies of item recognition, Wilding and Rugg (1996, 1997a) argued that the right frontal old/new effect reflects 'post-retrieval' processes. Specifically, processes associated with the requirement to strategically employ retrieved information in order

to discriminate between different classes of old item (a task demand imposed by the source judgement). This aspect of the 'post-retrieval' account of the right frontal effect was investigated.

The explicit requirement to strategically employ retrieved information was removed by requiring subjects to make old/new judgements, but not a subsequent associative recognition judgement. Although the old/new effects were smaller in size than those found in experiment 1, the left parietal and right frontal old/new effects were nonetheless present. In contrast to the findings of experiment 1 however, the frontal old/new effect did not exhibit an initial bilateral distribution, a fact that was attributed to the use of a single, rather than two stage, response (cf. Wilding and Rugg, 1997a). More significantly, the findings demonstrated that the explicit requirement to engage in strategic post-retrieval processing is not a necessary condition for the engagement of the generators of the right frontal old/new effect.

The findings from experiments 1 to 3 permitted a further conclusion to be drawn. As was discussed in chapter 2, Rugg et al. (1996) found that the right frontal old/new effect was not present in the ERPs for successful associative recall. The associative recall task employs the same study task as associative recognition, but at test subjects are required to discriminate single old from new items, and for items judged old, to report the study associate. Rugg et al. (1996; see also Allan et al., in press) accounted for the absence of the right frontal effect in the ERPs for this task, relative to source tasks, in terms of the nature of the information that is retrieved. The source memory tasks employed by Wilding and colleagues required the retrieval of extrinsic (common or background) information, whereas the associative recall task employed by Rugg et al. required the retrieval of intrinsic (unique or trial specific) information. However, the associative recognition task employed in experiments 1 to 3 also required the retrieval of intrinsic (rather than extrinsic) information, negating Rugg et al.'s account.

Thus, experiment 4 directly compared the ERP old/new effects for successful associative recognition and recall, attempting to resolve the discrepancy between the findings of experiments 1 to 3, and the conclusions of Rugg et al. (1996). A randomised experimental design was employed, with subjects switching between tasks on a trial by trial basis. Behavioural performance on both tasks was consistent with subjects having recollected a large proportion of prior study episodes. The ERPs for

successful associative recognition elicited left parietal and right frontal old/new effects, and as in experiment 1, the right frontal effect was initially bilaterally distributed. Contrary to the findings of Rugg et al. however, successful recall was associated with qualitatively similar old/new effects – including a frontally distributed effect that became increasingly right-sided with time.

Experiment 5 investigated whether the inconsistency between the findings of Rugg et al. and experiment 4 reflected the fact that, in the later case, subjects were required constantly to switch between tasks. To remove this requirement, experiment 5 compared associative recognition and recall, using a blocked experimental design. Once again, successful associative recognition elicited a sustained left parietal old/new effect, and a frontally distributed effect that became more right-sided over time. Moreover, the effects found for successful associative recall were similar to those seen in experiment 4, with the exception that the right frontal old/new effect onset around 1400 msec post-stimulus, and was not preceded by the earlier bilaterally distributed effect.

The results of experiment 5 resolved the apparent contradiction between the findings of experiment 4 and those of Rugg et al. (1996). The ERP findings for associative recall in experiment 5 were remarkably similar to those from Rugg et al. (1996) – because less electrodes and a shorter recording epoch were employed by Rugg et al., the late onsetting right frontal old/new effect could not be seen in their data. However, despite the absence of the early frontal old/new effect in the ERPs for recall in experiment 5, topographic analyses suggest that the absence of the effect likely reflects a quantitative rather than qualitative difference. Consistent with this suggestion, the magnitude of the later right frontal old/new effect was smaller. More important however, the right frontal old/new effect was clearly present in the ERPs for both tasks regardless of the requirement to switch between tasks.

### **Functional accounts of the ERP old/new effects**

The five experiments presented in the present thesis were specifically designed to investigate the functional significance of the ERP old/new effects. As is discussed below, the findings are broadly consistent with the suggestion that the left parietal and right frontal old/new effects reflect the operation of retrieval and post-retrieval

processes (respectively). However, the results further suggest that the right frontal old/new effect can be dissociated from an earlier frontal old/new effect, which cannot be accounted for in terms of a 'post-retrieval' hypothesis.

### **The left parietal old/new effect**

An impressive array of evidence (discussed in chapter 3; see Allan et al., in press, for a recent review) suggests that the left parietal old/new effect is associated with recollection – the retrieval of information about specific prior episodes – indexing the activity of the medial temporal lobe memory system. Studies of both item recognition and source memory suggest that the magnitude of the effect is sensitive to the degree or amount of information that is retrieved from memory, suggesting that recollection is a graded retrieval process (cf. Rugg et al., 1994, for detailed discussion).

### **An ERP correlate of 'recollection'**

As would be expected of a neural correlate of recollection, the left parietal effect was present in the ERPs for both successful associative recognition and recall. Moreover, in the studies of associative recognition, the magnitude of the effect was larger in the ERPs for recognised same than rearranged pairs, the former response category being more likely to elicit recollection than the later. The later finding is especially difficult to reconcile with the alternative account of the left parietal effect, i.e., that the effect is associated with familiarity (as discussed in chapter 3). If this were the case then the effect would have been expected to be of equivalent magnitude for the same and rearranged pairs; all of the items are old and should therefore be equally familiar. Thus, the present findings are consistent with the 'recollection' account of the left parietal old/new effect.

The significance of the present findings is particularly clear in relation to the rejection of single process 'global memory models' in favour of dual process theories of recognition memory (as discussed in chapter 1). The inability of the global memory models to account for the data from studies of item and associative recognition has been interpreted as evidence that performance on tests of item and associative recognition differ in terms of the information content and/or the retrieval processes engaged (cf. Clark and Gronlund, 1996; Gronlund and Ratcliff, 1993). Consistent with this proposal, dual process models suggest that associative recognition is dependent



upon recollection, and cannot be performed on the basis of familiarity, whereas item recognition is dependent upon both recollection and familiarity (cf. Yonelinas, 1997). Thus, the present findings converge with a range of evidence in suggesting that accurate associative recognition requires the recollection of prior study episodes, and cannot be accounted for in terms of familiarity.

The present ERP data are consistent with dual process accounts, which characterise recollection as being dependent upon the retrieval of contextual information, and thus support the suggestion that the processes supporting item and associative recognition differ in terms of the information content retrieved from memory. Unfortunately, the present findings are ambiguous with regard to the exact characterisation of the retrieval mechanism underlying recollection. The present findings do not distinguish between the two theoretical possibilities – that recollection is either a graded or an all-or-none process. Both accounts can be used to explain the graded nature of the left parietal effect, and the present data do not rule out one or other account. Ultimately, the resolution of this issue requires an analysis of ERP data at the level of the single trial, to establish whether the magnitude of the effect in the averaged ERP is representative of the magnitude of the effect in the individual trials (cf. Chapter 2).

Thus, the ERP findings do not resolve the question of whether dual process theorists are correct to distinguish between recollection and familiarity in terms of both the information content of retrieval and the retrieval mechanism employed. It is worth noting however, that at least one piece of evidence suggests that global memory theorists are correct in arguing for a distinction between information content and retrieval mechanism. Yonelinas and Jacoby (1996) investigated ‘non-criterial’ recollection – the retrieval of contextual information that is not relevant to explicit task demands. They found that, despite being contextual, such ‘non-criterial’ or task irrelevant information functioned as ‘familiarity’. That is, ‘non-criterial’ information was automatically retrieved and was associated with fast response times. Thus, different types of contextual information appear to reflect the operation of either a graded single detection process, or an all-or-none threshold process, depending upon whether the information is relevant to current task demands. Whether recollection and familiarity can, ultimately, only be defined in functional terms, remains to be seen.

The foregoing discussion of the left parietal effect as an index of recollection has focused upon how the present data relate to dual process models of recognition memory. However, the significance of the current findings can also be appreciated in terms of the neuroanatomical systems that support explicit memory. As was noted in chapter 3, neuroanatomical accounts of the left parietal old/new effect suggest that it provides an index of the cortical-hippocampal interactions that result from the retrieval-related activity of the medial temporal lobe memory system (cf. Wilding and Rugg, 1996). Assuming that this is the case, the present findings suggest that it is contextual or relational information that is of critical importance to the hippocampal memory system, rather than mere familiarity – evidenced by the fact that the generators of the left parietal effect are extremely sensitive to whether the relations between stimuli were maintained or broken between study and test.

