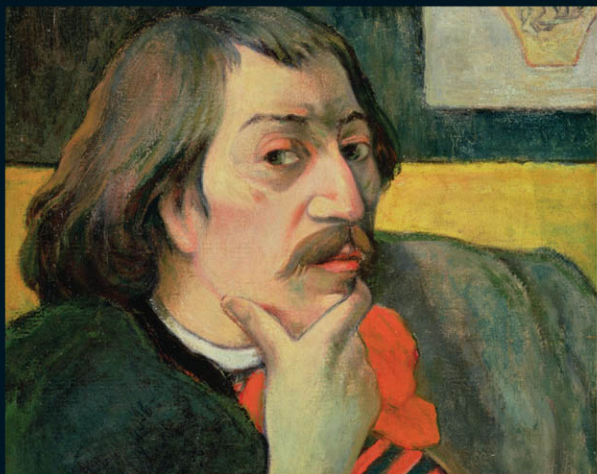


WORKING MEMORY, THOUGHT, AND ACTION

Alan Baddeley



OXFORD **PSYCHOLOGY** SERIES

Working Memory, Thought, and Action

OXFORD PSYCHOLOGY SERIES

Editors

Mark D'Esposito

Daniel Schacter

Jon Driver

Anne Treisman

Trevor Robbins

Lawrence Weiskrantz

1. *The neuropsychology of anxiety: an enquiry into the functions of the septohippocampal system*
J. A. Gray
2. *Elements of episodic memory*
E. Tulving
3. *Conditioning and associative learning*
N. J. Mackintosh
4. *Visual masking: an integrative approach*
B. G. Breitmeyer
5. *The musical mind: the cognitive psychology of music*
J. Sloboda
6. *Elements of psychophysical theory*
J. -C. Falmagne
7. *Animal intelligence*
Edited by L. Weiskrantz
8. *Response times: their role in inferring elementary mental organization*
R. D. Luce
9. *Mental representations: a dual coding approach*
A. Paivio
10. *Memory, imprinting, and the brain*
G. Horn
11. *Working memory*
A. Baddeley
12. *Blindsight: a case study and implications*
L. Weiskrantz
13. *Profile analysis*
D. M. Green
14. *Spatial vision*
R. L. DeValois and K. K. DeValois
15. *The neural and behavioural organization of goal-directed movements*
M. Jeannerod
16. *Visual pattern analyzers*
N. V. Graham
17. *Cognitive foundations of musical pitch*
C. L. Krumhansl
18. *Perceptual and associative learning*
G. Hall
19. *Implicit learning and tacit knowledge*
A. S. Reber
20. *Neuromotor mechanisms in human communication*
D. Kimura
21. *The frontal lobes and voluntary action*
R. E. Passingham
22. *Classification and cognition*
W. Estes
23. *Vowel perception and production*
B. S. Rosner and J. B. Pickering
24. *Visual stress*
A. Wilkins
25. *Electrophysiology of mind*
Edited by M. Rugg and M. Coles
26. *Attention and memory: an integrated framework*
N. Cowan
27. *The visual brain in action*
A. D. Milner and M. A. Goodale
28. *Perceptual consequences of cochlear damage*
B. C. J. Moore
29. *Binocular vision and stereopsis*
I. P. Howard
30. *The measurement of sensation*
D. Laming
31. *Conditioned taste aversion*
J. Burs, F. Bermúdez-Rattoni, and T. Yamamoto
32. *The developing visual brain*
J. Atkinson
33. *Neuropsychology of anxiety, second edition*
J. A. Gray and N. McNaughton
34. *Looking down on human intelligence: from psychometrics to the brain*
I. J. Deary
35. *From conditioning to conscious recollection: memory systems of the brain*
H. Eichenbaum and N. J. Cohen
36. *Understanding figurative language: from metaphors to idioms*
S. Glucksberg
37. *Active vision*
J. M. Findlay and I. D. Gilchrist
38. *False memory*
C. J. Brainerd and V. F. Reyna
39. *Seeing black and white*
A. Gilchrist
40. *The case for mental imagery*
S. Kosslyn
41. *Visual masking: time slices through conscious and unconscious vision*
B. G. Breitmeyer and H. Ögmen
42. *Motor cognition: what actions tell the self*
M. Jeannerod
43. *The visual brain in action, second edition*
A. D. Milner and M. A. Goodale
44. *The continuity of mind*
M. Spivey
45. *Working memory, thought, and action*
A. Baddeley

Working Memory, Thought, and Action

ALAN BADDELEY

Department of Psychology
University of York
UK

OXFORD
UNIVERSITY PRESS

OXFORD

UNIVERSITY PRESS

Great Clarendon Street, Oxford OX2 6DP

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide in

Oxford New York

Auckland Cape Town Dar es Salaam Hong Kong Karachi

Kuala Lumpur Madrid Melbourne Mexico City Nairobi

New Delhi Shanghai Taipei Toronto

with associated companies in Berlin Ibadan

Oxford is a registered trade mark of Oxford University Press
in the UK and in certain other countries

Published in the United States

by Oxford University Press Inc., New York

© Oxford University Press 2007

The moral rights of the author have been asserted

Database right Oxford University Press (maker)

First published 2007

All rights reserved. No part of this publication may be reproduced,
stored in a retrieval system, or transmitted, in any form or by any means,
without the prior permission in writing of Oxford University Press,
or as expressly permitted by law, or under terms agreed with the appropriate
reprographics rights organization. Enquiries concerning reproduction
outside the scope of the above should be sent to the Rights Department,
Oxford University Press, at the address above

You must not circulate this book in any other binding or cover
and you must impose this same condition on any acquirer

British Library Cataloguing in Publication Data

Data available

Library of Congress Cataloging in Publication Data

Baddeley, Alan D., 1934-

Working memory, thought, and action / Alan Baddeley.

(Oxford psychology series ; no. 45)

Sequel to: Working memory / Alan Baddeley. 1986.

Includes bibliographical references.

ISBN-13: 978-0-19-852800-5 (hbk. : alk. paper)

ISBN-13: 978-0-19-852801-2 (pbk. : alk. paper)

1. Short-term memory. I. Baddeley, Alan D., 1934- Working
memory. II. Title. III. Series.

[DNLM: 1. Memory, Short-Term—physiology. 2. Consciousness—physiology.

3. Emotion. 4. Social Behavior. 5. Volition—physiology. BF 378.S54 B132w 2007]

BF3788.S54B332 2007

153.1'3—dc22

2006037291

10 9 8 7 6 5 4 3 2 1

Typeset in Minion

by Cepha Imaging Private Ltd., Bangalore, India

Printed in Great Britain

on acid-free paper by

Clays Ltd., Bungay, Suffolk

To
Hilary

This page intentionally left blank

Contents

Preface xi

Acknowledgements xvii

- 1 Introduction and overview 1**
 - 1.1 Some history 2
 - 1.2 Multicomponent working memory 5
 - 1.3 The multicomponent model 7
 - 1.4 Conclusions 13
- 2 Why do we need a phonological loop? 15**
 - 2.1 The evolutionary relevance of the loop 15
 - 2.2 Language acquisition 16
 - 2.3 Sublexical short-term memory 21
 - 2.4 The problem of serial order 25
 - 2.5 Chaining models 26
 - 2.6 Contextual models 27
- 3 The phonological loop: challenges and growing points 35**
 - 3.1 Nairne's critique 35
 - 3.2 The word length effect 38
 - 3.3 Disrupting the phonological loop 49
 - 3.4 The irrelevant speech effect 51
 - 3.5 The phonological loop: an overview 60
 - 3.6 Conclusion 62
- 4 Visuospatial short-term memory 63**
 - 4.1 The case for a separating visuospatial and verbal working memory 63
 - 4.2 Fractionating visuospatial working memory 64
 - 4.3 Memory for spatial location 65
 - 4.4 Object-based short-term memory 67
 - 4.5 Sequential storage in visuospatial short-term memory 73
 - 4.6 Separating the threads 77
 - 4.7 Conclusions 83
- 5 Imagery and visuospatial working memory 85**
 - 5.1 Visuospatial coding and verbal memory 86
 - 5.2 Modelling the visuospatial sketchpad 91

