MODELS OF WORKING MEMORY

Mechanisms of Active Maintenance and Executive Control

Edited by

AKIRA MIYAKE AND PRITI SHAH

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http: //www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http: //www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1999

Printed in the United States of America

Typeface Stone Serif 9/12 pt. *System* QuarkXpress™ [HT]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Models of working memory : mechanisms of active maintenance and
executive control / edited by Akira Miyake, Priti Shah.
p. cm.
Includes bibliographical references and indexes.
ISBN 0-521-58325-X. – ISBN 0-521-58721-2 (pbk.)
1. Short-term memory. I. Miyake, Akira, 1966– . II. Shah,
Priti, 1968– .
BF378.S54M63 1999
153.1´3 – dc21 98–35134
CIP

ISBN 0 521 58325 X hardback
ISBN 0 521 58721 2 paperback

1 Models of Working Memory

An Introduction

PRITI SHAH AND AKIRA MIYAKE

Working memory plays an essential role in complex cognition. Everyday cognitive tasks – such as reading a newspaper article, calculating the appropriate amount to tip in a restaurant, mentally rearranging furniture in one's living room to create space for a new sofa, and comparing and contrasting various attributes of different apartments to decide which to rent – often involve multiple steps with intermediate results that need to be kept in mind temporarily to accomplish the task at hand successfully. "Working memory" is the theoretical construct that has come to be used in cognitive psychology to refer to the system or mechanism underlying the maintenance of task-relevant information during the performance of a cognitive task (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980). As reflected by the fact that it has been labeled "the hub of cognition" (Haberlandt, 1997, p. 212) and proclaimed as "perhaps the most significant achievement of human mental evolution" (Goldman-Rakic, 1992, p. 111), it is a central construct in cognitive psychology and, more recently, cognitive neuroscience.

Despite the familiarity of the term, however, it is not easy to figure out what working memory really is. To begin with, the term *working memory* is used in quite different senses by different communities of researchers. In the behavioral neuroscience and animal behavior fields, for example, the term is associated with the radial arm maze paradigm. In this paradigm, a hungry animal (usually a rat) is placed in a multipronged maze and searches for food located at the end of each arm. If the animal has a good "working memory" and can remember which arms it has already visited, it should not return to those arms because the food there is already gone. Thus, in this context, working memory has a specific operational definition different from that generally used by cognitive psychologists: "the ability of an animal to keep track of its location in space by remembering where it has been" (Olton, 1977, p. 82; see Gagliardo, Mazzotto, & Divac, 1997, for a recent study of "working memory" in this sense).

The confusion remains even within the discipline of cognitive psychology. First of all, there is not always a clear-cut distinction between working mem-

We thank Andrew Conway, Peter Delaney, Arthur Graesser, Reid Hastie, Janice Keenan, Daniel Kimberg, Peter Polson, Satoru Saito, and Sashank Varma for reading an earlier version of this chapter and giving us useful comments and suggestions.

ory and the still prevalent concept of "short-term memory" or STM (Brainerd & Kingma, 1985; Engle, Tuholski, Laughlin, & Conway, in press; Klapp, Marshburn, & Lester, 1983; see also a collection of articles in the March, 1993, issue of *Memory & Cognition* on STM). Textbooks, in particular, often contradict one another and are sometimes even internally inconsistent in their discussion of the distinction between STM and working memory. Adding to the confusion is that a number of different metaphors are used to refer to working memory and to highlight different characteristics of the concept, including the "box" or "place" metaphor, the "workspace" or "blackboard" metaphor, the "mental energy" or "resources" metaphor, and the "juggling" metaphor.

To make things even worse, the working memory literature is filled with seemingly contradictory claims. For example, some articles emphasize the unitary nature of working memory (e.g., Engle, Cantor, & Carullo, 1992), whereas others focus on its non-unitary nature and argue for a more domain-specific view of working memory (e.g., Daneman & Tardif, 1987). Some articles put forth a theory in which individual differences in working memory capacity are conceptualized in terms of variation in the total amount of mental resources available (e.g., Just & Carpenter, 1992), whereas others claim that long-term knowledge and skills provide a better account of individual differences in working memory (e.g., Ericsson & Kintsch, 1995). The common practice of capitalizing on differences in viewpoints is understandable in terms of the sociology of science, but it is not always clear from these articles whether such different conceptualizations are fundamentally incompatible or merely reflect differences in emphasis.

A variety of models and theories proposed earlier reflect such diverse – and one might say, disparate – perspectives on the nature, structure, and functions of working memory (e.g., Anderson, Reder, & Lebiere, 1996; Baddeley, 1986; Barnard, 1985; Cowan, 1988; Ericsson & Kintsch, 1995; Just & Carpenter, 1992; Schneider & Detweiler, 1987). Attempts to figure out what characteristics working memory has and how it is organized by carefully reading these theoretical articles sometimes leave one even more confused than before. We ourselves experienced this frustration prior to editing this volume and would imagine that our frustration might be somewhat analogous to what Eysenck (1986) once felt about various psychometric theories of intelligence: "Discussions concerning the theory, nature, and measurement of intelligence historically have resulted more in disagreement than in agreement, more in smoke than in illumination" (p. 1). Many people might agree that this quote would continue to make sense if the phrase *working memory* were substituted for the word *intelligence*. Indeed, this suspicion has been confirmed by one embarrassing question repeatedly raised by different colleagues and students of ours, all aware of different conceptions of working memory: "What is working memory, anyway?"

We believe that the time has come to take a step toward clarifying this confusing state of affairs in the field. In this volume, we tackle this challenge by systematically comparing existing influential models and theories of working memory. As a casual skimming of the subsequent chapters (Chapters 2 to 11) makes clear, the models included in this volume represent a wide range of theoretical perspectives that, on the surface, look quite different from one another. Our primary goal is to closely examine how these different models characterize working memory and elucidate some commonalities among them – commonalities that may help us better define and understand working memory.

The specific approach we decided to adopt for this purpose is to ask each theorist to address the same set of important (and often controversial) theoretical questions that have been guiding working memory research. This "common-question" approach to theory comparison has rarely been used in cognitive psychology. To the best of our knowledge, the only book that has explicitly used this approach is a volume edited by Baumgartner and Payr (1995), entitled *Speaking Minds: Interviews with Twenty Eminent Cognitive Scientists*. In that volume, Baumgartner and Payr interviewed leading cognitive scientists and asked them the same set of theoretical questions such as, "Do you think the Turing Test is a useful test (or idea)?" We found their approach quite effective in elucidating the commonalities and differences of various researchers' opinions because the shared questions provide a useful common ground against which different theorists' ideas can be compared and contrasted. Because existing models of working memory differ radically in their scope and focus, we thought that, without such shared questions, it might be difficult to compare seemingly disparate models and identify their commonalities.

WHY THEORY COMPARISON? In our view, systematically comparing and contrasting different models of working memory in terms of the common set of designated questions has several important merits that are worth pointing out in addition to the ones mentioned above. First, systematic issue-by-issue comparisons help clarify common misconceptions or misinterpretations of different models of working memory. Theoretical articles often provide detailed specifications of some aspects of a model, but give cursory or no treatment to other aspects of the model. Although there is nothing inherently wrong with this common practice, it invites a lot of guessing on the part of readers about various issues, sometimes leading to confusion and even wrong interpretations.[1] Asking different theorists to address all major aspects of working memory may reduce the confusion and misinterpretations.

---

[1] For example, one common misinterpretation prevalent in the literature is that Just and Carpenter's (1992) model assumes a unitary, domain-general notion of working memory. The model described in the 1992 paper included only one "resource pool," but it only reflected the fact that the model was restricted to the domain of language comprehension. Just and Carpenter themselves had a more domain-specific view of working memory, assuming at least a distinction between language and visuospatial working memory. Another common misinterpretation concerns the processing capabilities of the visuospatial sketchpad system in Baddeley's (1986) model. Although Baddeley himself has consistently argued that it can actively manipulate mental images, some researchers have portrayed Baddeley's sketchpad system as a pure storage buffer without any processing capability.