Several authors (e.g., Cohen and Eichenbaum, 1992; Gaffan, 1994; Eichenbaum and Bunsey, 1995) have noted that associative memory tasks are the quintessential tests of episodic memory, and moreover, that one of the core functions of the medial temporal lobe memory system is to act as a 'relational' processor. As Tulving (1983) suggests, learning a word pair in a word association task is the experimental equivalent of learning about a complex episodic event. At test the subject does not simply remember information about isolated words, rather, it is the association or episodic relationship between the words that is remembered. Clearly, the present experiments were not designed to investigate the neural origins of the ERP old/new effects *per se*. However, the finding that the left parietal old/new effect is present in the ERPs for successful associative recognition and recall adds weight not only to the suggestion that the effect provides an ERP correlate of recollection, but also that the effect provides an indirect index of the activity of the medial temporal lobe memory system.

The significance of the present findings can be highlighted by examining three quite different investigations of episodic memory retrieval. First, strong support for the link between the medial temporal lobe memory system and the retrieval of associative or contextual information can be found in studies of scene specific memory in monkeys (Gaffan, 1994; see also Gaffan, 1996). Lesions to the fornix (a major output pathway for the hippocampal memory system, cf. Chapter 1) produce impairments in object discrimination learning, however, the impairment is heavily tied to the context in

which objects are presented. When objects are presented in background scenes that vary from trial to trial, lesioned monkeys exhibited no impairment in learning. By contrast, when objects are presented in unique background scenes, lesioned monkeys are severely impaired. Thus, it appears that fornix lesions do not cause a general impairment in object memory per se. Rather, such lesions produce a specific impairment in scene-specific object memory, where the unique relationship between the object and the scene has to be remembered (i.e., the object must be 'bound' with the background context). As Gaffan (1994) notes, scene specific memory in monkeys provides an analogue of human episodic memory because it requires the retrieval of trial unique information from specific learning episodes.

A second piece of evidence linking the medial temporal lobe memory system to the retrieval of 'bound' information comes from a study of false memory in amnesic patients. Kroll, Knight, Metcalfe, Wolf and Tulving (1996) employed a recognition memory task in which certain distracter (new) items presented at test were compounds or conjunctions of studied items (e.g., for study items FICTION and BUCKLE, it is possible to generate FICKLE as a distracter item). Significantly, Kroll et al. found that amnesic subjects (with left hippocampal damage) were likely to misclassify such distracter items as old, despite being able to correctly discriminate veridical old from new items. This finding provides evidence in support of the hypothesis that the hippocampal memory system is critically involved in binding the constituent features of an episode together. Damage to the hippocampus disrupts the normal process of binding, such that unrelated features or 'memory fragments' are retained without being appropriately bound together, leading to an inability to distinguish false conjunctions between the memory fragments.

Thirdly, evidence from studies of normal human subjects suggests that recollection is specifically associated with the retrieval of contextual information. Perfect, Mayes, Downes and Van Eijk (1996) employed the R/K procedure, and addressed the question of whether subjects are actually able to remember more contextual information when they make Remember responses, compared to when they make Know responses. Across five experiments, Perfect et al., found that subjects were able to accurately report information about all aspects of the spatiotemporal context (e.g., temporal order, spatial location and presentation font) in which Remembered items were experienced.

Know responses were associated with the retrieval of contextual information to some degree however, motivating Perfect et al. to suggest that the distinction between R and K responding may be one of degree rather than kind. Nonetheless, the data largely support the Remember/Know distinction, and indicate that Remember responses are specifically associated with the retrieval of contextual information.

Thus, in sum, it seems reasonable to conclude that the left parietal old/new effect provides an index of recollection, the retrieval of contextual information about specific prior study episodes. Moreover, the present findings converge with a range of evidence in suggesting that the neural systems underlying this form of memory retrieval are highly sensitive to the relations or associations that are formed between items in memory, not simply to the fact that the items are old.

Finally, it should be noted that recent attempts have been made to draw together dual process models of recognition memory and neuroanatomical accounts of the medial temporal lobe memory system. For example, based upon a review of 112 amnesics' subjects, Aggleton and Shaw (1996; see also Aggleton and Brown, in press) suggest that recollection is specifically associated with the hippocampus (and projections via the fornix to the diencephalon), whilst familiarity is dependent upon extra-hippocampal cortical regions (perirhinal and entorhinal cortex). By this account, highly localised damage to the hippocampus is likely to lead to a selective impairment in recollection based responding, whereas more widespread damage to the medial temporal lobes is likely to produce severe deficits in both recollection and familiarity. It remains to be seen whether current functional and neuroanatomical accounts of the left parietal old/new effect will be able to accommodate this form of neuroanatomical dual-process model.

#### **The duration of the left parietal effect**

One aspect of the experimental data has not been discussed previously. The left parietal old/new effect seen in the ERPs for successful associative recognition is considerably more sustained than in studies of item and source memory. Why should the effect be longer lasting in the ERPs for successful associative recognition? One possible explanation comes from Smith and Guster (1993), who argued that the duration of the effect is related to the length of study list employed. Smith and Guster's account is difficult to reconcile with the present data however. The duration of the left

parietal effect differed for same and rearranged pairs, despite the fact that they came from a single study list. Moreover, the duration of the effect was considerably longer for recognition than recall, yet both tasks involved the same number of studied items.

One other variable differentiates associative recognition; namely, the number of words presented to the subject during each test trial. Associative recognition test trials involve the presentation of two words, whereas associative recall, item and source memory all involve the presentation of just a single word. By this account, the left parietal effect is sensitive not only to the amount of information retrieved from memory, but also to the amount of information that is actually presented to subjects at test. Whilst this explanation is superficially attractive, it receives little support from two recent ERP studies.

A study of retroactive interference by Tendolkar et al. (1997) involved the presentation of word pairs, however, the left parietal effect declined towards the end of the recording epoch (1434 msec post-stimulus), considerably earlier than in the majority of the experiments reported here. Similarly, Schloerscheidt and Rugg (1997) compared the ERP correlates of recognition memory for words and pictures, and found similar left parietal effects for both classes of stimuli. If the duration of the effect was linked to the amount of information presented to subjects, then the effect would have been expected to be longer lasting in the ERPs for pictures – the more detailed, perceptually richer, retrieval cues.

The foregoing discussion suggests that the duration of the left parietal effect is not specifically related to either the nature of the information retrieved, or the amount of information presented to subjects as a retrieval cue. Unfortunately, the experiments reported in the present thesis were not designed to investigate this feature of the ERP old/new effects. Further investigation of the variables that influence the time course of the parietal effect would however be worthwhile; one possible line of enquiry is noted below, in relation to the negative-going shift<sup>11</sup>.

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11 It should be noted that, technically, differences in the duration of the left parietal effect could reflect little more than greater latency jitter here than in previous studies (M. D. Rugg, personal communication). As a crude check against this possibility the standard deviations of the reaction times in experiment 1 were compared to those from Wilding and Rugg's (1996) original study of source memory, and were found to be similar. This suggests that the present findings do not solely result from unusual variation in the onset of effects in the individual trials that compromise the averaged ERPs (cf. Chapter 2).

### **The late negative shift**

The ERPs for both associative recognition and recall elicited an additional component, a late onsetting negative shift, which onset at approximately 900 msec post-stimulus, and was broadly distributed over right hemisphere temporal-parietal electrodes. A similar effect has been found in previous studies of item and source memory (e.g., Rugg et al., 1995, Wilding and Rugg, 1997a,b). Notably, Wilding and Rugg (1997a), reported that the effect is dissociable from the left parietal effect, and is related to response factors – the amplitude of the negative shift co-varied with the mean RT to different classes of response category.

The present results are consistent with the suggestion that the effect is related to response time. Where RT data was available, the magnitude of the negative shift was found to be larger in the ERPs for rearranged than same pairs, the former class of response being associated with longer response times. Moreover, whilst RT data was not available in experiments 4 and 5, the negative shift was considerably more prominent in the ERPs for recall, the task that would be expected to elicit longer response times.

The late negative shift provides a potential explanation for the varying duration of the left parietal effect discussed above. Because of the overlapping time course and distribution of the two ERP effects it is possible that the frequently observed decline of the left parietal old/new effect reflects little more than the contribution to the ERPs of the late onsetting negative shift. Thus, the long duration of the left parietal effect in the ERPs for successful recognition may simply reflect the relative absence of the late onsetting negativity. This possibility is highly plausible. The topographic distribution of the old/new effects did not differ for same and rearranged pairs, despite the fact in the ERPs for the rearranged pairs the left parietal old/new effect was relatively short lived (being replaced by the negative going effect). Similarly, the topographic distribution of the old/new effects did not differ for successful recognition and recall, yet in the ERPs for successful recall the left parietal old/new effect was relatively short lived (again, being replaced by the negative going shift).