5.3	Visual imagery	94
5.4	Conclusions	100
6	Recency, retrieval and the constant ratio rule	103
6.1	Recency in free recall	103
6.2	The constant ratio rule	105
6.3	Theories of the recency effect	108
6.4	The evolutionary function of recency	114
7	Fractionating the central executive	117
7.1	The central executive as rag-bag	118
7.2	Executive processes and the frontal lobes	119
7.3	Working memory and executive processes	122
7.4	Focusing the limited capacity	124
7.5	Task switching and the central executive	129
7.6	Division of attention as an executive skill	133
7.7	Conclusions	138
8	Long-term memory and the episodic buffer	139
8.1	Some reductionist views	139
8.2	Some skeletons in the working memory cupboard	141
8.3	The episodic buffer	148
9	Exploring the episodic buffer	157
9.1	Binding in visual working memory	157
9.2	Binding in memory for prose	160
9.3	Some implications	169
10	Individual differences and working memory span	175
10.1	The psychometric tradition	175
10.2	The concept of intelligence	176
10.3	Individual differences in working memory	181
10.4	What does working memory span measure?	184
11	What limits working memory span?	189
11.1	The speed hypothesis	189
11.2	The resource pool hypothesis	190
11.3	The inhibition hypothesis	192
11.4	Components of working memory	198
11.5	Fractionating the central executive	203
11.6	Working memory and education	205
11.7	Conclusion	209

12	Neuroimaging working memory	211
12.1	Positron emission tomography (PET)	211
12.2	Functional magnetic resonance imagery (fMRI)	213
12.3	Electroencephalography (EEG)	213
12.4	Other techniques	214
12.5	The naming of parts	216
12.6	What have we learned from imaging working memory?	217
12.7	Imaging the central executive	224
12.8	Meta-analysis of executive processing	228
12.9	Imaging retrieval processes	230
12.10	Some conclusions	231
13	Working memory and social behaviour	235
13.1	What controls behaviour?	235
13.2	Habits, schemata and deterministic control	236
13.3	The sense of agency	242
13.4	Working memory and self-control	246
13.5	Conclusions	255
14	Working memory and emotion I: fear and craving	257
14.1	Cognition in extreme emotion	258
14.2	Clinical studies of anxiety and cognition	265
14.3	Modelling the impact of anxiety and cognition	269
14.4	Addiction and craving	272
14.5	Conclusion	275
15	Working memory and emotion II: depression and the wellsprings of action	277
15.1	Comparing the effects of anxiety and depression	277
15.2	Psychological theories of depression	284
15.3	The wellsprings of action	286
15.4	Working memory and depression	289
15.5	Emotion and the multicomponent model	293
15.6	Emotion: a broader view	295
15.7	Conclusions	300
16	Consciousness	301
16.1	A pragmatic approach to consciousness	301
16.2	Core consciousness	302
16.3	Consciousness under anaesthesia	304
16.4	Conscious control and the global workspace hypothesis	306

- 16.5 A neural basis for cognitive workspace 309
- 16.6 Consciousness and working memory 314
- 17 The multilevel control of action 317**
 - 17.1 Implicit control of action 317
 - 17.2 A model of motor control 323
 - 17.3 Implications of motor control for working memory 332
 - 17.4 Conclusions 334
- 18 Working memory in context: life, the universe and everything 335**
 - 18.1 An evolutionary perspective 336
 - 18.2 Some philosophical implications 339
 - 18.3 Epilogue 348
- References 351*
- Index 405*

Preface

This is a book that I said I would never write. It is a sequel to *Working Memory*, a book I completed some 20 years ago which was basically an account of an extended programme of research that began in the 1960s when the study of short-term memory (STM) was in its hey day and continued during its loss of popularity in the 1970s as the broader and more functionally-based concept of working memory proposed by Graham Hitch and myself (Baddeley and Hitch, 1974). By the publication of *Working Memory* in 1986, interest had substantially begun to increase, with some 51 papers published with 'working memory' in their title, a process that has continued to a point at which there are now around 800 papers a year with working memory in their title and some 3700 papers in their title, key words or abstract. Not all of these, of course, will be of direct relevance to the multicomponent model, but when, from time to time, it was suggested that I should update the 1986 book, realizing the huge literature that was accumulating, I declared that I never would.

And yet, I kept noting that colleagues would make statements about our model, usually by suggesting that their data were incompatible with it, despite the fact that the model had subsequently evolved, in a way that made the specific criticism no longer appropriate. There was clearly a need for an updated account of the model, but I still balked at the sheer amount of material to be covered by a thorough review. I then hit on the apparently more tractable plan of writing an extended essay, setting aside a summer for this purpose. As autumn arrived, I found I was only half way through the first section on the phonological loop. So much for tractability. Somewhat later, the opportunity for a second attempt came along when I was invited to spend the academic year 2001-2002 at the Center for Advanced Study in Behavioral Sciences at Stanford. I decided to try again.

The Center seemed a particularly appropriate place for such an enterprise, given that the term 'working memory' appears to have been invented there by Miller, Galanter and Pribram (1960) in producing their classic contribution to cognitive science, *Plans and the Structure of Behavior*. Furthermore I discovered that I was assigned the room previously occupied there by Richard Atkinson, whose model together with Shiffrin (Atkinson and Shiffrin, 1968) is probably where Graham Hitch and I acquired the term 'working memory', although our own model differed in important ways from theirs. The omens seemed good.

Each year, the Center hosts some 40 fellows with backgrounds ranging from history and political science through anthropology and sociology to psychology and neuroscience. The availability of this breadth of expertise encouraged me, perhaps foolishly, to undertake the even more ambitious task of locating the concept of working memory within a broader intellectual context. There is always a temptation when introducing the concept of working memory to make rather grand claims for its importance as the basis of complex cognition and rational thought. And yet, from our very first experiments, much of the progress in refining the model has come from finding out what it *does not* do. With a full year ahead, and my prior commitments cleared away, I decided I would think more deeply about the broader implications of the multicomponent working memory model, and investigate a range of areas that might throw interesting light on how the model should be developed. I began my task in late summer, hoping to have completed it by Christmas. Some five years later I am finally completing the book that has turned into rather more than an extended essay. So what went wrong?

Having previously begun with the phonological loop, and finding myself drowning in detail, I decided I would start with the central executive component, on the misguided grounds that this was the topic we knew least about; indeed in the 1986 book, it had only emerged as the final chapter. There has however, been a huge amount of research in recent years concerned with executive processing, much of it related to the study of the frontal lobes. Furthermore, the central executive is the component of working memory that most naturally links to a range of other fields. For example, discussions with two social psychologist colleagues at the center, John Bargh and Roy Baumeister, suggested that their research could be linked very neatly to the account of action control given by Norman and Shallice (1986) that formed the basis of my own account of the central executive. I began also to see potential links with some of the classic philosophical issues such as the nature of consciousness and freewill. At the same time I discovered exciting and important evidence from cognitive neuroscience that appeared to bear directly on the multicomponent working memory model. The result is both a longer, broader and more ambitious book than I ever anticipated.

I would like to have produced a book that was a seamless whole, with detailed experimentation building up to general theory which in turn leads to speculation as to the broader role of the theory. Sadly, this did not work. The gap was just too large between, for example, the detailed analysis of the phonological loop, and speculations on the broader implications of the concept of working memory for consciousness and the control of action. Consequently, the book divides into two halves, the first concerned with developments within

the multicomponent model, and the second with its potential role in social and emotional behaviour, consciousness and the control of action.

The first section takes on the task which, perhaps wisely, I declared that I would never attempt, namely that of surveying the last 20 years of research on working memory. Its strength lies in the fact that I have been actively involved in most of the areas discussed. However, I make no claim to having covered the enormous literature that has occurred over this period in a thorough, balanced and scholarly manner, although I have tried to do so. Inevitably, I have tended to view the literature from the perspective of the multicomponent WM model, and to make more use of my own research than would be ideal. I can certainly not claim to have read all the literature, even in areas closest to my own research. Furthermore, I am sure that, in line with the self-performed-task literature (Englekamp, 1998), I remember what I have done rather better than what I have read. So if you are working in this area yourself, then I am sure you will know studies, perhaps performed by yourself, that could and should have been included. Please accept my apologies.

The second part of the book is very different in both its strengths and weaknesses. It attempts to place the concept of working memory in a broader context, looking for links with the study of social behaviour, emotion, conscious awareness and the control of action, which in turn raises some of the classic philosophical issues of consciousness and freewill. I found these potential links fascinating, and hope that my enthusiasm might encourage further work on these interface areas. I cannot however claim expertise in the topics covered, and have relied more on review papers than I would have liked. In a few cases I have found such reviews particularly helpful, and have tried to make this clear in the text. So what has emerged?

I wanted to produce a book that would be accessible and useful to a wide range of potential readers. I therefore begin with an introductory chapter providing an overview of the model as it stood when I completed my 1986 book. I then move on to discussing the phonological loop, which is probably the simplest and best understood component of working memory. This immediately presented a problem however. It is an area that has seen a great deal of detailed analysis, leading to complex controversies and sophisticated computational modelling. It is I think, essential to cover this as it reflects most clearly the potential for development of what began as a simple verbally described model. However, a reader from outside the field encountering this in the first chapter could very reasonably decide that 'this is not for me!' So, rather than start by bombarding the reader with computational models and third order interactions, I begin with the question of what function the phonological loop

might serve, with a view to convincing the reader that this is an area of some importance, whether or not they proceed to the more specialised Chapter 3. It is perhaps worth stressing at this point, that I have tried to write the chapters in such a way that they do not depend upon the book being read sequentially from start to end, although where, as is often the case, the topic is covered by two chapters, it is sensible to read them in that order.