Second, systematic issue-by-issue comparisons can also crystallize which seemingly conflicting theoretical claims are indeed mutually incompatible (rather than merely complementary) and, hence, must be resolved in future research. The identification of mutually incompatible claims not only sharpens the focus of research, but also provides an important basis for rigorous tests of competing ideas by way of "competitive argumentation" (VanLehn, Brown, & Greeno, 1984) – pitting competing models (or alternative versions of a single model) *directly* against one another to analyze and clarify theoretical issues often left implicit. VanLehn et al. clearly articulate the importance of this approach:

> To show that some constraint is crucial is to show that it is *necessary* in order for the theory to meet some criteria of adequacy. To show that it is *sufficient* is not enough. . . . [W]hen there are two theories, one claiming that principle X is sufficient and another claiming that a different, incompatible principle Y, is sufficient, sufficiency itself is no longer persuasive. One must somehow show that X is better than Y. Indeed, this sort of competitive argumentation is the only realistic alternative to necessity arguments (VanLehn et al., 1984, p. 240).

Last but not least, unification is always an aim of science, as Newell (1990) pointed out in his book *Unified Theories of Cognition*. Identifying which seemingly conflicting theoretical claims are in fact complementary could help unify or synthesize different models, possibly leading to a unified theory of working memory. As the broad range of the eight designated questions we discuss in the next section indicates (see Table 1.1), the key theoretical issues in current working memory research interface many (if not all) aspects of cognitive psychology. To borrow Haberlandt's (1997) expression, the study of working memory is essentially "a microcosm of the field of cognition" (p. 213). Thus, systematic comparisons of different models of working memory may even contribute strongly to the development of unified theories of cognition.

The Eight Designated Theoretical Questions for This Volume

The eight designated theoretical questions that provide a basis for the theoretical comparisons offered in this volume are listed in Table 1.1. They touch on all major theoretical issues of central importance to working memory research, including those that are currently highly controversial (particularly, Questions 3 and 4). We motivate the eight designated questions below, one by one, by discussing their importance in working memory research and providing a brief historical review. In addition, we offer some guidelines that might help readers in their endeavor of comparing and evaluating the models presented in this volume.

Table 1.1. The Eight Designated Questions for This Volume

(1) Basic Mechanisms and Representations in Working Memory
How is information encoded into and maintained in working memory? What is the retrieval mechanism? Also, how is information represented in working memory? Is the representation format for different types of information (e.g., verbal or visuospatial information) the same or different?

(2) The Control and Regulation of Working Memory
How is the information in working memory controlled and regulated? What determines which information is stored and which is ignored? Is the control and regulation of working memory handled by a central control structure (e.g., the central executive)? If so, what are the functions of the control structure? If your model does not postulate a central control structure, how do the control and regulation of information emerge?

(3) The Unitary Versus Non-Unitary Nature of Working Memory
Is working memory a unitary construct, or does it consist of multiple separable subsystems? If the latter is the case, then what are the subsystems of working memory and how do they interact with one another? What evidence or theoretical considerations justify your view?

(4) The Nature of Working Memory Limitations
What are the mechanisms that constrain the capacity of working memory (e.g., a limited supply of activation, processing speed, decay, inhibition, interference, skills)? If your model postulates multiple subsystems within working memory, does the same set of constraining mechanisms apply to each subsystem? What evidence or theoretical considerations have motivated the postulation of those capacity-constraining mechanisms?

(5) The Role of Working Memory in Complex Cognitive Activities
How is working memory implicated in the performance of complex cognitive tasks, such as language comprehension, spatial thinking, mental arithmetic, and reasoning and problem solving? What complex cognitive phenomena have you examined from the perspective of your model, and, according to your analysis, what role(s) does working memory play in these tasks? How does your model account for the performance limitations associated with these tasks?

(6) The Relationship of Working Memory to Long-Term Memory and Knowledge
What is the relationship between working memory and declarative long-term memory? Are they structurally separate entities? Or is working memory simply an activated portion of long-term memory? How do they interact with each other? How does working memory also relate to procedural skills? How might working memory limitations or functions be influenced by learning and practice?

continued

Table 1.1, continued

(7) The Relationship of Working Memory to Attention and Consciousness
What is the relationship between working memory and attention? Do these terms refer to the same construct? Or are they somehow separate from each other (either partially or completely)? If so, what differentiates them, and how do they interact with each other? Also, how does working memory relate to consciousness or awareness?

(8) The Biological Implementation of Working Memory
How does your model relate to various neuroscience findings on working memory (e.g., studies of brain-damaged patients, neuroimaging data, electrophysiological measures, animal studies)? How might your view of working memory be implemented in the brain?

Question 1: Basic Mechanisms and Representations in Working Memory

How is information encoded into and maintained in working memory? What is the retrieval mechanism? Also, how is information represented in working memory? Is the representation format for different types of information (e.g., verbal or visuospatial information) the same or different?

The traditional view of human memory (e.g., Atkinson & Shiffrin, 1968; Waugh & Norman, 1965) offers an elegant account of the basic mechanisms (encoding, maintenance, and retrieval) and representations in working memory or, rather, STM. According to this view, there are a number of structurally separate components or stores through which information is transferred. A subset of the information in the sensory registers is chosen for later processing via *selective attention* and is transferred into a short-term store (STS) (encoding). The information in the STS is considered fragile and decays quickly, so *rehearsal* is necessary to keep it within the STS (maintenance) and to transfer it to a more durable long-term store (LTS). The information in the STS is assumed to be accessible relatively quickly and effortlessly (retrieval), but there may be a slight slowdown of retrieval speed as a function of the number of items within the STS (Sternberg, 1966). Once lost from the STS, information cannot be retrieved unless it is encoded in the LTS. Retrieval from the LTS, however, is generally considered a slower and more effortful process than that from the STS.

As for the representation issue, the traditional view emphasizes speech-based codes (i.e., acoustic, phonological, or verbal) as the predominant memory code in STM, as reflected in the fact that most of the STM experiments in the 1960s and 1970s were done using verbal materials, despite the fact that Atkinson and Shiffrin (1968) themselves explicitly acknowledged the possibility of other STM codes (e.g., visual, spatial). The emphasis on speech-based codes in STM is contrasted with meaning-based (semantic) codes considered dominant in LTM.

This traditional view is simple and intuitively makes sense, but the story is too simplistic. It could be argued that the overall framework of the "modal" model is defensible (Healy & McNamara, 1996; Pashler & Carrier, 1996), but the basic mechanisms and representations of the model need to be modified, qualified, or elaborated further, given the recent empirical and theoretical advances in the field, particularly those associated with working memory research. The first question, thus, asked each contributor to outline his or her current view of the encoding, maintenance, and retrieval mechanisms as well as the nature of the representational codes in working memory.

Although all 10 theory chapters in this volume (Chapters 2 to 11) address the basic mechanism and representation issue, the types of answers they provide and the manners in which they answer this question vary considerably. Indeed, of all the eight questions, answers to the first question seem to be the most difficult to discern, perhaps because it is such a basic issue that, with the exception of Cowan (Chapter 3), the question is answered in an implicit, highly distributed fashion. Even though some chapters have a section dedicated to it, the arguments relevant to the basic mechanism and representation issue tend to be made in many different places throughout the chapter. Moreover, the chapters describing computational models tend to answer this question by outlining the overall architecture and the basic assumptions of their respective models. Although most of their descriptions have important implications for the issue of basic mechanisms and representations, those descriptions are not always directly cast in terms of the concepts we used in formulating this first question (i.e., encoding, maintenance, retrieval, and representational format). Thus, readers interested in comparing and contrasting the answers to Question 1 should keep these provisos in mind when they go through the chapters in this volume.

Question 2: The Control and Regulation of Working Memory

How is the information in working memory controlled and regulated? What determines which information is stored and which is ignored? Is the control and regulation of working memory handled by a central control structure (e.g., the central executive)? If so, what are the functions of the control structure? If your model does not postulate a central control structure, how do the control and regulation of information emerge?