Unfortunately, while the duration of the left parietal old/new effect could be influenced by the negative going effect, the reverse is equally possible. That is, the relative prominence of the late negative going effect may be, in part, influenced by the size of

the parietal old/new effect. For example, Rugg, Schloerscheidt and Mark (in press) made precisely this claim in accounting for the findings from an ERP study comparing source memory and the 'remember/know' task. Nonetheless, contrary to their account, the pattern of response times was consistent with the aforementioned connection between the magnitude of the late negative shift and response-related factors.

At first sight the two accounts of the relationship between the left parietal effect and the late negative shift may appear to be equivalent (i.e., opposite sides of the same argument). However, the later account, that the magnitude of the negative shift is dependent upon the left parietal effect, provides no explanation for why the left parietal effect varies in duration. Unfortunately, there is no way to discriminate between these two possibilities. Further investigation of the relationship between the left parietal old/new effect and the late negative shift is clearly necessary. Although the two effects have been already been dissociated (the negative shift is present in the ERPs to false alarms and misses – response categories that do not elicit the left parietal effect), it would be of interest to characterise the functional role of the negative shift more precisely. If the late negative shift is closely related to response time, it may be possible to tease apart the two effects by systematically varying the response time available to subjects (e.g., using a response-deadline procedure). Ultimately however, it may be necessary to model the generators of the ERPs if one wishes to disambiguate the contribution of the individual effects to the overall pattern of activity recorded at the scalp.

### **The early frontal old/new effect**

As discussed previously, the present findings produce more definite conclusions regarding the frontally distributed old/new effect, suggesting that it is composed of two components, early and late frontal old/new effects (the later, right-sided frontal old/new effect is discussed in more detail below). In the present experiments the early frontal old/new effect onset at approximately the same time as the left parietal effect, and exhibited a bilateral distribution. This effect can be detected in the data from earlier studies of source memory (e.g., Wilding and Rugg, 1996, 1997a). Unlike in the present studies however, the early bilateral component could not be reliably isolated

from the later right frontal effect because of a possible interaction with the decline over time of the left parietal effect.

The time course of the early frontal effect in the present experiments makes it difficult to reconcile this effect with the 'post-retrieval' hypothesis that accounts for the later right-sided frontal effect. Further evidence in support of the distinction between early and late frontal old/new effects comes from recent studies of source memory (Wilding and Rugg, 1997b), retroactive interference (Tendolkar et al., 1997), and recognition memory for pictures (Schloerscheidt and Rugg, 1997). These studies suggest that under certain circumstances the early frontal effect may onset before the left parietal effect, adding weight to the suggestion that the effect cannot be encompassed by the 'post-retrieval' hypothesis. Rather, it seems more likely that the effect reflects processes that either initiate or support episodic memory retrieval<sup>12</sup>.

#### **An ERP correlate of 'familiarity'**

One specific proposal regarding the functional significance of the early frontal old/new effect comes from a recent study of item recognition by Rugg, Mark, Walla, Schloerscheidt, Birch and Allan (1998), employing a depth of processing manipulation at study. Rugg et al., found that recognised words were associated with an early (300-500 msec post-stimulus) bilaterally distributed frontal old/new effect, which was present in the ERPs for both deep and shallowly studied words, but was insensitive to the depth of processing manipulation. This bilateral frontal old/new effect was taken to provide an index of 'familiarity'. Consistent with this proposal, the bilaterally distributed effect was not found in the ERPs for unrecognised old words from the shallow condition. More significantly for present purposes, the bilateral frontal old/new effect was followed by a left parietal old/new effect (500-800 msec post-stimulus). However, the later effect was only present in the ERPs for recognised words that were deeply studied, and not for items that were shallowly studied. Thus, Rugg et al. proposed that shallowly studied items were recognised solely on the basis of the familiarity (reflected by the early bilateral frontal effect), whereas deeply studied items were associated with both familiarity and recollection (reflected by the later left parietal effect).



Whilst Rugg et al. provide a plausible account of the functional significance of the bilateral frontal old/new effect in their data, the interpretation rests on the assumption that depth of processing differentially influences recollection and familiarity based responding. Rugg and colleagues have criticised other authors for making similar assumption (e.g., see Allan et al., in press). However, support for this assumption comes from Gardiner, Java and Richardson-Klavehn (1996), who suggest that depth of processing selectively influences 'Remember' but not 'Know' responses (based on a review of studies employing the R/K procedure). Nonetheless, when the data are reanalysed using Jacoby's independent R/K model to provide an estimate at the processing level of analysis (cf. Chapter 1), the data suggest that depth of processing influences both recollection and familiarity based responding. This is significant, because if depth of processing does influence familiarity and recollection, Rugg et al.'s account of the early bilateral frontal effect becomes implausible. By this account, the neural correlates of both recollection and familiarity should have been modulated by the depth of processing manipulation.

The suggestion that the early bilateral frontal old/new effect reflects processes associated with familiarity is also difficult to reconcile with the present findings (assuming that the effects reflect the activity of equivalent generators). As noted above, same and rearranged pairs are equally familiar, thus the finding that the bilateral frontal old/new effect is larger in the ERPs to same than rearranged pairs is inconsistent with a familiarity account of this effect. Nonetheless, the absence of a neural correlate of familiarity might simply reflect the limited sensitivity of the technique, and should not be interpreted as strong evidence for the absence of such an effect per se (cf. Chapter 2; Allan et al., in press).

#### **Random versus blocked designs**

One feature of the frontal old/new effect is worth considering in more detail. The early bilateral effect was present in the ERPs for successful recall when the recall and recognition tasks were randomised, but was absent when the tasks were blocked. As has been discussed previously, this difference appears more likely to reflect a quantitative than qualitative difference in the activity of the generators of the effect.

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12 The interpretation presented here rests or falls upon the sufficiency of the recollection account of the left parietal effect reflects (M. D. Rugg, personal communication). Although future studies might undermine this

Either way, the difference in the ERPs indicates that the generators of this effect are not automatically engaged by the retrieval of episodic information. Moreover, the finding that the early frontal effect was differentially modulated in the ERPs to recall but not recognition adds weight to the suggestion that the effect is highly sensitive to the context in which retrieval occurs. This finding is important, contributing to evidence that the 'context' in which a task is performed (as defined by the difference between random and blocked experimental designs) can have a significant impact upon the neural correlates of memory retrieval.

A similar finding was reported in a recent study by Johnson, Nolde, Mather, Kounios, Schacter and Curran (1997), who investigated the ERP correlates of true and false memory using the Deese 'false memory' paradigm (Deese, 1959; Roediger and McDermott, 1995). Johnson et al. compared the ERP correlates of the correct recognition of old items with those for the false recognition of associatively related (but unstudied) lures, employing both blocked and random experimental designs. When test items were presented in separate blocks the ERPs associated with true and false recognition differed, especially over frontal electrode sites. By contrast, when the test items were randomly intermixed the difference between the ERPs to true and false memories was reduced. Johnson et al., suggested that the change from a random to blocked design forced subjects to perform the tasks in a different way. That is, subjects may have attempted to discriminate between genuine old items and lures on the basis of perceptual information in the blocked test, whereas in the random test performance could rely more upon semantic or conceptual information.

The results from the present studies converge with those of Johnson et al. in suggesting that the neural activity associated with performance on a memory task is sensitive to the context in which retrieval occurs. This is of particular significance in relation to neuroimaging studies employing PET (and until recently, fMRI) which have necessarily used blocked experimental designs (cf. Chapter 2). The neural correlates of performance in such studies need not necessarily correspond to the neural correlates that would have been found had a randomised experimental design been employed, as is more commonly employed in cognitive behavioural studies. As Johnson et al. (1997) note, it is not that one type of experimental design is better (i.e., more correct) than the

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account, there appears to be little reason for dismissing it given the current weight of evidence.

other, but that the context in which performance occurs must be taken into account when interpreting the results of neuroimaging experiments.

The significance of this finding can be illustrated by considering a recent PET study by Cabeza, Kapur, Craik, McIntosh, Houle and Tulving (1997), comparing associative cued-recognition and associative recall. They investigated the neural correlates of episodic memory retrieval, employing a blocked experimental design with three conditions. The initial presentation of novel word pairs as to-be-remembered items served as a baseline (reference) condition. An 'associative recall' condition involved the presentation of the first item from each old word pair, and required subjects to report the word's original study partner. An 'associative cued-recognition' condition also involved presenting the first item of each pair as a cue, alongside either the study partner or a novel (unstudied) lure, and required subjects to report any word that was the original study partner of a cue word.