From the phonological loop, I move on to the visuospatial sketchpad, with one chapter focusing on the short-term storage of visual and spatial information, and a second concerned with imagery and the manipulation of visuospatial information. Chapter 6 is concerned with a rather different method of storage that was classically linked to the concept of STM, namely the recency effect which is interpreted as a combination between passive priming and an active retrieval mechanism.

The next three chapters are concerned with the central executive and episodic buffer components of working memory. They do not attempt to review the vast and growing literature on executive control but focus on my own attempt to fractionate and elaborate the initial concept of a central executive, leaving the broader implications of executive and attentional control to later chapters, with the analysis of executive processing featuring prominently in the next two chapters on individual differences in working memory. The first part of book concludes with a discussion of the application of neuroimaging techniques to the study of working memory.

As mentioned earlier, the second part of the book attempts to place working memory in a broader perspective. A chapter concerned with potential links with social psychology is followed by two concerned with working memory and emotion. The first of these focuses on the effects of fear and anxiety, an area in which clear links between working memory and the disruption of cognition by emotion are already being actively explored, and extended to other clinically important issues such as craving and addiction. The link between working memory and depression, explored in Chapter 15 is less clear. I found this the most challenging chapter to write, but potentially the most productive, in that it led to a more detailed specification of the links between emotion and working memory, together with a new theoretical framework that has the potential to provide a conceptual link between psychological and neurobiological approaches to depression.

Continuing in a speculative mode, Chapter 16 is concerned with empirically-based explanations of the phenomenon of conscious awareness, stressing the potential link between working memory and theories of consciousness based on the global workspace hypothesis. The role of conscious awareness, and by

implication, working memory in the control of action forms the focus of the next chapter. The book ends with an attempt to place working memory in a broad evolutionary context and to explore its implications for tackling the classical philosophical questions of consciousness and free will. If you think this is rather a heady way for an experimental psychologist to end a book, I can only agree with you; I blame it on my year in California.

This page intentionally left blank

Acknowledgements

This book was largely written during a year spent in Stanford California at the Center for Advanced Studies in the Behavioural Sciences, generously supported by a fellowship from the John D. and Catherine T. MacArthur Foundation. I am also grateful to the British Medical Research Council who have supported the programme of research on working memory which forms the basis of the book since its inception over 30 years ago, latterly through grant G9423916. I am also grateful for financial support to the Universities of Bristol and York.

It will be clear I hope, that the book has gained from interaction and collaboration with a range of colleagues that is too numerous to list. Over the years however, I have gained particularly from discussions with Sergio Della Sala, Susan Gathercole, Graham Hitch, Chris Jarrold and Robert Logie. During my time at the Center in Stanford, I benefited greatly from discussions with my fellow Fellows, and in particular with Robert Bjork, and with John Bargh and Roy Baumeister, whose influence on the chapter relating working memory to social psychology will be obvious. The two chapters on working memory and emotion also profited greatly from advice and discussion from a range of colleagues, notably including Rainer Banser, Joseph LeDoux, Karin Mogg and Mark Williams.

I am grateful to Nelson Cowan, who read the whole book in draft form, providing timely and constructive advice, and to Bernard Baars, Donna Bayliss Gary Green, Graham Hitch, Satoru Saito and Tim Shallice, all of whom read and commented on one or more chapters. The book gained substantially from their suggestions.

I always produce my first writing drafts by dictation, largely while walking through the countryside. While this is a pleasant way of writing, it does require someone with greater transcription skills than I possess. I would therefore like to acknowledge the major part played by Megan Stokes-Holt, who came to my rescue at the Center, when a combination of ambient noise and my English accent proved too much for the available automatic speech recognition package. Back in Bristol I was fortunate that Dee Roberts was happy to split her time between completing a PhD and applying her combined secretarial and psychological skills to advance progress on the book. I am particularly grateful to Lindsey Bowes for applying her considerable secretarial and IT skills, not only to the last stages of writing, but also to the tricky process

of tracking down the elusive references that inevitably seem to slow down the final stages of producing a book.

Finally, this book is dedicated to my wife Hilary with thanks for her sustained support and encouragement, and her stoicism in the face of sympathy from neighbours for having an idle husband who paces the countryside talking to himself when he should be mowing the lawn or painting the fence. Her support is greatly valued.

Chapter 1

Introduction and overview

Working memory is assumed to be a temporary storage system under attentional control that underpins our capacity for complex thought. Consider the task of instructing a friend how to get from the railway station to your house: you probably need to form some kind of visuospatial representation of the district, work out the best route, and turn this into verbal instructions your friend is likely to understand. They will have to perform a similar task, although in the reverse order, then taking notes or relying on long-term memory. Or consider the simple exercise of multiplying 27 by 9. Having multiplied the 7 by 9, you need temporarily to store the 3, and ‘carry’ the 6, holding it while you multiply 2 by 9, then adding the 6, retrieving the 3 and coming up with the answer 243. Once complete, you can no doubt remember the result, at least briefly, but probably not the results of the individual stages.

The study of working memory is concerned with the way in which such temporary manipulation and storage is carried out. Its study was based initially on the concept of a simple unitary temporary memory store, short-term memory (STM). Over the years, however, it has become increasingly clear that considerably more than simple storage is required for a system that effectively forms the crucial interface between perception and memory, and between attention and action.

There are many approaches to working memory, most of which have common features, although this basic agreement may be obscured by the fact that different theorists often emphasize different phenomena and use a range of methods of theory development. My own approach has been largely empirically driven, relying principally on the methods of cognitive memory research, and influenced strongly by neuropsychology. As such, it has tended to stay close to the data, neglecting the broader implications of the model that was evolving. The chapters that follow attempt to do two things; to give an updated account of the more empirically based model, and then to place the concept of working memory in its broader theoretical context. Inevitably this requires a good deal of speculation, extending as it does to such classic issues as the nature of consciousness and the will. I will begin with a brief historical overview.

1.1 Some history

William James (1890) proposed a distinction between a temporary *primary memory*, which he described as ‘the trailing edge of consciousness’, and the more durable *secondary memory*. By the middle of the twentieth century, however, the dominant view within experimental psychology was of a single memory system in which learning reflected the formation of associations, and forgetting was due to interference between competing associations (McGeoch and Irion 1952). In 1949, Donald Hebb revived the two-component view, speculating that there may be two types of memory, short-term memory (STM) which depended upon temporary electrical activity in the brain, and long-term memory (LTM) which was represented by more durable neurochemical changes. This view was supported by Brown (1958) in the UK, and Peterson and Peterson (1959) in the US. In each case, they observed a rapid loss over a matter of seconds of even small amounts of information if rehearsal was prevented. Since the rehearsal prevention task did not involve material that was similar to the items being recalled, they ruled out classic similarity-based interference theory, proposing instead the existence of a memory trace that faded rapidly over time.

1.1.1 How many kinds of memory?

This led in the 1960s to a vigorous controversy. Keppel and Underwood (1962) showed that forgetting in the Peterson task was minimal on the first trial of the experiment, building up rapidly over the next few trials, suggesting that forgetting could readily be interpreted in terms of proactive interference from earlier items in the experiment. Melton (1962) demonstrated that digit span, the classic STM task involving immediate serial recall of a string of digits, also had a long-term component, concluding that there was no need to assume a separate STM system. In response to this, Waugh and Norman (1965) pointed out the need to distinguish between experimental paradigms and the hypothetical cognitive system, or systems that were assumed to contribute to performance on such tasks. Following William James (1890), they use the term *primary memory* for the hypothetical short-term system, and *secondary memory* for the long-term system, using STM and LTM to refer to the respective experimental paradigms, accepting that performance on STM tasks was always likely in practice to have a component based on LTM.

Further evidence for at least two memory systems came from a detailed study of neuropsychological patients. Classic amnesic patients who typically had bilateral damage to the temporal lobes and hippocampi (Milner 1966) show a devastatingly poor capacity for performance on LTM tasks, but perform well on classic STM tasks such as digit span (Baddeley and Warrington 1970).

At the same time, Shallice and Warrington (1970) described patients who showed the opposite pattern, with normal LTM, coupled with a digit span of only one or two items, and very poor Peterson performance. This so-called double dissociation between performance on LTM and STM tasks strongly suggested the need to assume separate processes.

Further evidence for a dichotomy came from two-component tasks such as free recall in which subjects attempt to recall a list of words in any order: the most recent items tend to be well recalled if recall is immediate, the recency effect. The recency effect is lost, however, if a brief filled delay is introduced between presentation and test, while earlier items assumed to reflect the long-term component are unaffected by this brief delay (Glanzer 1972; Glanzer and Cunitz 1966). The recency effect is preserved in amnesic patients but impaired in patients with defective STM performance, while recall of earlier items, assumed to depend on LTM, shows the opposite pattern, being greatly impaired in amnesic patients but preserved in patients with defective STM (Baddeley and Warrington 1970; Shallice and Warrington 1970).