From the beginning of modern working memory (or STM) research, the issue of control and regulation has been considered of central importance. Indeed, the notion of "control processes" was already present in Atkinson and Shiffrin's (1968) modal model of human memory. The control processes in that model, however, were limited to those involved in pure memorization, such as rehearsal, coding, and search strategies. In contrast to the traditional, storage-oriented notion of STM, working memory is considered a more processing-oriented construct and is sometimes conceptualized as the "workspace" or "blackboard" of the mind in which the active processing and temporary storage of task-relevant information dynamically take place. Such a view of working memory necessitates a more sophisticated account of control mechanisms that go beyond simple memorization strategies. In addition, there is an increasingly popular view of working memory as consisting of multiple subsystems. This view requires a satisfactory explanation of how these different subsystems are regulated so that working memory as a whole functions smoothly. The second designated question, therefore, asked the contributors to specify the mechanisms of control and regulation.

The classic answer to this "control and regulation" question is to postulate a central control structure like the central executive, as Baddeley and Hitch (1974) did in their influential multicomponent model. As often pointed out by critics, however, this approach has the danger of implicating a mysterious little "homunculus" inside working memory. In addition, as Baddeley (1986) himself admitted, the central executive may have become almost synonymous with a theoretical "ragbag" for all functions not attributable to the peripheral slave systems (i.e., the phonological loop and the visuospatial sketchpad).

Donald (1991) vividly described these problems associated with the notion of the central executive: "The 'central executive' is a hypothetical entity that sits atop the mountain of working memory and attention like some gigantic Buddha, an inscrutable, immaterial, omnipresent homunculus, at whose busy desk the buck stops every time memory and attention theorists run out of alternatives" (p. 327). The challenge, therefore, is to more precisely specify the mechanisms underlying the control and regulation of information in working memory without postulating an explicit homunculus-like entity.

The chapters in this volume provide interesting answers to this formidable challenge. As we discuss in more detail in the concluding chapter (Miyake & Shah, Chapter 13), the general approaches to the control and regulation issue represented in this volume range from specifying the subcomponents or subfunctions of a "central executive," through relying on regulatory mechanisms inherent in the underlying computational architecture, to conceptualizing control and regulation as an emergent property (i.e., a natural consequence of dynamic interactions among different subsystems). Readers might be interested in speculating on how well these models as a whole manage to address the "homunculus" or "ragbag" problem, a focus of the commentary provided in Chapter 12 by Kintsch, Healy, Hegarty, Pennington, and Salthouse.

Question 3: The Unitary Versus Non-Unitary Nature of Working Memory

Is working memory a unitary construct, or does it consist of multiple separable subsystems? If the latter is the case, then what are the subsystems of working *memory and how do they interact with one another? What evidence or theoretical considerations justify your view?*

The issue of whether working memory is unitary or non-unitary has been a source of controversy in the working memory literature. Some researchers have emphasized the unitary nature of working memory (e.g., Anderson et al., 1996; Engle et al., 1992; Kyllonen & Christal, 1990), whereas others have emphasized its non-unitary nature (e.g., Daneman & Tardif, 1987; Martin, 1993; Monsell, 1984; Shah & Miyake, 1996). Within the non-unitary camp, different researchers fractionate working memory in different ways, and there has been little consensus as to the number of subsystems and the nature of each subsystem. Some researchers, for example, are relatively conservative, proposing only a few domain-specific subsystems such as those for verbal and visuospatial storage or processing (e.g., Baddeley, 1986), whereas others postulate other subsystems or types of codes or representations, such as auditory, motor, lexical, semantic, syntactic, and so on (e.g., Barnard, 1985; Martin, 1993; Schneider & Detweiler, 1987). Some accounts go even further, postulating separable subsystems at a much finer level of analysis. One study of aphasic language comprehension, for example, argues for the independence of processing resources for computing a verb's thematic representations and those for computing the syntactic trace-antecedent relations (Shapiro, Gordon, Hack, & Killackey, 1993). The third designated question, thus, asked the contributors to discuss their current thoughts on the unitary or non-unitary nature of working memory.

This controversy has an interesting historical parallel in the domains of intelligence and attention.[2] In the case of intelligence, the Spearman–Thurston controversy is well known. Spearman (1904) argued that a single entity called *general intelligence* or *g* (conceptualized by Spearman as neurologically based "power" or "energy") underlies intellectual performances of various types, whereas Thurston (1938) argued that seven independent primary abilities can explain intellectual functioning well without postulating a general factor. Guilford (1967) went even further than Thurston, postulating 120 distinct ability factors in his "Structure of Intellect" model. Indeed, Eysenck's (1986) remark quoted earlier illustrates how radically different these psychometric theories looked from one another. Analogously, the "unitary versus non-unitary" debate also surrounded the resource (or capacity) theories of attention, some theorists

---

[2] The similarity of the unitary vs. non-unitary debate in intelligence and attention research is perhaps no coincidence. The factor analysis technique, used to develop psychometric theories of intelligence, and the analysis of performance-operating characteristics (POC), used to specify resource theories of attention, share some underlying commonalities (Heuer, 1985).

proposing a unitary view (e.g., Kahneman, 1973) and others a non-unitary view (e.g., Navon & Gopher, 1979; Wickens, 1984).[3]

At first glance, the answers to the question of the unitary versus non-unitary nature of working memory provided in this volume appear rather disparate. Some models strongly emphasize the unitary characteristics of working memory (e.g., Engle, Kane, & Tuholski, Chapter 4; Lovett, Reder, & Lebiere, Chapter 5), whereas others argue for a non-unitary position (e.g., Baddeley & Logie, Chapter 2; Barnard, Chapter 9; Schneider, Chapter 10). However, we would like to invite interested readers to evaluate if those seemingly different answers are fundamentally incompatible. The answer we offer in the final two chapters of this volume (Kintsch et al., Chapter 12; Miyake & Shah, Chapter 13) is "no." Whereas there are clearly some unresolved issues (see Chapter 13), we argue that a global consensus seems to be emerging and that some sort of synthesis may even be near.

Question 4: The Nature of Working Memory Limitations

What are the mechanisms that constrain the capacity of working memory (e.g., a limited supply of activation, processing speed, decay, inhibition, interference, skills)? If your model postulates multiple subsystems within working memory, does the same set of constraining mechanisms apply to each subsystem? What evidence or theoretical considerations have motivated the postulation of those capacity-constraining mechanisms?

The fourth designated question concerns the hallmark characteristic of working memory, identified and studied for over a century – the severe limitations in its capacity (e.g., Jacobs, 1887; James, 1890). In his classic book, William James (1890) stated that, unlike the virtually unlimited amount of knowledge that can be stored in a person's "secondary memory," only a small amount of information can be kept conscious at any one time in one's "primary memory." Moreover, the early scientific work reviewed by James suggests that there was much interest in the 1800s in just how much information can be temporarily maintained and for how long.

Despite the wide consensus on the existence of capacity limits in working memory, there has been little consensus, since the beginning, on the underlying mechanisms responsible for these limitations. For example, James (1890)

---

[3] Of course, this unitary vs. non-unitary debate still continues in both intelligence and attention research, but in a new direction. In intelligence research, the notion of *g* is still popular (Dennis & Tapsfield, 1996; Jensen, 1998), but modern versions of the non-unitary perspective that explicitly deny the necessity of postulating *g* also abound (e.g., Gardner, 1983/1993; see also Ceci, 1990/1996, for a detailed critique of *g*). In attention research, although the seemingly unitary characteristic of attention is noted by many researchers (e.g., Engle et al., Chapter 4; Lovett et al., Chapter 5), different ways of fractionating attention into different components or aspects have also been strongly advocated recently (e.g., Allport, 1993; Pashler, 1997; Posner & Raichle, 1994).

himself described a limitation in the absolute amount of information that can be maintained, whereas Hebb (1949) later described the limitation in terms of the amount of time that reverberatory circuits of neurons (so-called cell assemblies) can remain activated.

Undoubtedly, however, the best-known account of working memory limitations is George Miller's (1956) proposal of capacity limits, in which he argued that people are able to keep track of a "magic number 7 plus or minus 2" chunks of information. Perhaps influenced by the implication of Miller's analysis that most or all limits on mental processes could be attributed to a single source, subsequent proposals on the nature of working memory limitations tended to draw dichotomies between pairs or general classes of mechanisms. The most famous dichotomy is the one between "decay" and "interference" accounts of the forgetting mechanism in STM. Numerous studies have been conducted to resolve this still ongoing debate (Baddeley & Logie, Chapter 2; Cowan, Chapter 3).