Of central interest here is the finding that, relative to the baseline condition, the right prefrontal cortex was found to be active in both the recall and cued-recognition conditions, but that there was no difference in activity between the two retrieval conditions. However, the present findings demonstrate that the amount of neural activity associated with task performance may have been dependent upon the use of a blocked experimental design. Thus, although Cabeza et al. demonstrate the involvement of the prefrontal cortex in the retrieval of associative information, and therefore provide support for the assumption that frontally distributed ERP old/new effects reflect activity with the prefrontal cortex, conclusions drawn on the basis of the amount of prefrontal activation must be regarded as tentative.

### **The late right frontal old/new effect**

As discussed above, perhaps the most significant feature of the present studies is in their contribution to the dissociation of the late right frontal effect from the earlier bilateral component. The late right frontal old/new effect was first found in studies of source memory (Wilding and Rugg, 1996, 1997a), where it onset at approximately the same time as the left parietal effect. Interpretations of the effect have been in terms of post-retrieval support processes, rather than memory retrieval per se, however, the precise functional role of the right frontal old/new effect remains uncertain. The

present results have had an impact on functional accounts of the right frontal old/new effect, contributing to the refinement of several aspects of the original 'post-retrieval' hypothesis.

First, the present findings demonstrate that the right frontal effect is not confined to tasks such as source memory, where the correct response is dictated by the content of recollection. That is, the explicit requirement to engage in strategic discriminations between different classes of old item is not necessary for the engagement of the generators of the effect. Second, the present findings demonstrate that the information retrieved in tests of associative and source memory is sufficiently similar to engage equivalent post-retrieval processes. That is, the generators of the effect are not selectively engaged by the retrieval of specific forms of contextual information (i.e., intrinsic versus extrinsic to individual study episodes). Third, as was the case for the early bilateral frontal old/new effect, the neural generators of the right frontal old/new effect are, at least under certain circumstances, sensitive to the context in which memory retrieval occurs (as discussed above).

Notwithstanding the above issues, the properties of the right frontal old/new effect remain strongly characteristic of a post-retrieval process. Although the present studies suggest that the right frontal effect is a relatively obligatory correlate of the recollection of associative information, a study by Wilding and Rugg (1997a) suggests that it is not an obligatory correlate of the recollection of source information. In that study, the right frontal effect was present in the ERPs to old target but not old non-target items, however, as in the present experiments, this study did not demonstrate a qualitative difference in the engagement of the neural generators of the right frontal effect. Wilding and Rugg performed no topographic analyses, thus, it is possible that their findings simply reflect a quantitative change in the activity of the underlying neural generators. Nonetheless, the fact that under certain circumstances the right frontal effect has been found to onset very late in the recording epoch (e.g., as late as 1400 msec post-stimulus in experiment 5 for associative recall) favours a functional interpretation in terms of 'post-retrieval' support processes.

A more general conclusion can also be drawn from the present findings however, with regard to the data for successful associative recall in experiment 5. Rugg et al. interpreted the absence of frontal old/new effects in the ERPs for associative recall as

evidence that the generators of the effects were not active. However, although the ERP waveforms appear to be almost identical in the present and previous studies, it was not possible to draw a similar conclusion here. Rather, as discussed previously, the present findings appear more likely to reflect a quantitative (rather than qualitative) modulation of the activity of the underlying generators. More broadly, the present findings highlight the difficulty of drawing strong conclusions on the basis of a null result – the absence of a positive or negative shift in the ERP waveforms can easily be over-interpreted as evidence that the generators of that effect are not active. Unfortunately, in the case of ERP data, the absence of evidence is not necessarily equivalent to evidence of absence (cf. Chapter 2). The significance of the foregoing conclusion can be seen in relation to studies of item recognition.

The absence of a significant positive shift over frontal electrodes in the ERPs for item recognition was central to the conclusion that the generators of the right frontal old/new effect are selectively engaged by tests of source memory (cf. Wilding and Rugg, 1996). This argument is directly analogous to that of Rugg et al. (1996) with regard to the absence of the frontal effect in the ERPs for associative recall – an argument that the present findings illustrate cannot be safely drawn. It is perhaps unsurprising therefore, that recent evidence has revealed frontal old/new effects in standard tests of item recognition (e.g., see Allan and Rugg, 1997; Schloerscheidt and Rugg, 1997). Moreover converging evidence in support of the conclusion that item recognition is associated with the processes reflected by the frontal old/new effects can be found in the neuroimaging studies (discussed below), which have consistently shown that the prefrontal cortex is activated in studies of item recognition.

### **A proposal regarding the frontal old/new effects**

Although the present findings cannot provide a definitive account of the functional significance of the frontally distributed old/new effects, the general discussion seems an appropriate place to propose a possible, if somewhat speculative, account. The differences in the time course and distribution of the two frontally distributed old/new effects strongly suggests that they are unlikely to reflect functionally equivalent psychological processes. However, little progress has been made in elucidating the functional role of the early frontal old/new effect.

In a similar vein, Stuss, Eskes and Foster (1994) point out that neuropsychological research into the role of the frontal lobes in memory highlights the difficulty of defining the component processes of the frontal lobes, and dissociating general 'supervisory' functions from more 'central' aspects of memory. Nonetheless, there is a range of evidence that suggests damage to the frontal lobes is not associated with amnesia *per se* (i.e., as found in patients with damage to the medial temporal lobe or diencephalic regions). Rather, memory deficits found in frontal lobe patients appear to be associated with manipulating and organising to-be-remembered information, in the initiation or maintenance of retrieval strategies, and in the monitoring and verification of retrieved information. These are processes involved in elaborate and organised encoding and retrieval strategies, rather than with retrieval. Thus, the frontal lobes appear to play an important role in supporting episodic memory retrieval, in terms of the adoption of memory retrieval strategies, and in the operation of post-retrieval monitoring and control processes (e.g., see Moscovitch, 1992, 1995a; Shimamura, 1995; Shallice, 1988; Stuss and Benson, 1984; cf. Chapter 1).

Neuroimaging studies have provided firm evidence that performance on explicit memory tests is associated with neural activity in several regions of the brain, including posterior parietal cortex and the prefrontal cortex (e.g., Shallice, Fletcher, Frith, Grasby, Frackowiak and Dolan, 1994; for reviews see Buckner and Tulving, 1995; Cabeza and Nyberg, 1997; Fletcher, Frith and Rugg, 1997). The results from a range of studies have been summarised in the HERA (hemispheric encoding/retrieval asymmetry) model, which proposes that encoding relies primarily upon the left prefrontal cortex, whereas retrieval relies more upon the right prefrontal cortex. More specifically, it appears that explicit memory retrieval involves the activity of right prefrontal cortex in addition to the areas of left prefrontal cortex that are found to be active in studies of encoding. Thus, areas of left and right prefrontal cortex are often activated together, either bilaterally or with a right greater than left hemispheric asymmetry.

How do these findings relate to the frontally distributed ERP old/new effects? Wilding and Rugg (1997b) suggested that the two frontally distributed old/new effects reflect the activity of distinct neural circuits within the prefrontal cortex. Specifically, that the findings from neuroimaging studies provide converging evidence that the prefrontal

cortex may support multiple, functionally distinct, memory processes located in the left and right prefrontal cortex. Unfortunately, without the aid of modelling techniques it is impossible to determine the precise location of the neural generators of the effects. Thus, the aim here is not to attempt to tie the frontal old/new effects to specific regions of the prefrontal cortex. Rather, the emphasis is on functional comparisons, drawing on the findings from neuroimaging studies to suggest that the prefrontal cortex may be involved in supporting different stages of mnemonic processing. It is important to remember however, that the assumption that the frontal old/new effects reflect activity within the prefrontal cortex has not been tested directly.

Of central interest here is the finding that the prefrontal cortex has been associated with episodic retrieval in a number of studies, employing a variety of procedures (e.g., recognition and cued recall) and experimental materials (e.g., words, faces, objects and pictures). Significantly, debate exists over whether activation of the prefrontal cortex reflects 'retrieval effort' or 'retrieval success'. Retrieval effort refers to processes that are associated with the attempt to retrieve information from memory, regardless of whether the attempt to retrieve is successful<sup>13</sup>. By contrast, retrieval success refers to processes that are engaged when information is actually obtained from memory. Several studies have employed PET to investigate whether the prefrontal cortex is sensitive to retrieval effort or success using episodic memory tasks (e.g., Nyberg, Tulving, Habib, Nilsson, Kapur and Houle, 1995; Tulving et al., 1994; Schacter et al., 1996; Kapur et al., 1995; Rugg et al., 1996).