1.1.2 The modal model

By the late 1960s, the weight of opinion was tending to favour a distinction between two or more kinds of memory, a state of affairs that was reflected in a number of models of memory, of which the most influential was that of Atkinson and Shiffrin (1968), which became known as the modal model. This model assumed three separate types of memory (see Fig. 1.1). The briefest of

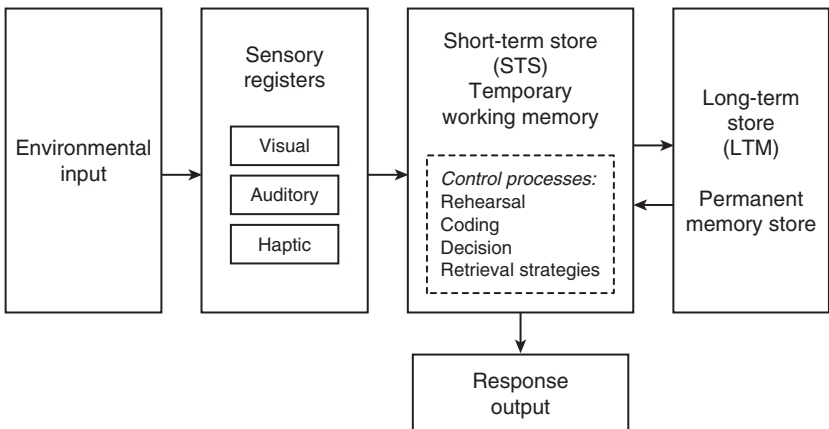


Fig. 1.1 The information-processing model of memory proposed by Atkinson and Shiffrin (1968). Information flows from the environment through a series of sensory registers into a short-term store, which plays a crucial role in controlling the flow of information into and out of the long-term store.

these was a series of sensory memory systems that are perhaps best regarded as components of perceptual processing. These included visual sensory memory (Sperling 1960) sometimes termed iconic memory, and its equivalent sensory acoustic storage system (Crowder and Morton 1969), termed echoic memory by Neisser (1967). Other sensory systems, however, were also thought to include some form of temporary storage (Atkinson and Shiffrin 1968). Information was assumed to flow from a parallel array of sensory memory systems to a single short-term store. This acted as a working memory of limited informational capacity, the *short-term store* (STS). The STS could both hold information and manipulate it, and was assumed to be responsible both for encoding information into LTM and subsequently retrieving it. The limited capacity STS system thus interacted with the much larger capacity *long-term store* (LTS). Hence long-term learning depended on both LTS and STS.

1.1.3 Problems with the modal model

Initially, it seemed as if the modal model provided a good account of the available data. It did however, run into at least two problems. The first of these concerned its learning assumptions, which proposed that merely holding information in the STS was sufficient for it to be transferred to LTS; the longer the information was held, the higher the probability of transfer, and the better the learning. However, attempts to test this directly were unsuccessful (e.g. Craik and Watkins 1973; Tzeng 1973; Bjork and Whitten 1974). Much more important than simple time was the nature of the operations performed on the material being learned, with items that were processed purely in terms of their physical appearance being poorly retained and items that were verbalized being somewhat better recalled, but not as well as items that were richly encoded in terms of their meaning, interpreted by Craik and Lockhart (1972) in terms of their highly influential Levels of Processing hypothesis. This proposed that degree of long-term learning depended on the depth and richness of encoding and not on the length of time the material was held in the STS, as Atkinson and Shiffrin had assumed.

A second problem was inherent in the neuropsychological evidence. If the STS provides a crucial stage in the process of long-term learning, then patients with a deficit in the STS system should also show impaired LTM performance, which they did not (Shallice and Warrington 1970). Furthermore, if the system serves as a general purpose working memory, then such patients should be handicapped on many different cognitive tasks. This was clearly not the case. One STM patient was performing effectively as a secretary, while another ran a shop and a family and a third was a successful taxi driver. Their problems appeared to be limited in nature, showing no evidence of a general cognitive

dysfunction such as one might expect of a patient with a grossly impaired working memory.

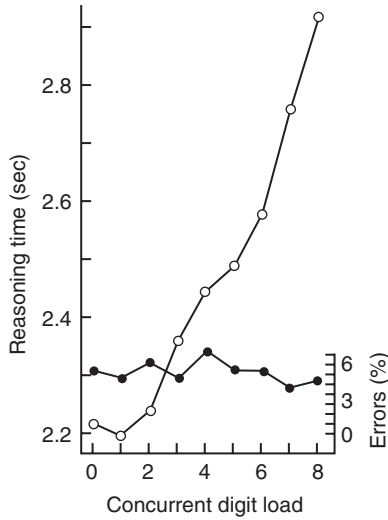
1.2 Multicomponent working memory

This was the situation when Graham Hitch and I began research using a grant that was targeted at understanding the relationship between long- and short-term memory, at a point when the study of STM was rapidly losing its popularity in favour of research into new and exciting areas of LTM such as levels of processing (Craik and Lockhart 1972), and the nature of semantic memory (Collins and Quillian 1969; Collins and Loftus 1972).

We chose to tackle the simple question of what function was served by STM, if it was not a working memory? We did not have access to STM patients, but instead decided to use dual task methodology in order to selectively disrupt STM in normal subjects. Despite their differences, all existing models of STM appeared to agree that it was necessary for the immediate serial recall of digits, and all agreed that the limited span for digits resulted from the limited capacity of the STS. We therefore required our subjects to continuously repeat random sequences of digits, while performing a second task which was assumed to depend upon the operation of a limited capacity working memory system. Simply requiring one item to be repeated would prevent overt vocal rehearsal, but impose only a minimal storage load. Increasing the number of digits to three or six or more should take up a successively greater proportion of available STS capacity. This successive increase in concurrent digits should be reflected in the progressively impaired performance of any task that was heavily dependent on working memory.

We chose to study verbal reasoning, comprehension and long-term learning in this way, in each case performing the task while reciting strings of digits. Our reasoning task involved the verification of sentences that varied in their syntactic complexity. Each sentence purported to describe the order of two letters, A and B and was followed by a letter pair, for example, *A follows B* – BA, to which the subject should respond ‘true’. The difficulty of the task was manipulated by also using negatives and passives, for example *B is not preceded by A* – AB, which should evoke the response ‘false’. Subjects performed this visually presented task while overtly rehearsing sequences of random numbers ranging in length from zero to eight digits. The results are shown in Fig. 1.2, which gives both the mean time to respond and mean percentage of errors at each level of digit load. There is a clear increase in response time with increasing digit load, although it is important to note that even the heaviest load increases response time by only 50 per cent. Perhaps more surprising is the error rate, which is quite unaffected by a concurrent load that reaches and in

Fig. 1.2 The influence of a concurrent memory task on verbal reasoning. The longer the concurrent digit sequence, the slower the response. However the decrement was far from massive, and there was no effect on accuracy. Data In: *Working Memory* from Baddeley (1986). Reproduced with permission from Oxford University Press.



some subjects' cases exceeds, digit span. Broadly similar results were obtained when we studied the effect of concurrent digit load on tasks involving either learning or prose comprehension. The system that underpins the retention of digits therefore *does* resemble a working memory system in that decreasing its capacity impairs cognitive functioning, but the degree of impairment is far less than would be predicted by the modal model. We decided to abandon the assumption of a unitary STS, and replace it with a multimodal system, which we termed *working memory*.

We chose the term *working memory* in order to emphasize the functional role of the proposed system, rather than simply its storage capacity. The term was already current though not common in cognitive psychology. It appears to have been coined by Miller, Galanter and Pribram (1960), although they say little about its characteristics. The term was also used by Atkinson and Shiffrin to describe the functional role of their short-term store. Both of these usages are broadly equivalent to our own, however two other usages that are different should be mentioned. The term *working memory* is also applied to a component of production system models in artificial intelligence (Newell and Simon 1972), referring to a system of unlimited capacity that holds the if-then production rules that underpin such models. It has also been used in yet another way within the animal learning literature (Olton 1979) to refer to performance on tasks such as the radial arm maze in which animals are required to remember the outcome of a series of related trials performed on the same day.