More recently, explorations of the nature of working memory limitations have focused on the sources of individual and/or age-related differences in working memory capacity. Although it is generally agreed that there is a substantial individual or age-related variation in the amount of information one can keep track of simultaneously, the specific factor assumed to underlie the variation is different from proposal to proposal, including the total amount of activation resources available to the system (Engle et al., 1992; Just & Carpenter, 1992), processing speed (Salthouse, 1996), efficiency of inhibitory mechanisms (Stoltzfus, Hasher, & Zacks, 1996), and domain-specific knowledge and skills (Ericsson & Kintsch, 1995).

Here again, a popular research strategy seems to be dichotomization. These different accounts are typically pitted against each other in a pairwise fashion, and only one account is usually favored for the sake of "parsimony." In particular, the debate between the camp that emphasizes a basic cognitive mechanism as the primary source (i.e., the total amount of resources, processing speed, and inhibition) and the camp that emphasizes an experience-based or practice-based factor (i.e., knowledge and skills) is reminiscent of the (in)famous nature versus nurture debate, another intriguing parallel to intelligence research.

Given this situation, it is perhaps not surprising that the chapters in this volume propose many different underlying mechanisms for working memory limitations. Some models even propose that working memory limitations may be an emergent property (Young & Lewis, Chapter 7; Barnard, Chapter 9; Schneider, Chapter 10; O'Reilly, Braver, & Cohen, Chapter 11). As Kintsch et al. summarize in Chapter 12 (see Table 12.1), the specific capacity-limiting factors mentioned in this volume are quite diverse and, at this microlevel of analysis, there seems to be no general consensus among the answers to this fourth designated question. As is the case with the unitary versus non-unitary issue, however, we are optimistic that the field may already be moving toward a resolution of this controversial issue regarding the nature of working memory limitations (see Miyake & Shah, Chapter 13). We invite readers to evaluate whether the answers given to this question indeed share some commonality that goes beyond the seemingly disparate capacity-limiting mechanisms advocated by each model.

Question 5: The Role of Working Memory in Complex Cognitive Activities

How is working memory implicated in the performance of complex cognitive tasks, such as language comprehension, spatial thinking, mental arithmetic, and reasoning and problem solving? What complex cognitive phenomena have you examined from the perspective of your model, and, according to your analysis, what role(s) does working memory play in these tasks? How does your model account for the performance limitations associated with these tasks?

One of the major driving forces behind the theoretical transition from STM to working memory was the realization that the memory models developed to account for STM phenomena cannot necessarily illuminate the kinds of temporary memory involved in the performance of complex cognitive tasks (Baddeley & Hitch, 1974; Reitman, 1970). Indeed, one could reasonably argue that working memory is a theoretical concept developed to bring studies of memory into closer alignment with studies of cognition. The fifth question, thus, asked the contributors to outline how their respective models represent this rapprochement between memory and cognition and how working memory is implicated in the performance of complex cognitive tasks.

This issue has typically been addressed in three complementary ways, all of which have been successful in demonstrating the importance of working memory in the performance of a variety of complex cognitive tasks. One popular approach, frequently used in the United Kingdom in the context of Baddeley's (1986) model of working memory, is to conduct experiments using the so-called dual-task interference paradigm. In this paradigm, a cognitive task of interest is performed by itself and with a secondary task considered to tap primarily one of the subcomponents of working memory.[4] If the secondary task disrupts the performance of the primary cognitive task when compared to the control condition, then it is usually inferred that the sub-

---

[4] In the case of the phonological loop, the secondary task typically used is articulatory suppression (repeatedly articulating familiar syllables, words, or phrases, such as "the, the, the . . ." or "one, two, three"). In the case of the visuospatial sketchpad, a spatial tapping task (sequentially tapping four corners of a square with a finger) is often used, particularly when a primary task is considered to implicate the maintenance of spatial (as opposed to purely visual) information. In the case of the central executive, the secondary task often used is a random generation task, which involves the oral generation of a random sequence of numbers or letters.

component tapped by the secondary task is involved in the performance of the primary cognitive task. This approach has successfully been used to specify whether a given cognitive task implicates a given subcomponent of working memory (Baddeley & Logie, Chapter 2).

Another approach, particularly popular in North America, has been to examine the role of working memory in complex cognitive tasks from the perspective of individual differences, using various working memory span tasks (such as reading, operation, and spatial spans) as a research tool (Daneman & Carpenter, 1980; Engle et al., 1992; Salthouse & Babcock, 1991; Shah & Miyake, 1996). These span tasks are designed to resemble the working memory demands during the performance of complex cognitive tasks by placing simultaneous demands on both processing and storage. This individual differences approach usually specifies the role of working memory in complex cognition either by correlating participants' performance on these span tasks with that on other target tasks or by classifying the participants into different groups on the basis of their performance on the span tasks and examining how these groups differ in their performance of complex cognitive tasks.

The third, most recent approach is to develop computational models that simulate the effects of individual differences and/or working memory load on participants' performance on various cognitive tasks. Previous examples of this approach include the models of sentence comprehension (Just & Carpenter, 1992), discourse comprehension (Goldman & Varma, 1995), mental algebra (Anderson et al., 1996), reasoning and problem solving (Just, Carpenter, & Hemphill, 1996), and human–computer interaction (Byrne & Bovair, 1997; Huguenard, Lerch, Junker, Patz, & Kass, 1997).

The 10 theory chapters in this volume, as a whole, discuss an impressively wide range of complex cognitive tasks, ranging from immediate serial recall of words (Kieras, Meyer, Mueller, & Seymour, Chapter 6) through syllogistic reasoning (Baddeley & Logie, Chapter 2) to human–computer interaction (Young & Lewis, Chapter 7). All three approaches outlined above are represented in the contributors' answers to this fifth question, but the recent studies discussed in the chapters incorporate some interesting new twists. We briefly mention a few examples here.

Although the dual-task methodology is usually used to demonstrate whether or not a certain subcomponent is implicated in a given cognitive task, Baddeley and Logie (Chapter 2) discuss several recent studies in which the dual-task methodology was successfully used to specify exactly what role a specific subcomponent plays in the performance of the target task. Engle et al. (Chapter 4) present their new individual differences work (Engle et al., in press), in which they go beyond simple correlational analyses by using a sophisticated latent variable technique to address what factors are driving the correlation between working memory spans and complex cognitive tasks. As for the computational modeling approach, Lovett et al. (Chapter 5) discuss work in which they go beyond the common practice of simulating aggregated group-level data (e.g., high-span vs. low-span participants) and predict participants' performance across multiple tasks on an individual-by-individual basis by manipulating a simple parameter.

In addition to these exciting new developments in the typical approach to studying the role of working memory in complex cognitive tasks, the chapters in this volume consider two relatively new directions. Some chapters (most notably, Ericsson & Delaney, Chapter 8), for example, argue for the necessity of extending the three approaches to include studies of how experts or skilled individuals maintain task-relevant information during the performance of familiar tasks. In addition, some chapters also argue for the importance of understanding how different areas of the brain are implicated in working memory (e.g., O'Reilly et al., Chapter 11). Thus, taken together, the answers to the fifth question presented in this volume delineate a useful overview of the state-of-the-art research that deepens our understanding of the role of working memory in complex cognitive tasks.

Question 6: The Relationship of Working Memory to Long-Term Memory and Knowledge

What is the relationship between working memory and declarative long-term memory? Are they structurally separate entities? Or is working memory simply an activated portion of long-term memory? How do they interact with each other? How does working memory also relate to procedural skills? How might working memory limitations or functions be influenced by learning and practice?

On the basis of the well-known serial position effects (i.e., the primacy and recency effects in free recall) and some neuropsychological dissociations (as demonstrated by such patients as HM), early information-processing models of memory assumed a structural distinction between STM (or working memory) and LTM (e.g., Atkinson & Shiffrin, 1968; Broadbent, 1958; Waugh & Norman, 1965). Moreover, these models considered STM a gateway or stepping stone to a more permanent LTM,[5] proposing that information that is either rehearsed, attended to, or organized properly in STS is transferred to an LTS. In contrast to this structural view of human memory, an alternative view emphasized the continuity between working memory and LTM and proposed that working memory can be considered an activated portion of LTM representations (Norman, 1968). This more continuous view gained some popularity in cognitive psychology (Anderson, 1983; Cowan, 1988), as empirical data that challenged the interpretations of the hallmark empirical findings for the

---

[5] James (1890) expressed this "gateway" idea more than a century ago, arguing that, for information to be in a retrievable "after-memory," it must have reached some state in our primary memory by having been active for a minimal period of time (see also Hebb, 1949, for a similar idea).

structural view – the serial position effects and the neuropsychological dissociations – started to accumulate (for a review of the evidence against the structural view, see Crowder, 1982, 1993). The sixth question, thus, asked the contributors to outline their current take on the nature of the distinction between working memory and LTM.