For example, Kapur et al. (1995) attempted to distinguish between retrieval effort and success by varying the number of old items that were presented to subjects at test. In the baseline (reference) condition subjects made a semantic categorisation judgement (living/nonliving) to a list of words. Subsequently, subjects were required to perform item recognition tests in two memory conditions. In the 'retrieval success' condition 85% of test items had been previously studied, such that subjects would attempt to retrieve and be successful in doing so. In the 'retrieval effort' condition only 15% of test items had been studied, such that subjects would attempt to retrieve, but would

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<sup>13</sup> Note that 'effort' is intended to imply the attempt or endeavour to retrieve, rather than the amount of exertion that subjects employ in trying to retrieve. Consequently, some authors have used the expression 'retrieval mode' as an alternative term. However, this term has been more closely associated with the idea of tonically maintained brain states, rather than the stimulus related brain activity measured in the ERP studies reported here.

have little success in doing so. Kapur et al. found that, relative to the semantic classification task, equivalent levels of right prefrontal activity was found in both the memory tasks, suggesting that the prefrontal activity reflected processes associated with retrieval effort rather than retrieval success.

A more recent study suggests that the activity of the right prefrontal cortex does vary as a function of whether retrieval is successful or unsuccessful. Rugg et al. (1996b) also manipulated the proportions of old and new items presented to subjects at test, but did so in manner that controlled for differences in retrieval effort. Subjects performed item recognition tests during 3 critical scanning conditions, whereby 80%, 20% or 0% of the items were old. Importantly, the critical scanning conditions were embedded within a test list in which, outside of the critical test conditions, 50% of the items were old. This procedure was intended to discourage subjects from noticing the variation in the proportion of old items, such that their retrieval effort would remain constant. Rugg et al. found that prefrontal activation co-varied with the proportion of old items, with greater activation in the 20% than 0% condition, and greater activation again in the 80% than 20% condition. Thus, this finding provides evidence that the prefrontal cortex supports processes that are engaged by successful memory retrieval.

In sum, the evidence from PET studies suggests that the prefrontal cortex may be activated in relation to both retrieval effort and retrieval success. Whilst the PET findings discussed above appear to be difficult to reconcile at first sight, they may in fact be complimentary. Although the findings of Rugg et al. (1996b) demonstrate that the prefrontal cortex is sensitive to retrieval success, they are in no way inconsistent with the earlier suggestion that the prefrontal cortex is sensitive to retrieval effort. Rather, as Fletcher et al. (1997, p10) note, "right prefrontal cortex is activated when there is an intention to retrieve episodic information, and that it is further activated when retrieval is successful."

The current proposal is that the temporal resolution of ERP data allows temporally overlapping (but possibly independent) retrieval support processes to be distinguished. As has been discussed previously, the characteristics of the late right frontal old/new effect, onsetting as late as 1400 msec post-stimulus in the case of experiment 5 in the present thesis, are clearly consistent with a post-retrieval function. By contrast, the early frontal effect has been found to onset prior to the left parietal old/new effect, the



putative index of processes associated with retrieval (cf. Tendolkar et al., 1997; Schloerscheidt and Rugg, 1997), making it unlikely to reflect post-retrieval processes. Rather, the early frontal old/new effect seems likely to reflect processes that either initiate or support the process of episodic retrieval. The ERP findings can therefore be interpreted as providing evidence that the prefrontal cortex plays a role in supporting strategic processes that are involved in both the effort to retrieve and in retrieval success. The high temporal resolution of the ERP data allows these processes to be distinguished in a way that is not possible using other neuroimaging methods. Thus, the findings from both ERP and neuroimaging studies provide convergent evidence that the activity of the prefrontal cortex is modulated both by retrieval effort and retrieval success, and that the frontal lobes play an important role in supporting the retrieval of episodic information from memory.

It might appear that the findings from the present and previous ERP studies address an issue that is not directly related to the debate over 'retrieval effort' versus 'retrieval success' in the neuroimaging literature. One possible objection is that in the studies where it has been found, the early frontal old/new effect has only been seen in the ERPs for successful performance. An ERP correlate of pre-retrieval strategic processes should however, be seen in the ERPs to response categories that are not associated with successful performance. Certainly, given that the frontal old/new effects reflect the ERP correlates of successful memory retrieval, they present convergent evidence in support of the finding that the prefrontal cortex is associated with retrieval success. However, just as the neural correlates of the post-retrieval strategic processes reflected in the late right frontal old/new effect co-occur with successful performance, it might be expected that the ERP correlates of pre-retrieval processes would also do so. Furthermore, it seems reasonable to argue on *a priori* grounds that retrieval success is likely to vary as a function of retrieval effort, and thus that the neural correlates of these processes might co-occur.

One attractive aspect of this proposal is that it provides a possible interpretation of the differential presence of the frontal old/new effects for associative recall in experiments 4 and 5 of the present thesis. The fact that the probability of successful retrieval was almost identical in both experiments suggests that the generators of the frontal effects can be modulated independently of retrieval success. It seems likely that changing

from a random to blocked experimental design may alter subjects performance by shifting the degree to which they employed the frontally mediated support strategies. An interpretation of the ERP data that does not distinguish between retrieval processes, and more general support processes, would have difficulty in accommodating these findings.

The distinction between retrieval effort and success has considerable heuristic value. For example, it allows the operational definitions of the component processes to be proposed, such that the processes can be experimentally investigated. Nonetheless, it remains to be seen whether the distinction is ultimately either complete or truly informative. Indeed, in interpreting the findings from a recent PET study, Rugg and colleagues (Rugg, Fletcher, Allan, Frith, Frackowiak and Dolan, in press) raise doubts over the utility or helpfulness of the distinction. As was suggested above, post-retrieval processes are likely to be engaged regardless of whether retrieved information actually corresponds to a veridical prior episode. Moreover, Rugg et al. (in press, p12) suggest that "these operations require the allocation of attentional resources, and hence cognitive effort." Thus, Rugg et al. suggest that elements of the retrieval effort and success hypotheses must be combined.

Notwithstanding the possibility that the distinction between retrieval effort and success may be ultimately unhelpful, the proposal presented here provides an account that is broadly consistent with the findings from both ERP and neuroimaging studies. The proposal remains to be tested however. To investigate the hypothesis that the frontal old/new effects reflect pre- and post- retrieval support processes, it is important to compare the ERP correlates for response categories that have been design to differ in relation to the strategies that subjects employ, whilst holding the likelihood that subjects successfully retrieve, and the contents of such retrieval, constant. One way in which this can be done would be to employ a single class of new (unstudied) items, for which subjects have been instructed to attempt (and/or expect) to retrieve different types of information. If subjects were able to perform the task with and without recourse to the use of strategic processes (associated with either initiating retrieval, or in monitoring and evaluating the products of retrieval), then the extent of prefrontal activity would be expected to vary, despite the fact that veridical successful retrieval could, by definition, not occur.

## Summary

The present findings provide a significant contribution to current understanding of the ERP correlates of episodic memory retrieval. Whilst supporting the previous functional accounts of the left parietal and right frontal old/new effects, the findings suggest that the right frontal old/new effect can be dissociated from an early bilaterally distributed frontal old/new effect. The time course and functional characteristics of this effect appear likely to reflect strategic processes that initiate and support the act of retrieval.

The present findings also highlight broader issues. The demonstration that the ERP correlates of retrieval are sensitive to the use of a random versus blocked design suggests that researchers must be cautious in interpreting neuroimaging data as a direct or straightforward index of the neural correlates of cognitive processes. More significant perhaps, the suggestion that the successful memory performance is associated with multiple dissociable ERP components provides support for the view that memory retrieval is an active, multi-component process. Although dual process models of recognition memory represent recollection as a unitary process, the neurologically inspired view presented here proposes that a network of brain regions is involved in supporting recollection. By this view, recollection is neither a neurally nor a functionally homogeneous process.

As Baddeley (1985) notes, the concept of recollection as an active search and retrieval process has become peripheral to an essentially passive interpretation, whereby retrieval is simply seen as dependent on the presentation of appropriate cues. However, whilst the automatic aspects of retrieval are important, they only provide a partial account. If retrieval is an active process, memory may be triggered not just by appropriate stimulus cues, but also by actively setting up plausible retrieval cues for oneself. Equally, some form of checking procedure must occur, because not every retrieved memory will be either veridical or appropriate. By this view recollection is an active process of iteratively generating prospective retrieval cues and evaluating the output from memory.