However, for better or worse, the term *working memory* has increasingly come to be used in the sense that we adopted, to refer to a limited capacity

temporary storage system that underpins complex human thought. Such a system is often, though not always, assumed to comprise multiple components (Miyake and Shah 1999a; Smith and Jonides 1996, 1997). The term STM continues to be used to describe tasks in which the immediate recall of small amounts of information is required with the term working memory being used to refer to a broader system typically involving attentional control and allowing the *manipulation* of information held in short-term storage. The term STM is still used to describe a range of tasks such as digit span or the short-term Peterson forgetting paradigm. As previously noted, such tasks are likely to have both long-term and short-term components. However, many studies that focus explicitly on short-term *storage* (see Chapters 2-4) may continue to use the term STM to refer both to tasks and to the theoretically assumed underlying processes, relying on the context to make clear whether they are referring to a task or a system (e.g. Gathercole 1996; Vallar and Papagno 2002).

1.3 The multicomponent model

In order to explain our pattern of data, we suggested that the unitary short-term store proposed by Atkinson and Shiffrin should be replaced by a three-component working memory (Baddeley and Hitch 1974). This comprised an attentional control system – the *central executive* – together with two subsidiary storage systems, the *phonological loop* and the *visuospatial sketchpad* (see Fig. 1.3). All three systems were limited in capacity, although the nature of their limitations differed. The phonological loop was assumed to be capable of holding speech-based and possibly purely acoustic information in a temporary store. The storage was assumed to be dependent on a memory trace that would fade within seconds unless refreshed by rehearsal. Rehearsal was assumed to depend on either overt or covert vocalization.

The visuospatial sketchpad performed a similar function for both visual and spatial information. Rehearsal was assumed to occur, possibly though not necessarily involving eye movements (Baddeley 1986, p. 116-121; Postle *et al.* 2006). In the initial model, the central executive was assumed to comprise a limited pool of general processing capacity. We left its precise nature unspecified, concentrating instead on the subsystems, which seemed to offer a more tractable challenge. In the longer term of course, a working memory model that gives no account of executive control becomes effectively a simple storage model, albeit a two-component STS. Over the years the attempt to fill the gap left by the unspecified executive has been a major concern, and is reflected repeatedly in later chapters. Each of the three components is described in more detail below.

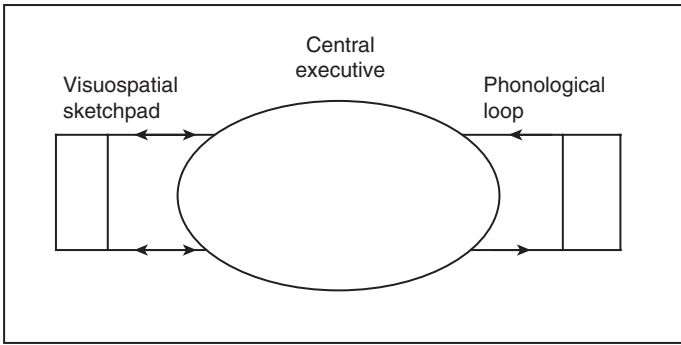


Fig. 1.3 The three-component working memory model proposed by Baddeley and Hitch (1974). Reproduced with permission from Oxford University Press.

1.3.1 The phonological loop

The loop was assumed to comprise a phonological store and an articulatory rehearsal mechanism: evidence of the nature of the store came principally from the phonological similarity effect. Conrad (1964) observed that when subjects attempted to recall sequences of *visually* presented consonants, that they tended to make ‘acoustic’ errors, for example mis-recalling *B* as *V* or *F* as *M*. Conrad and Hull (1964) demonstrated that sequences of phonologically similar letters such as *B D T G C P* were recalled less accurately than dissimilar sequences such as *F K Y W R Q*. They proposed that STM depended upon an acoustic memory trace, with visually presented items being converted into an acoustic code by subvocalization. Conrad used the term ‘acoustic’ similarity, since it was defined in terms of listening errors in noise. I myself prefer the term ‘phonological’ to refer to the underlying storage systems. The term is intended to leave open the precise nature of the code, earlier attempts to specify this having proved inconclusive (Hintzman 1967; Wickelgren 1969). I myself extended this finding to words, finding that a sequence such as *man cat cap map can* was recalled correctly only about 10 per cent of the time, in contrast to a dissimilar sequence such as *pit day cow pen sup*, which was correct on approximately 80 per cent of occasions. Similarity of meaning (e.g. *huge big long wide tall*) reduced recall by a significant but very small amount (Baddeley 1966a).

A very different pattern of results emerged when the same sets of words were used in a study of long-term memory, presenting a sequence of ten items for several trials. Under these circumstances similarity of meaning disrupted performance, while phonological similarity had little effect (Baddeley 1966b). These results were consistent with the use of a phonologically based store for

immediate recall of small amounts of information, in contrast to long-term learning which, in line with the subsequent levels of processing hypothesis (Craik and Lockhart 1972) appeared to rely principally on semantic coding.

The process of rehearsal was assumed to be reflected in the word length effect. Immediate memory for sequences of words declined as the words became longer, with a sequence of five short words such as *wit, sum, pad, beg, top* being correctly recalled on 90 per cent of trials, compared to around 50 per cent for a polysyllabic sequence such as *university, refrigerator, hippopotamus, tuberculosis, auditorium* (Baddeley *et al.* 1975). This result was consistent with the assumption of a fading trace, coupled with a rehearsal process that operates in real time. Memory span is thus assumed to be set by two factors – the rate at which the trace fades, and the speed at which items can be rehearsed. Shorter words can be rehearsed more rapidly leading to a greater span, and subjects who rehearse rapidly tend to have longer spans (Baddeley *et al.* 1975). The process of rehearsal can, however, be blocked by requiring the subject repeatedly to utter an irrelevant sound such as the word ‘the’. Although this involves only a minimal memory load, it prevents rehearsal and impairs performance (Murray 1968).

One further assumption was made, namely that items presented auditorily gained automatic access to the phonological store, while those presented visually had to be subvocalized to gain access. This latter point is reflected in an interaction between acoustic similarity, modality of presentation and suppression of articulation. The finding in question contrasts the phonological similarity effect – which is assumed to reside within the store – and the word length effect – which is assumed to reflect the process of transfer and rehearsal. When material is presented visually, articulatory suppression through the repetition of a single word removes both the phonological similarity effect and the word length effect. This is because the visually presented items cannot readily be translated into an appropriate phonological code. However, when presented auditorily a phonological similarity effect is again found (Murray 1968; Levy 1971), but there is still no effect of word length. This is because auditory items gain automatic access to the store. The word length effect still does not occur because it depends directly on subvocal rehearsal which is prevented by articulatory suppression (Baddeley *et al.* 1975; Baddeley *et al.* 1984a).

The storage-rehearsal distinction was subsequently supported by neuropsychological evidence from patients with lesions that disrupted either storage or rehearsal (Vallar and Papagno 2002), and by neuroimaging evidence which located the storage component in the temporo-parietal region of the left

hemisphere, while rehearsal was more frontally located in Broca's area (Paulesu *et al.* 1993; Jonides 1998).

As we shall see in Chapter 3, the concept of a phonological loop has not gone unchallenged. However, as Chapter 2 illustrates, despite (or perhaps because of) the fact that this remains an area of theoretical controversy, it has proved very fruitful in stimulating research on language acquisition and processing. It is important to bear in mind however, that the loop is only one relatively small component of the complex of systems and processes that constitute working memory.

1.3.2 The visuospatial sketchpad

This system performs the same function for visual and spatial information as is served by the phonological loop for verbal and acoustic stimuli. My own involvement with studying this system stemmed from a personal experience. While on sabbatical in California, I became very interested in American football. On one occasion, when driving on the freeway from Los Angeles to San Diego, I listened to the Stanford-UCLA game on the radio, forming a clear image of the field and the relevant teams. I then noticed that I was drifting from one lane to another, switched to music and survived.

On returning to Britain, I attempted to simulate my experience experimentally. We did not have access to a driving simulator, so instead used a pursuit rotor. This involved a spot of light following a circular path, which the subject was required to track with a stylus. Difficulty level could be set by varying the speed of rotation. Tracking was combined with a range of memory tasks, some involving rote verbal rehearsal while others encouraged the use of imagery. One such task, for example, used the classic location mnemonic, first teaching the subjects a route through the campus involving a number of specific locations. They were then instructed to form an image of each of the sequence of objects, one at each location, and to retrieve them by mentally performing the walk. When the task was performed alone this reliably enhanced recall performance as compared to rote rehearsal. Concurrent tracking, however, removed this advantage while having no effect on rote memory. As we shall see in Chapters 3 and 4, subsequent studies have investigated the relationship between visual STM and visual imagery, showing that it is possible to separate *visual* aspects of the system, concerned with patterns or objects, from a *spatial* component concerned with location. This distinction has been supported by studies on brain-damaged patients and by studies of normal brain function using neuroimaging techniques (Jonides *et al.* 1993; Smith and Jonides 1997; Della Sala and Logie 2002). Unlike the loop, the sketchpad relies principally on the right hemisphere of the brain.