Another issue raised by Question 6 concerns the role of long-term knowledge and skills in the performance of working memory tasks. Historically, much STM research followed the Ebbinghaus tradition, using stimulus materials and experimental paradigms that were not particularly meaningful or familiar to participants. However, as more researchers started to examine people's temporary memory performance using tasks more familiar and more meaningful to them, such as chess positions (Chase & Simon, 1973) and restaurant orders (Ericsson & Polson, 1988), the role of long-term knowledge and skills in STM or working memory tasks became more obvious. Even the signature task for STM research, the serial recall of digit sequences, was not an exception in this regard: Individuals could be trained to use their existing long-term knowledge to strategically encode the digit sequence to enhance later retrieval (Chase & Ericsson, 1981). Moreover, developmental studies highlighted the strong impact of content knowledge on temporary memory by demonstrating that knowledgeable children can outperform less knowledgeable adults in the children's domains of expertise, such as chess (Chi, 1978) and soccer (Schneider, Körkel, & Weinert, 1989) (for more details, see Ericsson & Delaney, Chapter 8).

The important question, then, is what implications the effects of long-term knowledge and skills have for models of working memory. Ericsson and Kintsch (1995) recently proposed the notion of "long-term working memory" (LT-WM) to account for such phenomena, arguing that long-term knowledge can be used to supplement the severely limited capacity of what they called "short-term working memory" (ST-WM). They also put forth a provocative claim that individual differences in long-term knowledge and skills may be able to provide a complete, parsimonious account of individual differences in working memory performance, without postulating any systematic differences in the capacity of ST-WM per se (e.g., the total amount of activation available, as proposed by Just & Carpenter, 1992). This claim is controversial because it could essentially be interpreted as arguing for an extreme "nurture" view of individual differences in working memory capacity, if we revert back to the parallelism to intelligence research. The second part of the sixth question, thus, asked the contributors to express their theoretical position on the role of long-term knowledge and skills in working memory performance.

The chapters in this volume provide interesting answers to both of the theoretical issues regarding the relationship between working memory and LTM. Although there are some important differences, readers will undoubtedly notice that the answers to this sixth question reveal a surprisingly high degree of consensus among the contributors (see Miyake & Shah, Chapter 13, for a detailed discussion of the nature of the general agreement). Briefly put, the chapters highlight the necessity to go beyond the traditional structural distinction assumed in the classic information-processing models of human memory (e.g., Atkinson & Shiffrin, 1968; Waugh & Norman, 1965). As for the role of LTM in working memory performance, several chapters explicitly discuss Ericsson and Kintsch's (1995) LT-WM proposal and some even point out analogous mechanisms present in their own models (Baddeley & Logie, Chapter 2; Cowan, Chapter 3; Young & Lewis, Chapter 7; O'Reilly et al., Chapter 11; see in particular Cowan's proposal of "virtual short-term memory" in Chapter 3). Ericsson himself offers an interesting synthesis of the working memory analog of the nature versus nurture controversy (Ericsson & Delaney, Chapter 8).

Question 7: The Relationship of Working Memory to Attention and Consciousness

What is the relationship between working memory and attention? Do these terms refer to the same construct? Or are they somehow separate from each other (either partially or completely)? If so, what differentiates them, and how do they interact with each other? Also, how does working memory relate to consciousness or awareness?

Perhaps because there are clear limitations in the amount of information one can attend to or be conscious of, as well as in the amount of information that can be maintained in working memory, it is widely acknowledged that the constructs of working memory (or STM), attention, and consciousness are related to one another. Indeed, these constructs are sometimes used almost interchangeably. Atkinson and Shiffrin (1971) expressed a view that essentially equates STM to the content of consciousness: "In our thinking we tend to equate the short-term store with 'consciousness,' that is, the thoughts and information of which we are currently aware can be considered part of the contents of the short-term store" (p. 83). Similarly, Baddeley (1993) once remarked that working memory may actually be better construed as "working attention." Despite the apparent close interrelationship among working memory, attention, and consciousness, many researchers draw some distinctions among them or propose a subset or overlapping relation (e.g., Baars, 1997a; Cowan, 1988). The seventh question, thus, asked the contributors to speculate on the question of how working memory is related to the concepts of attention and consciousness or conscious awareness.

Traditional models of human memory characterized attention as a filtering mechanism that limits the amount of information entering or remaining in a memory store (Atkinson & Shiffrin, 1968; Broadbent, 1958). In these conceptions, temporary memory and attention were considered distinct, associated with separate functions. This distinction was blurred, however, as the notion of "processing resources," originally proposed within the context of resource theories of attention (Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1984), gained some popularity and was eventually incorporated into models of working memory (Baddeley & Hitch, 1974; Just & Carpenter, 1992). In addition, Baddeley's (1986, 1993) emphasis on the control functions of the central executive and, more specifically, his proposal that Norman and Shallice's (1986) Supervisory Attentional System (SAS) may be considered a model of the central executive might have also contributed to the blurring of the distinction between the notions of working memory and attention.

Just as working memory and attention have been considered related, the idea that there is an intimate link between working memory and consciousness also has a long history. For example, William James (1890) cited many of his contemporaries or predecessors who noted the inextricable link between primary memory and consciousness (e.g., Richet's remark, "Without memory no conscious sensation, without memory no consciousness"). More recent specific proposals about the relation between working memory and consciousness seem to center around the view reflected in the previous quote from Atkinson and Shiffrin (1971), namely that the contents of working memory are what we are conscious of at the moment. Although this view seems prevalent (e.g., Moscovitch & Umiltà, 1990), another view expressed by several researchers is that, to be aware of something, that something must be in working memory, but that not everything in working memory can be consciously experienced – only elements in working memory under the "focus of attention" or a "spotlight" can (e.g., Cowan, 1988). Baars's (1997b) Global Workspace theory, which argues for the "theater" metaphor of consciousness, expresses this viewpoint particularly clearly:

> [In the Global Workspace theory,] conscious contents are limited to a brightly lit spot of attention onstage, while the rest of the stage corresponds to immediate working memory. Behind the scenes are executive processes, including a director, and a great variety of contextual operators that shape conscious experience without themselves becoming conscious. In the audience are a vast array of intelligent unconscious mechanisms. . . . Elements of working memory – on stage, but not in the spotlight of attention – are also unconscious (Baars, 1997b, p. 43).

The answers to this seventh designated question extend the previous accounts of the relationship between attention and working memory in exciting new ways. Just to give an example, Engle et al. (Chapter 4) put forth an intriguing proposal that working memory essentially amounts to STM plus what they call "controlled attention," thereby arguing for a clear separation between the storage and (attentional) control functions of working memory (see Baddeley & Logie, Chapter 2, for a similar claim and O'Reilly et al., Chapter 11, for an opposing claim). Although most chapters provide interesting discussions of the relationship between attention and working memory, this is one area where we feel that there is not yet a general point of agreement. In Chapter 13, we will discuss how we might go about developing a more comprehensive account of how working memory and attention interact. As for the relationship between working memory and consciousness, most chapters in this volume acknowledge a close relationship between the two, but their accounts do not go much beyond the previous accounts we outlined earlier, even though the models in this volume have a theoretical scope broad enough to serve as a basis for exploring how working memory and consciousness relate to each other.

Question 8: The Biological Implementation of Working Memory

How does your model relate to various neuroscience findings on working memory (e.g., studies of brain-damaged patients, neuroimaging data, electrophysiological measures, animal studies)? How might your view of working memory be implemented in the brain?