The view of memory described by Baddeley fits well with the correspondence metaphor of memory (discussed in chapter 1). Rather than characterising memory retrieval as a passive process, it is proposed that memory retrieval is a constructive

process that involves strategic support process both before and after information is actually retrieved from memory. The cognitive neuroscience approach to memory described within this thesis provides support for the idea that memory retrieval is an active, multi-component process. Neuropsychological evidence suggests that the medial temporal lobe memory system plays a central role in supporting episodic memory retrieval, but as Moscovitch and Melo (1997, p1030) point out, “memory begins and ends with the frontal lobes.”

## APPENDIX A

Appendix A contains the word pool from which word lists were generated (the procedures used to create study-test lists are provided in the relevant methods sections for each experiment). The words were selected from the Francis and Kucera corpus (Francis and Kucera, 1982), with the criteria that they medium frequency (mean 19.1 per million, range 10 to 30 per million) nouns and verbs that were between 4 and 8 letters in length.

RUMOUR	INVADE	INSPECT	DEED
CHOKE	PRETEND	BENEFIT	HALF
AIDE	SUICIDE	FOLIAGE	FREE
REPAIR	CLIMATE	WRECK	SEGMENT
WALNUT	NEGLECT	DIAGRAM	CLUE
BULL	CURRENT	LOAD	CIRCUIT
ELBOW	ECHO	WHITE	STUFF
LICK	MINGLE	LENS	SWITCH
LOGIC	SHAVE	PUZZLE	COLD
STEAM	TRACT	SITUATE	OUTSET
STRIDE	DENOTE	DRAFT	RISK
BEHALF	PREACH	TITLE	MISLEAD
ARCH	GLIMPSE	DIET	SALOON
TERRACE	STAMP	BUNDLE	REFUSAL
CHART	TUNE	DISRUPT	FLAME
ORGAN	RENT	TOLL	COMPASS
AVERAGE	SHIP	BRICK	BISHOP
COPE	BASTARD	MERGER	MARE
DOUGH	SCOPE	GARAGE	TESTING
VIRGIN	NATIVE	CAKE	PREMISE
TUMOUR	AWAKE	WEAVE	SPHERE
DONATE	SCRATCH	GENIUS	SILVER

CRIPPLE	PLEAD	POTATO	SWALLOW
SPONSOR	SAMPLE	VANISH	HEAL
LINK	PURSE	ADJOIN	CANYON
LUXURY	FERRY	FOCUS	PERTAIN
FRIEZE	CONSENT	TOAST	FASHION
CLOCK	MISERY	DILEMMA	REALM
DRAWER	HEATER	LECTURE	JUNGLE
PLANT	MATE	ESSENCE	COMBAT
BEARING	VACUUM	MAJOR	ASSESS
COTTAGE	PROFESS	CANDY	BLAST
ALERT	TASTE	ACID	MINIMUM
PROTEST	EMBODY	RESENT	CULT
LINGER	PINE	BLOW	PIPE
CHARITY	REGIME	SIXTY	LAYMAN
COOK	SUMMARY	AUGMENT	WOUND
QUARREL	TRAY	SWEAT	FOLK
BLACK	TRACE	URGENCY	CAFE
HARASS	PROFILE	STALL	PICKET
OFFER	EPISODE	MAGIC	DRIFT
DEPICT	HUNGER	REWARD	SCAN
NOON	SPRAY	LOBBY	DESPISE
INJECT	FORBID	RESORT	CHEER
SPUR	ROAR	ANCHOR	PROGRAM
HYMN	ALARM	MAGNIFY	DESPAIR
WIND	TOTAL	PACE	GHETTO
CONVEY	PENSION	VITAMIN	TRIBE
VERIFY	RANCHER	PAVE	DOORWAY
SLUM	CRASH	CHERISH	PAINT
ARRAY	AFFIRM	DEMON	MIST
PERSIST	GIANT	CHIP	OUTFIT
SLEEVE	RITUAL	TANK	SITTER
RESCUE	DEPRESS	FAULT	RUBBER
CYCLE	BOWL	METER	INFEST
COUPLE	GLOBE	LIVER	PIGMENT
MERIT	SHEEP	BULK	VENTURE
RETREAT	MONK	CANE	BOOST
MURMUR	DEPOSIT	BEAT	DICTATE
GHOST	TUMBLE	SNATCH	TREATY
STAKE	TUNNEL	TERM	BITE

CURL	PLOT	ANKLE	LANE
HATRED	LEMON	BANKER	SWING
UPSET	TRICK	NUMBER	GRIN
USAGE	MUTUAL	INVOKE	GREASE
MAKING	DELIGHT	GAIETY	LAMB
LOCK	POLL	TILE	GREEN
FEVER	REVOLVE	DUKE	DESCEND
ARREST	LESSEN	GAMBLE	SOAK
FLAT	FRAME	THRUST	EQUAL
COMPLY	MORTAR	LANDING	AUTUMN
DUMP	SCREW	ENHANCE	TOBACCO
PICKUP	TRIBUNE	THUMB	FURY
MIRROR	DRUM	REUNION	BORE
CANCER	BALLOON	SAVING	FISH
HERD	FLOOD	ENTAIL	DEFECT
COMPEL	MARCH	BOSS	PITCH
WANT	DETECT	WARD	APPLAUD
ROBE	AIRPORT	CHAPEL	DIALECT
FINISH	ASSAULT	COPPER	DAZZLE
BECKON	MORALE	ANALOGY	APPEAL
MILL	STATUE	CAPITOL	BLUFF
HAIL	CLARIFY	SLIDE	NOTIFY
COMFORT	VIOLATE	GLOW	DWELL
FREIGHT	REFINE	PLUNGE	WARNING
SEAL	DENTIST	CROSS	BATTERY
BARGAIN	PUMP	SHAME	NAIL
THREAD	CARVE	FEATHER	SOFTEN
ENSUE	PROMPT	WASH	MIDST
SPREAD	DECENCY	GOWN	LABEL
SPAN	EXTRACT	BASKET	ARRIVAL
WHIP	OBJECT	CAST	REBEL
MINE	DAMAGE	CAVE	LOYALTY
CONFIDE	DOMAIN	NEAR	DISMISS
ATTIC	CONFESS	KNIGHT	LEVEL
HEADING	PLASTER	EXPORT	PAUSE
CRUSH	STAY	COMMUTE	CREEP
JAIL	MATCH	PARADE	BUTTON
DECLINE	PROVOKE	BREAK	EARNING
WORTH	RAGE	SAILOR	DAIRY

GUIDE	SPELL	PACK	SUBDUE
SHORTEN	EXCESS	DARKEN	BOUND
RATE	CHEW	NARROW	DIAMOND
RIDER	MARGIN	WATER	SKIRT
BREED	HOLD	MOLD	EVOKE
DEPRIVE	SETTLER	INTENT	PORK
TIDE	GROVE	WEALTH	INFLECT
CONFER	PULL	WRONG	FRINGE
PIANIST	REVERSE	DELAY	ZONE
CONFORM	TAXI	PATRON	COMING
OVERLAP	BOOT	FOIL	TENT
COIN	INFANT	FROWN	CROWN
SLAP	COWBOY	TOMB	PROBE
MURDER	RAILWAY	EMBRACE	MOTIF
CUSTOM	CURTAIN	FANTASY	KILLER
RIBBON	LADDER	PRESUME	ENACT
HEAP	TRIM	GLORY	SUBJECT
STACK	BUTTER	GUARD	POVERTY
ESCAPE	CORRECT	MENACE	NEST
TACTIC	FULFILL	CALF	CAPE
TIMBER	SHIVER	MERCY	TOWER
NOVELTY	HOLIDAY	EMBASSY	HANDLE
AROUSE	GULF	AMAZE	PILL
SPIT	PLUG	EMPTY	RECOVER
SIGH	HARVEST	PROLONG	VIGOR
CHAOS	JOINT	PILE	FOSTER
OUTSIDE	SHOP	BOAST	ENTITY
LION	POLISH	CONTEND	SPOT
MARBLE	FEATURE	SLIP	DRAIN
DESERT	PERMIT	FLAG	THRIVE
INSERT	EXHIBIT	FORTUNE	MAIL
ELITE	BARRIER	SOUP	MUTTER
WIRE	DISPOSE	TRANSIT	DESTINY
CHILL	CREATOR	PHYSICS	SWAY
BARK	TURMOIL	ATHLETE	AWARD
BLOOM	FAME	SURPLUS	EXHAUST
LIVING	WARM	GARMENT	TEMPER
SMASH	SHERIFF	IMPAIR	ESCORT
POST	VENT	NUCLEUS	ASSET