1.3.3 The central executive

Our initial studies were concerned almost exclusively with the two subsystems, principally on the grounds that they seemed to offer more tractable problems. However in writing a book that attempted to summarize the progress made on the model (Baddeley 1986), I came to final chapter before fully realizing that I had said nothing about the executive. I set out to remedy this, basing my speculations on a model of attentional control proposed by Norman and Shallice (1986) which was unusual in being concerned with the attentional control of action, rather than with the role of attention in perception, of which there were a range of well-developed models. It is significant to note that the Norman and Shallice model, which I think continues to be extremely fruitful theoretically, was initially only available as a technical report and subsequently as a book chapter, apparently because of the difficulty in persuading a journal to accept it (Shallice, personal communication). Our journal reviewing system does not appear to favour innovation!

Norman and Shallice were both interested in the attentional control of action, but from somewhat different viewpoints. Norman was interested in slips of action, and wanted a framework that would provide a potential explanation as to why and when they might occur. Such lapses are usually trivial, such as absentmindedly driving to the office rather than the shopping centre on a Saturday morning. They can occasionally be devastating, however, for example in air accidents based on pilot error. Shallice on the other hand was interested in the control of behaviour by the frontal lobes, and wanted to explain the paradoxical behaviour of certain patients with bilateral frontal lobe damage. Such patients are found to perseverate, repeatedly performing the same action and showing considerable difficulty escaping that pattern. On other occasions they show what is apparently the opposite behaviour and their attention is captured by any passing stimulus.

In order to provide a framework for explaining both everyday lapses and frontal lobe performance, Norman and Shallice proposed that behaviour is controlled at two levels. One of these is relatively automatic, based on habits and schemas whereby predictable events give rise to appropriate behaviour. Driving along a familiar route would be a good example of this. The other component, which they term the *Supervisory Attentional System* (SAS), is a mechanism for overriding such habits. It is used when the existing habit patterns are no longer adequate, for example finding a traffic jam and needing to take appropriate action to circumvent it. The lapses of everyday attention such as setting off to drive to the market on a Saturday morning and finding oneself driving to work instead, represent the inappropriate dominance of such habit patterns over control by the SAS, and typically occur when one's attention is

diverted from the task in hand – planning a future holiday, for example, rather than thinking about the current shopping trip. Patients with frontal lobe damage are assumed to have defective operation of the SAS, with the result that attention may be captured by a single persistent stimulus or by a succession of irrelevant stimuli in the absence of central attentional control: their habit system is preserved while the frontally located SAS is not.

I proposed to accept the Norman and Shallice model as a basis for conceptualizing the central executive (Baddeley 1986). As subsequent chapters will indicate, I continue to find the model extremely useful.

1.3.4 The episodic buffer

One problem in having an executive that comprises general processing capacity is that it is potentially able to explain any result. This excessive flexibility means that it is not empirically productive in generating experiments that tell us more about how the system works. In an attempt to remedy this problem, I proposed to explore the possibility that the executive had a purely attentional role, and was itself incapable of storage (Baddeley 1993; Baddeley and Logie 1999). This led to a series of studies that attempted to fractionate the executive into an alliance of separate attentional control processes, each performing a different function. As Chapter 7 shows, this proved to be a major task, although one that was not without success.

However, it became increasingly clear that some form of additional storage was necessary if the model was to give an adequate account of some of the more complex functions of working memory, such as the capacity for remembering large chunks of prose. Furthermore, research on individual differences in working memory performance was yielding some very exciting results. The measure used in these studies was working memory span. This required subjects to combine memory with processing, for example verifying a sequence of sentences and then recalling the last word of each (Daneman and Carpenter 1980). Span was measured by the maximum number of such sentences which the subject could successfully process and recall. Working memory span predicts a wide range of complex cognitive activity from comprehension to computer programming (Daneman and Merikle 1996; Engle *et al.* 1999a).

At one level the success of this complex span measure was very gratifying in that it illustrates the breadth and usefulness of the general concept of working memory. On the other hand, however, it was far from easy to see how performance on such complex span tasks could be explained within the existing framework, where memory storage was limited to the loop and the sketchpad, each of which could hold information only briefly, and which had no specified means of interaction. This prompted the addition of a fourth component, the

episodic buffer (Baddeley 2000). This system was assumed to form an interface between the three working memory subsystems and long-term memory. It served as a binding mechanism that allowed perceptual information, information from the subsystems and from long-term memory to be integrated into a limited number of episodes. It was a buffer in the sense that it provided an interface between a number of different codes – visual, verbal, perceptual – and from LTM, semantic and episodic. Finally, it was assumed to be accessible through conscious awareness. It differs from episodic LTM in being temporary in nature, but provides an interface that allows access to LTM both for learning and retrieval. It is assumed to act as a workspace for which conscious awareness plays a crucial role (see Chapter 13). As such it provides a conceptual bridge between the Baddeley and Hitch model and a range of other approaches to working memory (Miyake and Shah 1999a). The episodic buffer is discussed in more detail in Chapters 8 and 9.

1.4 Conclusions

The multicomponent working memory model assumes a four- component system, comprising (1) an attentional controller, the central executive, and three temporary storage systems, namely (2) the visuospatial sketchpad, (3) the phonological loop, and (4) a more general integrated storage system the episodic buffer. The chapters that follow aim both to give a more detailed account of the model, and to place it in a broader context. Research in this area has developed enormously since the model was proposed more than 30 years ago, with the result that the account given will inevitably be selective, and determined by my own personal views on the topic. I have however attempted to acknowledge alternative approaches, providing references that would allow such approaches to be further explored, and explaining why I hold my current views, which are, of course, continually evolving as we learn more about working memory.

As the book progresses, I attempt to place the more detailed empirically based multicomponent model in a wider theoretical context. In attempting to say where, when and why working memory is important, I am led to discuss at least briefly those situations in which it plays little part. As a result, the final chapters are considerably broader in scope and more speculative in tone than I anticipated when I set out on what was planned originally as an extended essay on the current state of the multicomponent model.

This page intentionally left blank

Chapter 2

Why do we need a phonological loop?

Despite the fact that the phonological loop is limited in capacity to a few items and is only used in certain circumstances, it has generated a huge amount of research over the last 30 years. It also appears to be the component of working memory that is most strongly associated with the Baddeley and Hitch model, with the result that data that do not fit into the phonological loop component are often quite wrongly cited as evidence against the multicomponent model. One example of this will be discussed in detail later.

The amount of work that it has generated, and the fact that it remains both controversial and empirically productive after 30 years, presents a dilemma. Devoting a single chapter to the loop would inevitably mean skimming over controversies that are still active, and neglecting alternative hypotheses. On the other hand, a thorough treatment would be likely to involve a degree of detail that is out of balance with the rest of the book. Indeed, some might regard the system as one of minor importance, rather colourfully described by Jim Reason (personal communication) as little more than ‘a pimple on the face of cognitive psychology’. If this is the case, then it would be hard to justify further extensive coverage. I will therefore begin by discussing the question of what function might be served by the phonological loop. This will be followed by a chapter that attempts to summarize the controversies and gives a brief account of ways in which the loop model has been elaborated and extended.

2.1 The evolutionary relevance of the loop

In the days when digit span was assumed to be a good measure of STM, one could readily justify its study as reflecting the capacity of a general working memory (Atkinson and Shiffrin 1968). However, as noted earlier, patients whose span was a single digit appeared to have few problems in their everyday life, which clearly seemed inconsistent with a general working memory impairment. If digit span, and by implication the phonological loop does not reflect a general working memory system, what biological function might it serve?

2.1.1 Language comprehension

The possibility of working with PV, a patient with a very pure deficit in short-term phonological memory, offered an opportunity to tackle this question (Vallar and Baddeley 1984). My colleague, Giuseppe Vallar and I began by exploring the possibility that the loop might play an important role in language comprehension (Vallar and Baddeley 1987). We found that PV had no difficulty in processing simple sentences, but she did show a deficit in the capacity to verify certain complex sentences. These were constructed so as to require her to hold the initial part of the sentence until the end of the sentence, before the verification decision could be made. Hence, she could successfully reject short sentences such as *Sailors are lived on by ships*, and accept the converse (*Ships are lived on by sailors*), but was virtually at chance with a longer version, such as *Ships are believed, and with some considerable justification, to often be lived on by sailors*. This problem in processing and understanding long sentences is characteristic of STM-deficit patients (Vallar and Shallice 1990). It is, however, hard to argue convincingly that the capacity to interpret such convoluted sentences is likely to have bestowed a sufficiently major biological advantage as to justify the evolution of an apparently specialized system such as the phonological loop.

2.2 Language acquisition

Our second hypothesis was that the loop might conceivably play an important role in language *learning*, making it a crucial component for a child, but much less so for adults who have already acquired their native language. Some support for this view came from the observation that dyslexic children who often have delayed language development frequently show impaired digit span (Miles 1993). We decided to test this hypothesis by asking PV to learn items of the vocabulary of a foreign language, Russian (Baddeley *et al.* 1988). If the phonological loop plays an important role in language acquisition, she should perform poorly on this phonological long-term learning task.