Cognitive neuroscience has made remarkable progress in the understanding of the biological and neural basis of cognition during this "decade of the brain" (Gazzaniga, 1995; Gazzaniga, Ivry, & Mangun, 1998; Rugg, 1997). This new emerging field pursues the question of how the brain enables complex perceptual and cognitive processes, using a variety of research methodologies. These methodologies include (but are not necessarily limited to) (a) behavioral studies of brain-damaged patients (sometimes called "cognitive neuropsychology"); (b) neuroimaging (e.g., positron emission tomography [PET]; functional magnetic resonance imaging [fMRI]); (c) electrophysiological recordings from humans (e.g., event-related brain potentials [ERP]); (d) animal studies (e.g., lesioning, single-cell recordings, etc.); and (e) computational modeling of neurophysiological or neuropsychological phenomena (e.g., connectionist simulation).

Working memory is one of the major foci of current cognitive neuroscience research, and the progress and its impact on cognitive psychology have been impressive (for a recent overview, see Beardsley, 1997; Smith & Jonides, 1997; Wickelgren, 1997). This volume might have focused a great deal more on the purely cognitive aspects of working memory if it had been edited several years ago, but comprehensive models of working memory can no longer ignore the insights and constraints offered by rich cognitive neuroscience findings. Thus, the final designated question asked the contributors to discuss how their respective models can accommodate (or at least relate to) recent cognitive neuroscience findings. The question also asked them to speculate about how their respective views of working memory might be actually implemented in the brain.

Although the surge of interest in the neural basis of working memory is a quite recent phenomenon, the important role of the prefrontal cortex (PFC) in working memory, emphasized in several chapters of this volume (most notably, Engle et al., Chapter 4; O'Reilly et al., Chapter 11), has long been anticipated. In their influential book *Plans and the Structure of Behavior*, Miller, Galanter, and Pribram (1960) not only used the term "working memory" for the first time (Richardson, 1996), but also speculated that "[the] most forward portion of the primate frontal lobe appears to us to serve as a 'working memory' where Plans can be retained temporarily when they are being formed, or transformed, or executed" (Miller et al., 1960, p. 207). Recent cognitive neuroscience studies seem to confirm the involvement of PFC during working memory performance (see Fuster, 1997, for a comprehensive review of the PFC anatomy and functions). In particular, existing evidence seems to be converging on the view that various areas of the brain work together, perhaps orchestrated by PFC, to produce working memory phenomena (Wickelgren, 1997), a view that also seems to be generally endorsed by the chapters in this volume.

Although incorporating biological-level mechanisms is the primary concern of only two models in this volume (Schneider, Chapter 10; O'Reilly et al., Chapter 11), other contributors also offer extensive discussions of how their respective models can accommodate some of the recent neuroscience findings on working memory. The range of cognitive neuroscience evidence discussed in this volume is impressive, covering all five major approaches to cognitive neuroscience we listed above: neuropsychological dissociations (Baddeley & Logie, Chapter 2), neuroimaging (Schneider, Chapter 10; O'Reilly et al., Chapter 11), ERP (Cowan, Chapter 3), single-cell recordings from nonhuman primates (Engle et al., Chapter 4; O'Reilly et al., Chapter 11), and computational modeling (Lovett et al., Chapter 5; Schneider, Chapter 10; O'Reilly et al., Chapter 11). Thus, this volume as a whole serves as an up-to-date review of recent cognitive neuroscience research on working memory.

Organization of This Volume

Following this introductory chapter, the subsequent chapters (Chapters 2 to 11) present 10 different models of working memory. Figure 1.1 provides a schematic summary of the models presented in this volume, including the chapter number, the names of the contributors, and the name of the model. The figure also indicates some information about the perceived relatedness or compatibility of the 10 models; pairs of models that were informally judged to be closely related or highly compatible at a global level by the contributors to this volume are connected by the links on the left-hand side of the figure.[6] Note that these links are intended to serve only as a rough guideline of which

---

[6] The informal ratings were collected at the end of the companion symposium (July 10–13, 1997) on which this volume is based. The contributors to this volume (one questionnaire per chapter) were asked to rate the compatibility among different models in a pairwise fashion on an 11-point scale, ranging from 0 (totally incompatible) to 10 (totally compatible). The links included on the left-hand side of the figure shows the pairs of models that received an average rating of 6.0 or above and, hence, were judged to be relatively compatible with each other in some way by the contributors of this volume.

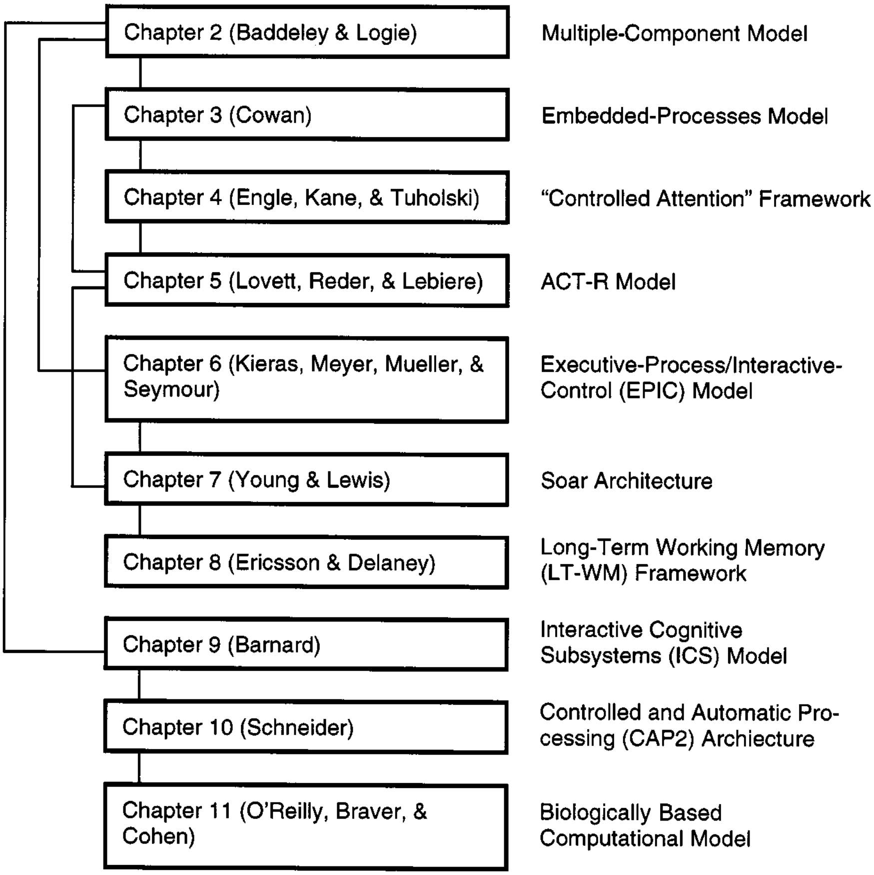

Figure 1.1. A schematic summary of the models included in this volume and their interrelationships. The name that is used to refer to the model, theory, or framework in this volume is included in the figure, as well as the chapter number and the names of the authors. The additional links, provided on the left-hand side of the figure, connect the models that were informally judged to be highly related or compatible by the chapter contributors (see footnote 6 for more details on the basis for these links).

models are particularly similar to one another. As the rich set of cross-references included in the chapters of this volume makes clear, the models that are not connected to one another in Figure 1.1 often share some important common features or ideas as well.

The first four models (Chapters 2 to 5) are closely related to one another because they emphasize a close relationship between attention and working memory. The presentation of the models begins with Baddeley and Logie's (Chapter 2) discussion of the well-known multiple component model of working memory (or "working attention," Baddeley, 1993). Although the

Baddeley–Logie model maintains the original tripartite structure proposed by Baddeley and Hitch (1974), it has undergone a number of important changes, particularly in regard to specifying the functions of the central executive. Chapter 2 documents these changes.

Chapter 3 presents Cowan's Embedded-Processes Model, a broad-scope information processing framework originally developed to synthesize a vast array of empirical findings on attention and memory (Cowan, 1988). Although it is not a model of working memory per se, it can serve as a basis for detailed, empirically well-supported answers to the eight designated questions.

In Chapter 4, Engle, Kane, and Tuholski describe their new theoretical perspective on working memory, which could be called the "controlled attention" framework. Recent cognitive neuroscience findings on the role of PFC in executive control and attentional processes provided an inspiration for this framework, and Engle et al. discuss an interesting series of studies to illustrate the important role of "controlled attention" in working memory and complex cognition.