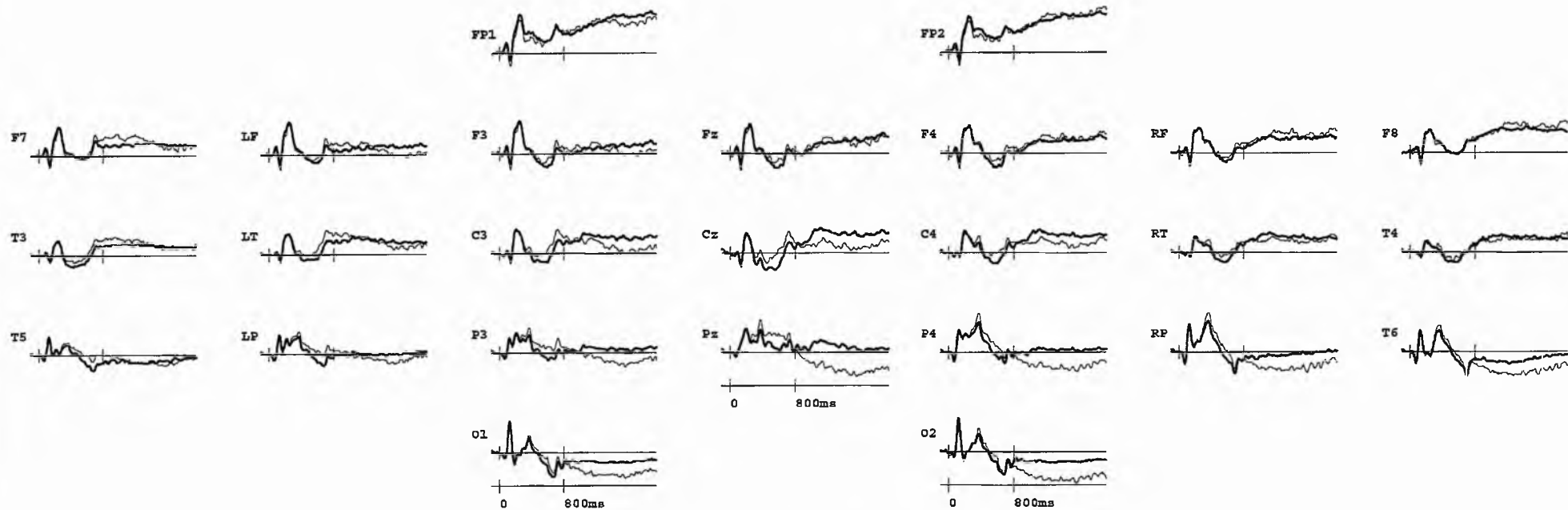
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TEXTURE	CONCEAL	REVIVE	SURGE
RUSH	COCKPIT	SADDLE	BALLAD
TILT	PORT	STOVE	ROTATE
PLAIN	HURRY	RENEW	SURVEY
HIGH	IMPORT	ORANGE	STROKE
SOLID	WEEP	RECKON	EXCITE
EXCLAIM	DESCENT	WAVE	ANALYST
SHOCK	TRAP	DISLIKE	LONG
DISORDER	THIGH	CLOSE	CURE
SHAFT	ENQUIRE	CURSE	BRAND
STREAM	DEAN	CHORD	BOIL
EQUALITY	ILLNESS	EMPEROR	CLING
EXCLUDE	LAWN	OBLIGE	ENROLL
ROUTINE	CREEK	SCAR	INHERIT
PRAISE	DRUNK	SLOW	TENNIS
CREAM	LAUGH	PUNISH	CREDIT
HANDFUL	CARPET	PANIC	DOME
DEPART	TWIST	COLLAR	GRIP
SWORD	RELY	BELL	DISTORT
KICK	EXPLORE	STRETCH	LATTER
SMOKE	ENCLOSE	MOCK	YIELD
WARRANT	VALUE	DAWN	BROADEN
VINE	SUCK	WRAP	STARTLE
ODOR	SPRAWL	ORIENT	FACET
PEEL	DISPEL	IRONY	SQUEEZE
HURL	ESSAY	PATRIOT	DUCK
REPEL	FUEL	CANVAS	FASTEN
AMATEUR	CONFINE	EXPLODE	RAID
ROOT	CARRIER	BUNCH	ETHIC
ALCOHOL	ALLEGE	REAR	ADVISER
REMEDY	SLUG	RUIN	PEAK
LEISURE	MENTION	SMELL	REQUEST
BRANCH	EXERT	FEEL	STRIP
PERFUME	ROPE	AUNT	QUIT
DOING	WAGE	PRINT	PASTURE
DOLL	FLEET	DISABLE	CALM
EDGE	GRAVE	THIEF	UPHOLD
APPLE	ACHE	CONVICT	CHORUS

WIDEN	CHARM	BREEZE	LEAVE
FATIGUE	ROCK	SKIP	UNIFY
DOUBLE	SEWAGE	CANDLE	CLUSTER
STRIVE	PACKAGE	ALLY	LOOM
PERIL	PEASANT	SEAM	VEIL
SHIRT	FLASH	VITALITY	INCUR
MOUSE	PREMIUM	DOUBT	DEPUTY
MASTER	TICKET	TIME	INSIDE
REACH	SLAM	REGRET	GRIEF
HORROR	DEFEAT	RESIDE	PRIVACY
HONEY	FIGHTER	GAZE	GRASP
STEER	CLEANER	DEBATE	BURY
CABIN	INVENT	COUNSEL	DIVORCE
SINGLE	REALISM	REFUND	RABBIT
BLAME	RULER	TESTIFY	CAVALRY
SHRINK	RECRUIT	DISCARD	ELEVATE
DROWN	NEEDLE	EXPLOIT	EXPEND
MESS	SMOOTH	DECAY	SLASH
GAUGE	WELL	JOKE	EXCUSE
WANDER	PRAY	WORRY	INDUCE
LYRIC	EVEN	DEBT	FLOAT
INDULGE	STRAW	SUMMON	BOUNCE
HUNTER	DASH	BLESS	EDIT
RIDGE	MODIFY	JERK	DRILL
CROUCH	VESSEL	DETACH	SHED
OMIT	BLEED	WIDOW	CONTENT
SPOIL	SHELF	WHEEL	LINE
BUSH	SECTOR	TERROR	HOUSING
TOILET	BAKE	ROUND	GEAR
MOURN	CHORE	AMUSE	MIRACLE
MODE	STAIN	BLADE	CRACK
MINERAL	HALT	NURSE	DOSE
BASS	AWAIT	ORBIT	KINGDOM
PIONEER	CONTOUR	DEFY	VICE
SPRING	STAGGER	KNEEL	PLOW
EXECUTE	SWELL	RAIL	LEATHER
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BREAST	TOWEL	PALM	PENALTY

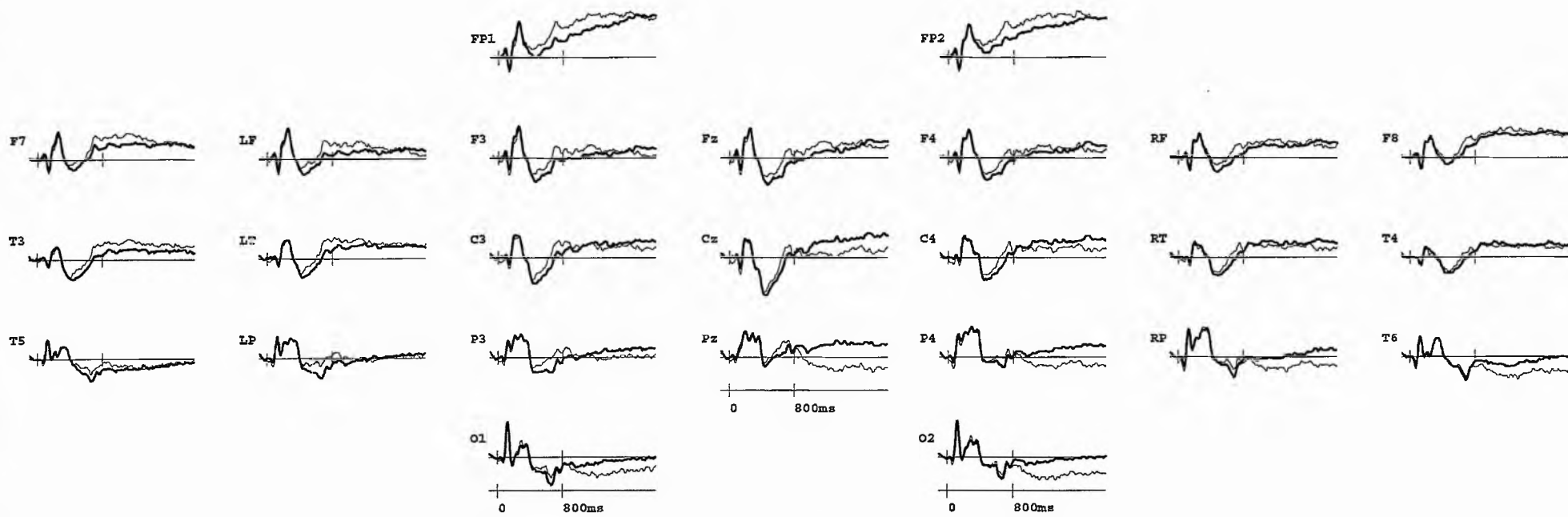
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ARROW	SORT
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CONSUME	WITCH
PRESIDE	ROLL
OUTLET	ALLOT
VOTER	INJURE
SQUARE	CURB
HARM	LOOP
TYPE	FADE
FOLD	ROSE
PURITY	CHIN
STREAK	HINT
TWIN	SPEED
CELLAR	GOSSIP
ENLIST	CANCEL
SCRIPT	PATCH
RACE	FURTHER
GUITAR	CRUELTY
SLOPE	UNLOCK
RAIN	DENIAL
INCLINE	DECK
SCRAP	QUEST
TOPIC	DEVISE
RICE	STOOP
RITE	RESTORE
SHATTER	KNIT
DRAPE	
SCATTER	
BROOD	
AUTO	
UNLOAD	
HASTEN	
PICNIC	