2.2.1 Evidence from patients

Our test simply involved eight Italian words and eight Russian equivalents, for example, when the familiar Italian word *rosa* (rose) was presented, PV had to learn to respond with the Russian word *svieti*. In order to control for a general verbal learning deficit, we also required her to learn to link eight pairs of words in her native Italian, for example, to associate *cavallo* (horse) and *tavola* (table). We also tested a group of control subjects who were matched for age and educational level. PV proved quite normal in her capacity to learn to associate pairs of Italian words, a task that is known to rely principally on

semantic coding, but over ten successive trials she completely failed to master even one item of Russian vocabulary, whereas by this time the control subjects had learned all eight. She did indeed have a problem in new phonological learning.

A later study based on a highly intelligent US graduate student extended this finding to a developmental STM subject, identified because he had very poor phonological STM. Like PV he showed normal acquisition of word pairs together with very poor learning of a foreign language vocabulary (Baddeley 1993). We subsequently discovered that he had previously experienced enormous difficulty in second language learning.

Vallar and Papagno (1993) describe a subject with Down syndrome who shows the converse. Despite her reduced level of general intelligence, she was fluent in three languages. She proved to have excellent phonological STM, rather than the impairment in STM that is typical of Down syndrome (Bellugi *et al.* 1994; Jarrold *et al.* 1999). In a similar vein, a study of polyglots who were fluent in several languages showed that they had longer digit spans than monoglot control subjects who were otherwise similar in age and educational background (Papagno and Vallar 1995).

2.2.2 Second language learning

The evidence so far described relies on data from rare cases in which the phonological loop is either specifically impaired, or is preserved despite more general cognitive deficits. A second approach to the issue studied the impact on new vocabulary learning of disrupting phonological processing in normal subjects. Papagno *et al.* (1991) disrupted the operation of the phonological loop in their subjects by articulatory suppression, the requirement continually to repeat an utterance, hence blocking rehearsal. This impaired the acquisition of foreign language vocabulary, while having little impact on native language paired-associate learning. Papagno and Vallar (1992) produced further evidence for the importance of the phonological loop in foreign language learning by showing that it was impaired by two variables known to have a major influence on the operation of the loop, namely phonological similarity and word length. Despite their interference with foreign vocabulary learning, neither of these phonological variables affected rate of learning pairs of native language words, again suggesting that learning new phonological forms depends on the loop.

2.2.3 Children with language impairment

All the work described so far has been concerned with the capacity for *second* language learning; the question of whether the phonological loop influences

native language acquisition is, of course, of potentially greater biological significance. Susan Gathercole and I began to investigate this question using a sample of children who had been categorized as having Specific Language Impairment (SLI). They averaged eight years of age, and had normal non-verbal intelligence, but their level of language development was that of six-year-olds. We gave them a battery of verbal memory tests, and found that they had a particularly marked deficit in the capacity to repeat spoken nonwords, typically monosyllables such as *wux*, or *pij*. We developed a more extended nonword repetition test which, in its final version, involved items ranging from two syllables (e.g. *ballop*) to five (e.g. *pristoractional*) (Gathercole and Baddeley 1990). Each nonword was spoken to the child, who was asked to repeat it back. We compared our SLI group with children of the same age and non-verbal intelligence, and also with six-year-olds, who matched the eight year old SLI children in their level of language development.

The SLI children were substantially impaired in nonword repetition, even when compared to six-year-olds, scoring at a level that subsequently proved appropriate for children of four years (Gathercole and Baddeley 1990). We were able to rule out problems in hearing or articulation, and suggested that our test provided a measure of the capacity of the phonological loop, one that was even more appropriate than digit span for predicting language acquisition, since it demanded the processing of items resembling real words. We assumed that digit span would depend on the same system, but would be likely to rely more upon the existing knowledge of digits, for which our SLI children would have had two more years experience than their language-matched controls. As we shall see later, our hunch was correct, in that nonword repetition and digit span tend to be correlated, but with nonword repetition (NWR) proving a better predictor of language acquisition (Baddeley *et al.* 1998a).

2.2.4 Vocabulary acquisition in normal children

We also investigated the extent to which our new test was able to predict level of vocabulary in normal children (Gathercole and Baddeley 1989). Our basic design involved testing a range of children of a given age, measuring nonword repetition, non-verbal intelligence, typically with the Raven's Matrices test, and vocabulary level. This was measured using the British Picture Vocabulary Scale (BPVS) in which a word is spoken while the child looks at an array of four pictures, and is asked to point to the item specified. While non-verbal IQ was correlated with vocabulary at age 4 ($r = 0.388$) and 5 ($r = 0.164$), nonword repetition was more strongly associated with vocabulary level ($r = 0.525$ and 0.492 respectively). This correlation has now been replicated many times across a range of different age groups (see Table 2.1).

Table 2.1 The relationship between vocabulary, non-word repetition and digit span. Data from a range of studies, as reported by Baddeley, Gathercole and Papagno (1998).

Mean Age	<i>n</i>	Nonword repetition		Digit span	
		Simple	Partial*	Simple	Partial*
3.00	54	0.34	0.31	0.15	0.16
4.01	70	0.49	0.47	0.28	0.22
4.07	80	0.56	0.46	—	—
4.09	57	0.41	0.41	0.28	0.29
5.03	70	0.34	0.36	0.20	0.18
5.06	48	0.48	—	—	—
5.07	80	0.52	0.50	—	—
5.09	51	0.41	0.31	0.38	0.28
5.09	65	0.61	0.53	0.44	0.38
6.07	80	0.56	0.48	0.44	0.33
8.07	80	0.28	0.22	0.36	0.23
13.10	60	—	—	0.49	0.46

* With other potential predictors statistically removed.

Of course, correlation does not necessarily imply causation. It could, for example, plausibly be argued that subjects with large vocabularies are able to use this knowledge to help them perform the nonword task. Hence the observation by Papagno and Vallar (1995) that polyglots who speak a number of different languages have higher digit span might reflect the fact the loop can draw upon the more extensive language habits acquired in learning the non-native languages. Such a view was espoused by Brown and Hulme (1996), who proposed that a good vocabulary led to good verbal memory rather than vice versa. Support for such a view came from a study by Gathercole (1995) of the performance of children who have high or low scores on the nonword repetition test. She compared performance on items that were similar in phonotactic structure to English, such as *prindle* and *contramponist*, with performance on less word-like items, such as *ballop* and *skiticult*. Both high and low nonword repetition groups gained a clear and broadly equivalent advantage from word likeness, strongly supporting the idea that language habits contribute to nonword repetition performance.

A second feature of Gathercole's data, however, told a somewhat different story. When the children's vocabulary acquisition over the year *following* this test was recorded, it proved to be unrelated to performance on the word-like

items, but clearly correlated with the capacity of the child to repeat the less word-like sequences. It seems likely, therefore, that there are two contributions to nonword repetition, one from existing language habits, which makes a broadly equivalent contribution across the two groups, and the other from a source that differs between the two groups. I suggest that this comprises the limited capacity phonological store. Language habits provide good support for both groups, but new learning depends on the capacity of the phonological store: children with higher phonological store capacity will be able to hold on to new words for longer, increasing the likelihood of long-term phonological learning.

Further evidence for the primacy of phonological storage came from a study using cross-lagged correlation to throw light on the causal link between existing vocabulary, nonword repetition and the capacity to acquire new words (Gathercole and Baddeley 1989). A group of children were tested at age four, and retested at five, on both vocabulary and nonword repetition. Using cross-lagged correlational logic, it was proposed that if the primary driving force was phonological memory, then nonword repetition at four years of age would predict vocabulary one year later significantly better than vocabulary at four would predict memory at five. On the other hand, if vocabulary were the driving factor, the reverse pattern should occur. The results were clear in indicating that nonword repetition predicted subsequent vocabulary acquisition rather than the reverse, although as children get older, the pattern becomes more reciprocal with both nonword repetition and vocabulary predicting subsequent performance (Baddeley *et al.* 1998a).

Sorting out clear causal links in cognitive development will inevitably be difficult, because a whole range of cognitive skills is likely to be developing in parallel, making it difficult to separate one from the other – the collinearity problem. The issue is further complicated by the tendency for cognitive development to involve a cyclic process whereby an initial capacity leads to the development of cognitive skills, which then further enhance that capacity which in turn enhances the developing skills. This has led to alternative accounts of our findings in terms of phonological processing rather than the phonological loop (Snowling *et al.* 1991, but see Gathercole *et al.* 1991). While one might argue for an unspecified phonological processing deficit as an explanation of the SLI results from children, the Snowling *et al.* interpretation can not readily account for our data from adults acquiring a second language. For example, it is implausible to suggest that PV's dramatic impairment in phonological STM results from a loss of language habits generally, as she has unimpaired vocabulary and syntax and speaks with perfectly normal speed and prosody (Basso *et al.* 1982). Similarly, while articulatory suppression, word length and phonological similarity all influence the phonological loop,

and all interfere with the acquisition of novel vocabulary, it is hard to see how any of these could be regarded as temporarily removing the person's access to language habits.