Chapter 5 presents Lovett, Reder, and Lebiere's ACT-R model of working memory (Anderson, 1993; Anderson & Lebiere, 1998; Anderson et al., 1996). Their conceptualization of working memory is similar to Just and Carpenter's (1992) model in a number of respects, but the characterization of working-memory limitations in ACT-R is different in that it postulates an attentional limit (i.e., how much information one can simultaneously attend to) by limiting the total amount of "source activation" (rather than the total amount of activation available to the system).

The ACT-R chapter is also the first of the three (Chapters 5 to 7) that are based on symbolic computational architectures. The focus of Chapter 6 is the Executive-Process/Interactive-Control (EPIC) architecture, developed by Kieras, Meyer, and their colleagues (e.g., Meyer & Kieras, 1997). EPIC is unique in its well-developed interface with perceptual and motor processes and its strong emphasis on strategic executive control of behavior. In Chapter 6, Kieras, Meyer, Mueller, and Seymour discuss this EPIC framework within the context of its application to one of the signature working memory tasks, the immediate serial recall of words.

Chapter 7 discusses working memory from the perspective of Soar (Laird, Newell, & Rosenbaum, 1987), a cognitive architecture that Newell (1990) presented as a candidate unified theory of cognition in his book. In this chapter, Young and Lewis provide interesting answers to one common criticism of the Soar architecture, namely that its working memory is too big as a theory of human cognition because virtually no constraints are placed on it (e.g., Carlson & Detweiler, 1992; Lewandowsky, 1992).

Soar's functional account of working memory emphasizes the important role of learning, knowledge, and skills and, in that sense, has a strong resemblance to Ericsson and Kintsch's (1995) LT-WM account. In Chapter 8, Ericsson and Delaney elaborate this LT-WM framework and argue for extending the scope of working memory research to encompass temporary maintenance of information in not just unfamiliar, lab-based tasks, but also skilled everyday activities.

Chapters 9 and 10 are closely related to each other in that both propose a distributed framework in which working memory emerges from multiple subsystems interacting with one another over a network. In Chapter 9, Barnard outlines the Interactive Cognitive Subsystems (ICS) architecture, which started as a psycholinguistic model of STM (Barnard, 1985), but has since been refined and applied to a wider range of phenomena, including human–computer interaction and normal and pathological cognitive-affective processing. Although strikingly different from the Baddeley–Logie model (Chapter 2) on the surface, it is highly compatible with their model (as reflected in the link between these two models in Figure 1.1) in that the three subcomponents of the Baddeley–Logie model (i.e., the phonological loop, the visuospatial sketchpad, and the central executive) can be nicely mapped onto the ICS framework.

The focus of Chapter 10 is Schneider's Controlled and Automatic Processing (CAP2) architecture, which has been strongly influenced by research in learning and skill acquisition as well as in cognitive neuroscience. Like the ICS architecture, the CAP2 system was originally presented as a model of working memory (Schneider & Detweiler, 1987), but is indeed a general cognitive architecture that can account for a wide range of cognitive performance. In Chapter 10, Schneider offers his latest account of this connectionist architecture that features hierarchically organized executive control mechanisms.

Schneider's (Chapter 10) emphasis on the neural basis of working memory provides a nice transition to the last model of this volume, O'Reilly, Braver, and Cohen's biologically based model of working memory (Chapter 11). O'Reilly et al.'s connectionist framework represents an attempt to start developing an explicit computational model of working memory and executive control that is biologically plausible and is firmly rooted in the principles of cognitive processing in the brain. Although the novel framework outlined in this chapter is not yet implemented in its entirety, it brings studies of working memory into closer alignment with our rapidly expanding knowledge of its underlying biological and neural basis.

This volume concludes with two integrative chapters (Chapters 12 and 13) whose goal is to put these 10 different models of working memory into perspective. Chapter 12, written by the researchers who served as discussants at a companion symposium that was held in July 1997 (Kintsch, Healy, Hegarty, Pennington, & Salthouse), provides issue-by-issue analyses and evaluations of the 10 models' answers to the eight designated questions outlined in this chapter.

Whereas the focus of Chapter 12 is the evaluation of the *current* status of the models, the primary focus of our final chapter (Miyake & Shah, Chapter

13) is the *future* of working memory models and research. In this final chapter, we go back to the original motivation for this volume mentioned at the beginning of this chapter (i.e., addressing the "What is working memory, anyway?" question). Based on our reading of Chapters 2 to 11, we offer six common themes or points of general consensus that we believe unify the 10 seemingly disparate models of working memory and, hence, jointly define what working memory really is. We then present our analysis of the major unresolved theoretical issues for each of the eight designated questions and also point out some other promising future directions that are not covered in this volume, but that we believe may become increasingly important in the future.

In summary, this volume offers detailed, systematic comparisons of 10 influential models of working memory by asking each contributor to address the same set of important theoretical questions. Our primary goal is to elucidate the commonalities and differences among these models to better define and understand working memory. Although the final two chapters (Chapters 12 and 13) provide detailed discussions of what commonalities and differences exist among the 10 models, we would like to emphasize here that they are nothing but our opinions, our reflections on what we have learned from this issue-by-issue comparison. Thus, we hereby urge readers to compare and contrast the models in this volume and to draw their own conclusions about the current status and future directions of the field.

REFERENCES

Allport, A. (1993). Attention and control: Have we been asking the wrong questions? A critical review of twenty-five years. In D. E. Meyer & S. M. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 183–218). Cambridge, MA: MIT Press.

Anderson, J. R. (1983). *Architecture of cognition.* Cambridge, MA: Harvard University Press.

Anderson, J. R. (1993). *Rules of the mind.* Hillsdale, NJ: Erlbaum.

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought.* Mahwah, NJ: Erlbaum.

Anderson, J. R., Reder, L. M., & Lebiere, C. (1996). Working memory: Activation limitations on retrieval. *Cognitive Psychology, 30,* 221–256.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 2, pp. 89–195). New York: Academic Press.

Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American, 225,* 82–90.

Baars, B. J. (1997a). Some essential differences between consciousness and attention, perception, and working memory. *Consciousness and Cognition, 6,* 363–371.

Baars, B. J. (1997b). *In the theater of consciousness: The workspace of the mind.* New York: Oxford University Press.

Baddeley, A. D. (1986). *Working memory.* New York: Oxford University Press.

Baddeley, A. D. (1993). Working memory or working attention? In A. D. Baddeley & L. Weiskrantz (Eds.), *Attention: Selection, awareness, and control. A tribute to Donald Broadbent* (pp. 152–170). New York: Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York: Academic Press.

Barnard, P. J. (1985). Interacting cognitive subsystems: A psycholinguistic approach to short-term memory. In A. W. Young (Ed.), *Progress in the psychology of language* (Vol. 2, pp. 197–258). London: Erlbaum.

Baumgartner, P., & Payr, S. (1995). *Speaking minds: Interviews with twenty eminent cognitive scientists.* Princeton, NJ: Princeton University Press.

Beardsley, T. (1997). The machinery of thought. *Scientific American, 277,* 78–83.

Brainerd, C. J., & Kingma, J. (1985). On the independence of short-term memory and working memory in cognitive development. *Cognitive Psychology 17,* 210–247.

Broadbent, D. E. (1958). *Perception and communication.* New York: Pergamon Press.

Byrne, M. D., & Bovair, S. (1997). A working memory model of a common procedural error. *Cognitive Science, 21,* 31–62.

Carlson, R. A., & Detweiler, M. (1992). A unified theory for psychologists? *Behavioral and Brain Sciences, 15,* 440.

Ceci, S. J. (1990/1996). *On intelligence: A bioecological treatise on intellectual development.* Cambridge, MA: Harvard University Press.

Chase, W. G., & Ericsson, K. A. (1981). Skilled memory. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 141–189). Hillsdale, NJ: Erlbaum.

Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215–281). New York: Academic Press.

Chi, M. T. H. (1978). Knowledge structures and memory development. In R. S. Siegler (Ed.), *Children's thinking: What develops*? Hillsdale, NJ: Erlbaum.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin, 104,* 163–191.