## APPENDIX B

Appendix B contains figures of the additional grandaverage ERPs from experiment 4, for the recognition and recall tasks. The ERPs to these response categories do not bear directly on the issue that the experiment was designed to address, and thus are not considered in detail. The ERPs are shown separately for each task, with the appropriate 'new' response category (the correct rejection baseline). For associative recognition, ERPs were formed for 'rearranged' responses (i.e., to rearranged pairs that were both recognised and correctly classified as being rearranged). For associative recall ERPs were formed for 'don't know' responses (i.e., old words for which the studied associate could not be correctly recalled). The waveforms are shown from all 25 recording sites.



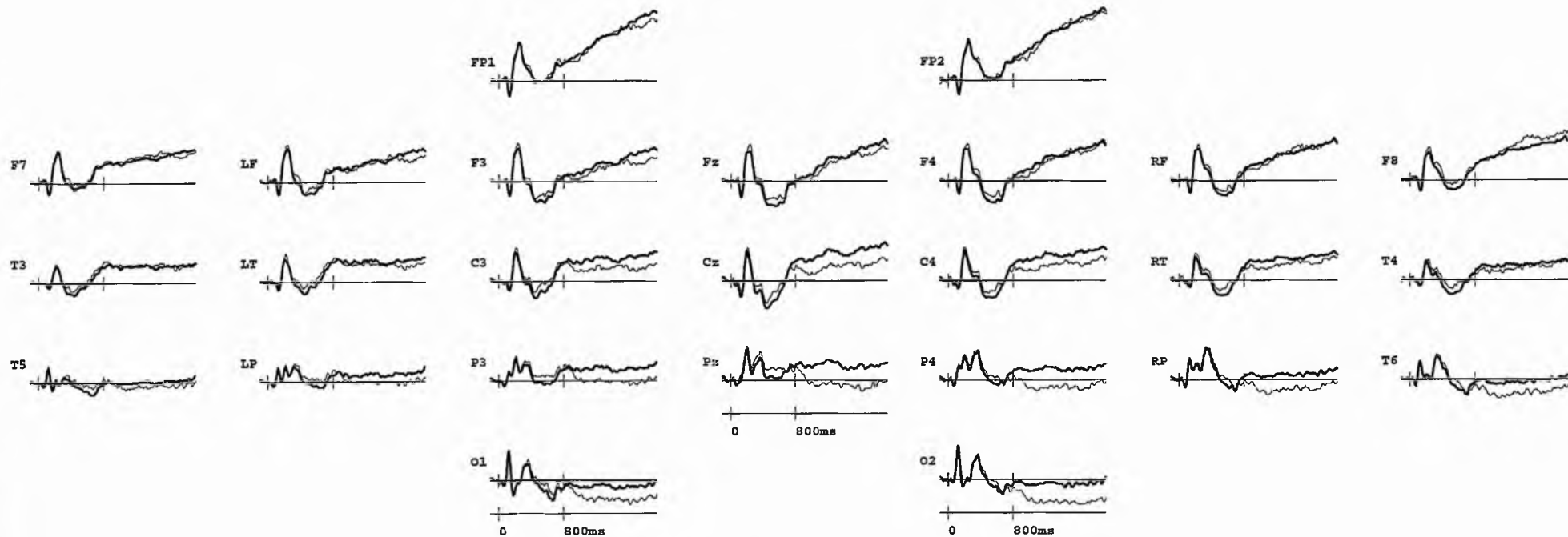
— RECOGNISED/UNRECALLED  
 — NEW  
 10μV



+ ——— REARRANGED  
 ——— NEW  
 10 $\mu$ V

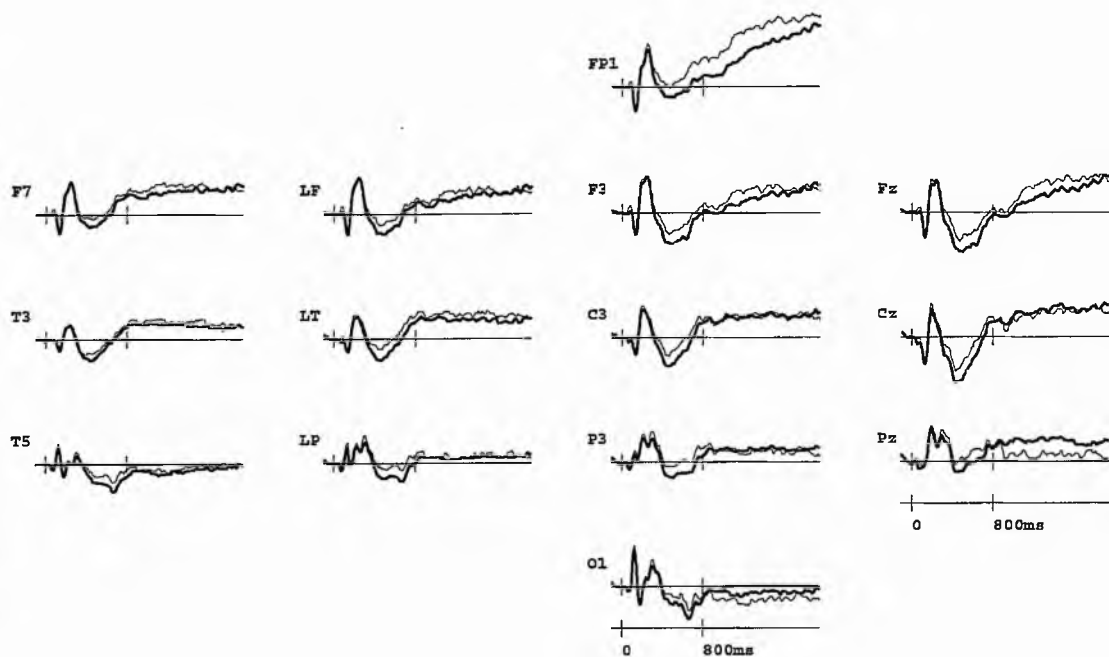
## APPENDIX C

Appendix C contains figures of the additional grandaverage ERPs from experiment 5, for the recognition and recall tasks. Again, the ERPs to these response categories does not bear directly on the issue that this study was designed to address, and are not considered in detail. For associative recognition ERPs were formed for 'rearranged' responses (i.e., to rearranged pairs that were both recognised and correctly classified as being rearranged), and for recall ERPs were formed for 'don't know' responses (i.e., old words for which the studied associate could not be correctly recalled). As in appendix B the ERPs are shown separately for each task, from all 25 recording sites, including the appropriate 'new' response category (the correct rejection baseline).

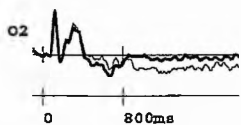
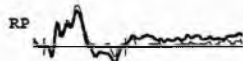
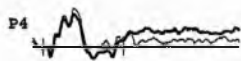
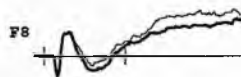
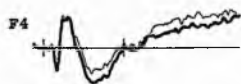
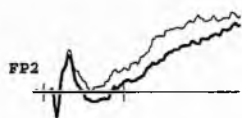


+ — RECOGNISED/UNRECALLED  
 — NEW  
 10 $\mu$ V





+ ——— REARRANGED  
 ——— NEW  
 10μV



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