2.2.5 Acquisition of syntax

The evidence for the role of the phonological loop in the acquisition of grammar is less strong than for vocabulary learning. It has been proposed that the capacity to store sequences of words plays an important role in syntactic development (Nelson 1987; Plunkett and Marchman 1993), a view supported by a study of two bilingual siblings by Speidel (1993). Both were of equivalent high general intellectual capacity, but one was slow to acquire individual words and made multiple syntactic errors, coupled with poor phonological memory. Daneman and Case (1981) showed that word span was a better predictor of performance on an artificial grammar learning task than chronological age. Studies by Blake *et al.* (1994) and Adams and Gathercole (1995; 1996) showed that phonological memory tests were able to predict mean length of utterance in spoken language while Ellis and Beaton (1993) implicated phonological memory in the acquisition of grammar in second language learning. We suggest, therefore, that the balance of evidence supports the idea that the phonological loop plays an important role in the acquisition of both native and second languages, a view that is discussed in detail by Baddeley *et al.* (1998a).

2.3 Sublexical short-term memory

As we have seen, the classic STM task is digit span, in which the subject remembers a sequence of digits, highly overlearned items from a very restricted set. In moving to word span, there has been a tendency, certainly on my own part, to keep to the repeated use of a limited set of words, explicitly to emphasize the need to store serial order and to minimize any contribution from long-term memory. This classic version of serial STM has indeed proved to be a surprisingly complex and empirically fruitful task, but if, as suggested by Baddeley *et al.* (1998a), the phonological loop has evolved to help acquire *novel* phonological sequences, then it seems paradoxical to study the process using components like digits that are already highly overlearned. For this reason, my colleagues have begun to move away from studying well-learned closed sets of items towards the study of nonwords, producing results that challenge and extend existing models of the phonological loop, as we shall see. The work focuses on two issues: a detailed analysis of error patterns, together with an analysis of the processes by which recall is influenced by lexicality, that is, by whether sequences of words or nonwords are to be remembered.

2.3.1 Word and nonword error patterns

A detailed analysis of errors has formed an important tool in developing and testing models of STM from its early days (Conrad 1960 1964; Sperling and Speelman 1970). For example, any precise model of digit span should be able to account for the observation that when sequence length exceeds span, subjects typically continue to recall most of the items, but do so in the wrong order. Such errors tend to move across relatively short distances within the sequence, with adjacent transpositions (e.g. 1, 2, 3, 4, 5, 6 to 1, 2, 3, 5, 4, 6) being the most probable when all items are recalled (Aaronson 1968; Bjork and Healey 1974; Lee and Estes 1997). The fact that errors occur between adjacent items suggests that although order information may have become less accurate, it has not been totally lost.

A study of the retention of consonant-vowel-consonant (CVC) *nonwords* by Trieman and Danis (1988) however, produced a somewhat different picture. In this case, what appeared to be item errors predominated: that is, CVCs were produced that had not been presented in the sequence. However, closer inspection indicated that these apparent item errors themselves resulted from order errors within the sequence of *phonemes*, hence *wux caz* might become *cux waz*. One might therefore redescribe the apparent item errors as order errors resulting from the consonants and vowels becoming ‘unglued’ from the novel CVCs. Again, the transpositions occurred across relatively short distances, implying that some order information was still being stored.

Gathercole *et al.* (1999) studied serial recall of CVCs that varied in phonotactic frequency, that is in the likelihood that that combination of phonemes would occur in the language. High phonotactic items were better recalled than those comprising less familiar sound sequences. Like Trieman and Danis, they found that errors were predominantly due to migrations of individual phonemes, rather than of complete CVC syllables. Order errors were predominantly attributable to consonants, with the retention of order information in the vowels being substantially more robust. They suggest that the retention of order information principally depends upon the vowels, which have been demonstrated across a number of studies to be retained more reliably than the consonants. For example, Drewnowski (1980) showed that similarity across items in vowel sound (e.g. *dah*, *fah*, *gah*) led to poorer recall than consonant similarity (e.g. *dih*, *dah*, *doh*), suggesting that the vowels play a more central role in STM.

This pattern of results is consistent with the hypothesis that order information is principally carried by the vowel sounds, with consonants being more or less strongly attached to the individual vowels. In the case of a limited and closed set of phonologically dissimilar items such as digits or dissimilar consonants,

retention of the order of the vowels is sufficient to allow the original string to be unambiguously regenerated, in contrast to a phonologically similar list, in which the common vowel would provide a relatively ineffective cue. Such an interpretation of the phonological similarity effect is common to a number of the computational models described later which separate the storage of order information from a later item selection stage. This process can be modelled relatively easily when the items already exist in some long-term lexicon, as in the case of digits and words, but presents more of a problem when, as in the present case, subjects are required to retrieve novel nonwords.

2.3.2 Lexicality and redintegration

Gathercole and colleagues found that the capacity to repeat nonwords was a good predictor of whether or not a child was likely to encounter reading problems (Baddeley and Gathercole 1992; Gathercole and Pickering 2001). However, although this *could* reflect a memory failure, the problem could be the plausible result of difficulty in either hearing or articulating the material. If hearing is the problem, errors should occur even on short sequences when presentation is auditory, allowing this possibility to be identified and the child's hearing then checked audiometrically. The complications of speech production may also be avoided by using recognition, rather than spoken recall, with the child hearing two nonword sequences varying in length, and detecting whether the order of the component sounds was the same or different. This, however, raises the further question of whether a nonword recognition measure would be comparable to the existing recall tasks as a predictor of vocabulary acquisition.

2.3.3 Lexicality and recognition

Gathercole *et al.* (2001) investigated this by measuring both recall and recognition span for words and nonwords. Their procedure was as follows: in the recall task, subjects would hear and attempt to repeat back sequences of monosyllabic words or nonwords of equivalent phonotactic frequency. Sequence length was increased to a point at which accurate recall broke down, i.e. span length for that type of material. Recognition was tested by presenting sequences of increasing length, and following each with a second sequence that was either identical, or had the order of two items switched (e.g. present *pig, hat, rug, day*; test *pig, rug, hat, day*). They found that words were substantially easier to *recall* than nonwords. Surprisingly however, there was little difference between word and nonword span when tested by recognition. This result was replicated across a range of studies by Gathercole *et al.* (2001), and further extended by Thorn and Gathercole (1999) in a study comparing span in monolingual and bilingual subjects for words in their first or second language.

They found a clear advantage for material in the subject's first language when tested by recall, whereas language type had little effect on recognition.

Returning to the practical issue that prompted the initial study, fortunately, nonword recognition did indeed prove to correlate with vocabulary acquisition (Gathercole *et al.* 2001), suggesting that it will provide a useful practical tool for testing children with speech production problems. This result also implies that it is the capacity to store novel phonological information, rather than existing language knowledge, that provides the predictive power of nonword repetition, at least during the earlier stages of language acquisition, and as such, it reinforces the earlier conclusions of Baddeley *et al.* (1998a) regarding the role of the phonological store in language acquisition.

2.3.4 Set size and recall

One final study will be described before attempting to pull together the evidence and consider its implications for the phonological loop model. In this study, Gathercole (In preparation) manipulated an important variable that distinguishes the standard memory span procedure from nonword repetition, namely that of whether a limited 'closed' set of items, for example the same ten words, is used repeatedly, or whether an 'open' set of words is used, with different words for every trial. As expected, she found an advantage to the closed set, in which the limited range of words made item recall much easier. Of more significance, however, was the pattern of errors obtained. She found that the closed set words behaved just as did digits, in that errors typically reflected the transposition of the order in which the words were recalled, with little tendency for the words themselves to be incorrect.

In contrast, words from the open sets were often incorrectly reported. On closer inspection, this proved to result from a tendency of consonants to switch their serial position. As in the case of nonwords, the typical pattern was for consonants to migrate to adjacent positions, for example, *hat-pen* to *pat-hen*. Combining the results from this and the Gathercole *et al.* (2001) study, she proposed that order information is stored at a sublexical level, with lexical knowledge being used at the later retrieval stage, at which the use of long-term knowledge to facilitate recall is often termed redintegration (Schweikert 1993; Brown and Hulme 1995). When a limited set of words is constantly reused, the range of potential candidates to match a given degraded memory trace is highly constrained, leading to better performance. When an open set of many potential CVC words is employed, however, the capacity for accurate redintegration is substantially reduced: although all items may be known to be real words, this is less helpful, as a large number of possible CVC items are real words, and are hence plausible candidates for recall.