Crowder, R. G. (1982). The demise of short-term memory. *Acta Psychologica, 50,* 291–323.

Crowder, R. G. (1993). Short-term memory: Where do we stand? *Memory & Cognition, 21,* 142–145.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466.

Daneman, M., & Tardif, T. (1987). Working memory and reading skill reexamined. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 491–508). Hillsdale, NJ: Erlbaum.

Dennis, I., & Tapsfield, P. (Eds.). (1996). *Human abilities: Their nature and measurement.* Mahwah, NJ: Erlbaum.

Donald, M. (1991). *Origins of the modern mind: Three stages in the evolution of culture and cognition.* Cambridge, MA: Harvard University Press.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 972–992.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (in press). Working memory, short-term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General.*

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102,* 211–245.

Ericsson, K. A., & Polson, P. G. (1988). A cognitive analysis of exceptional memory for restaurant orders. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 23–70). Hillsdale, NJ: Erlbaum.

Eysenck, H. J. (1986). The theory of intelligence and the psychophysiology of cognition. In R. J. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 3, pp. 1–34). Hillsdale, NJ: Erlbaum.

Fuster, J. M. (1997). *The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe* (3rd ed.). Philadelphia: Lippincott–Raven.

Gagliardo, A., Mazzotto, M., & Divac, I. (1997). Memory of radial maze behavior in pigeons after ablations of the presumed equivalent of mammalian prefrontal cortex. *Behavioral Neuroscience, 111,* 968–975.

Gardner, H. (1983/1993). *Frames of mind: The theory of multiple intelligences.* New York: Basic Books.

Gazzaniga, M. S. (Ed.). (1995). *The cognitive neuroscience.* Cambridge, MA: MIT Press.

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (1998). *Cognitive neuroscience: The biology of the mind.* New York: Norton.

Goldman, S. R., & Varma, S. (1995). CAPping the Construction-Integration model of discourse comprehension. In C. A. Weaver, S. Mannes, & C. R. Fletcher (Eds.), *Discourse comprehension: Essays in honor of Walter Kintsch* (pp. 337–358). Hillsdale, NJ: Erlbaum.

Goldman-Rakic, P. S. (1992). Working memory and the mind. *Scientific American, 267,* 110–117.

Guilford, J. P. (1967). *The nature of human intelligence.* New York: McGraw-Hill.

Haberlandt, K. (1997). *Cognitive psychology* (2nd ed.). Boston: Allyn & Bacon.

Healy, A. F., & McNamara, D. S. (1996). Verbal learning and memory: Does the modal model still work? *Annual Review of Psychology, 47,* 143–172.

Hebb, D. O. (1949). *The organization of behavior.* New York: Wiley.

Heuer, H. (1985). Some points of contact between models of central capacity and factor-analytic models. *Acta Psychologica, 60,* 135–155.

Huguenard, B. R., Lerch, F. J., Junker, B. W., Patz, R. J., & Kass, R. E. (1997). Working-memory failure in phone-based interaction. *ACM Transactions on Computer–Human Interaction, 4,* 67–102.

Jacobs, J. (1887). Experiments on "prehension." *Mind, 12,* 75–79.

James, W. (1890). *Principles of psychology.* New York: Holt.

Jensen, A. R. (1998). *The g factor: The science of mental ability.* Westport, CT: Praeger.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122–149.

Just, M. A., Carpenter, P. A., & Hemphill, D. D. (1996). Constraints on processing capacity: Architectural or implementational? In D. M. Steier & T. M. Mitchell (Eds.), *Mind matters: A tribute to Allen Newell* (pp. 141–178). Mahwah, NJ: Erlbaum.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice Hall.

Klapp, S. T., Marshburn, E. A., & Lester, P. T. (1983). Short-term memory does not involve the "working memory" of information processing: The demise of a common assumption. *Journal of Experimental Psychology: General, 112,* 240–264.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?! *Intelligence, 14,* 389–433.

Laird, J. E., Newell, A., & Rosenbloom, P. S. (1987). Soar: An architecture for general intelligence. *Artificial Intelligence, 33,* 1–64.

Lewandowsky, S. (1992). Unified cognitive theory: Having one's apple pie and eating it. *Behavioral and Brain Sciences, 15,* 449–450.

Martin, R. C. (1993). Short-term memory and sentence processing: Evidence from neuropsychology. *Memory & Cognition, 21,* 176–183.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: I. Basic mechanisms, *Psychological Review, 104,* 3–65.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63,* 81–97.

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior.* New York: Holt, Rinehart, and Winston.

Monsell, S. (1984). Components of working memory underlying verbal skills: A `distributed capacities' view—A tutorial review. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X* (pp. 327–350). Hillsdale, NJ: Erlbaum.

Moscovitch, M., & Umiltà, C. (1990). Modularity and neuropsychology: Modules and central processes in attention and memory. In M. F. Schwartz (Ed.), *Modular deficits in Alzheimer-type dementia* (pp. 1–59). Cambridge, MA: MIT Press.

Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review, 86,* 214–255.

Newell, A. (1990). *Unified theories of cognition.* Cambridge, MA: Harvard University Press.

Norman, D. A. (1968). Toward a theory of memory and attention. *Psychological Review, 75,* 522–536.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation: Advances in research and theory* (Vol. 4, pp. 1–18). New York: Plenum Press.

Olton, D. S. (1977). Spatial memory. *Scientific American, 236,* 82–98.

Pashler, H. E. (1997). *The psychology of attention.* Cambridge, MA: MIT Press.

Pashler, H. E., & Carrier, M. (1996). Structures, processes, and the flow of information. In E. L. Bjork & R. A. Bjork (Eds.), *Memory* (pp. 3–29). San Diego, CA: Academic Press.

Posner, M. I., & Raichle, M. E. (1994). *Images of mind.* New York: Scientific American Library.

Reitman, W. (1970). What does it take to remember? In D. A. Norman (Eds.), *Models of human memory* (pp. 469–509). New York: Academic Press.

Richardson, J. T. E. (1996). Evolving concepts of working memory. In J. T. E. Richardson, R. W. Engle, L. Hasher, R. H. Logie, E. R. Stoltzfus, & R. T. Zacks (Eds.), *Working memory and human cognition* (pp. 3–30). New York: Oxford University Press.

Rugg, M. D. (Ed.). (1997). *Cognitive neuroscience.* Cambridge, MA: MIT Press.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103,* 403–428.

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology, 27,* 763–776.

Schneider, W., & Detweiler, M. (1987). A connectionist/control architecture for working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 21, pp. 53–119). New York: Academic Press.

Schneider, W., Körkel, J., & Weinert, F. E. (1989). Domain-specific knowledge and memory performance: A comparison of high- and low-aptitude children. *Journal of Educational Psychology, 81,* 306–312.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125,* 4–27.

Shapiro, L. P., Gordon, B., Hack, N., & Killackey, J. (1993). Verb-argument structure processing in complex sentences in Broca's and Wernicke's aphasia. *Brain and Language, 45,* 423–447.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology, 33,* 5–42.

Spearman, C. (1904). General intelligence, objectively determined and measured. *American Journal of Psychology, 15,* 201–293.

Sternberg, S. (1966). High speed scanning in human memory. *Science 153,* 652–654.

Stoltzfus, E. R., Hasher, L., & Zacks, R. T. (1996). Working memory and aging: Current status of the inhibitory view. In J. T. E. Richardson, R. W. Engle, L. Hasher, R. H. Logie, E. R. Stoltzfus, & R. T. Zacks (Eds.), *Working memory and human cognition* (pp. 66–88). New York: Oxford University Press.

Thurston, L. L. (1938). *Primary mental abilities.* Chicago: University of Chicago Press.

VanLehn, K., Brown, J. S., & Greeno, J. (1984). Competitive argumentation in computational theories of cognition. In W. Kintsch, J. R. Miller, & P. G. Polson (Eds.), *Methods and tactics in cognitive science* (pp. 235–262). Hillsdale, NJ: Erlbaum.

Waugh, N. C., & Norman, D. A. (1965). Primary memory. *Psychological Review, 72,* 89–104.

Wickelgren, I. (1997). Getting a grasp on working memory. *Science 275,* 1580–1582.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63–101). New York: Academic Press.