Formal Modeling in Research on Episodic Memory and Aging

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Abstract

For about forty years, age-related differences in episodic-memory tasks have been a major focus of the growing field of cognitive-aging research. Most theoretical approaches invoked to explain such differences are based on a vast research literature consisting mostly of empirical studies, and making relatively little use of formal models of memory. We argue that formal modeling is an invaluable tool in meeting the unique theoretical and methodological challenges of the field. We provide an overview of formal models that address core theoretical issues in memory-and-aging research. These issues are age differences in encoding and retrieval processes, age differences in memory for contextual information, and the interplay of memory with judgment and decision processes. We also discuss areas that could benefit from further formalization.

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Older adults typically show lower performance in episodic-memory tasks as compared to younger adults (for reviews, see Light, 2000; Zacks, Hasher, & Li, 2000). The area of cognitive-aging research has grown rapidly in recent years, with one of its chief goals to understand age-related differences in episodic-memory performance. In this article, we argue that formal modeling can help meet this goal. We give a brief overview of the field of aging and episodic memory before reviewing how formal models have been used and how they could further contribute to theoretical advancement in the field.

Theories, Methods, and Major Findings of Research on Episodic Memory and Aging

Younger adults usually outperform older adults in episodic-memory tasks such as recall and recognition (for a meta-analysis, see Verhaeghen, Marcoen, & Goossens, 1993; for qualitative reviews, see Craik, 2000; Light, 2000; Zacks at al., 2000). In recall tasks, older adults reproduce less of the studied information and commit more intrusion errors than younger adults. In recognition tasks, older adults "are more likely than younger adults to accept as old never-presented items [called foils or lures], especially if those lures share a conceptual, schematic, or perceptual resemblance to the presented items" (Zacks et al., 2000, p. 311). A number of theories have been proposed to account for these findings. Among the currently most popular explanations are those that attribute the pattern of age differences to deficits in speed of processing (e.g., Salthouse, 1996), ability to inhibit irrelevant information (e.g., Hasher & Zacks, 1988), working-memory capacity (e.g., Light, Zelinski, & Moore, 1982; Salthouse, 1992), or attentional capacity (e.g., Salthouse, Fristoe, Lineweaver, & Coon, 1995; Anderson, Craik, & Naveh-Benjamin, 1998). Other approaches have sought to locate age-related deficits in encoding or retrieval processes (e.g., Rabinowitz et al., 1982; Schonfield & Robertson, 1966), or attributed age differences in episodic-memory performance to older adults' deficits in processing contextual information (e.g., Bayen, Phelps, & Spaniol, 2000; Kliegl & Lindenberger, 1993; Light et al., 1992), or deficits in recollective processes (e.g., Jennings & Jacoby, 1993). Neurobiological work has suggested that age-related declines in memory are linked to structural changes in the prefrontal cortex (e.g., Raz et al., 1997) or to changes in brain chemistry (e.g., Volkow et al., 1998). None of these cognitive-aging theories can, in their current form, explain all the data in the literature.

The main focus of this paper is on the experimental tradition within cognitive-aging research. This tradition has borrowed theories and experimental methods from the episodic-memory literature in cognitive psychology, which has typically dealt with younger-adult data. This literature is characterized by a higher degree of formalization than the memory-and-aging literature. Thus far only few of the formal models of memory developed in cognitive psychology have been utilized in cognitive-aging research. Well over a thousand research articles on aging and episodic memory have been published over the past 35 years, but we are aware of fewer than 50 published studies that have used formal models.[2] Throughout

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[2]This count does not include articles that use signal-detection theory to estimate discrimination and response bias from younger and older adults' old-new recognition data.

this paper we will point out how extant models could contribute to theoretical development in the area of normal aging and episodic memory. Before we turn to these issues we briefly describe characteristics of formal models and examine their advantages.

Why Formal Models?

What is a model, and how are models different from theories? Models make theoretically derived predictions about the relationships between unobservable hypothetical constructs, and they specify how overt behavior is related to these constructs. In formal models, predictions are made in mathematical form. Models are more limited in scope than are theories (e.g., Wickens, 1982). This makes models testable, whereas theories are fundamentally not testable or falsifiable. Models are often tailored to explain a specific phenomenon, task, or paradigm. If a model passes an empirical test, this supports the theory from which the model was derived. While theories often make specific claims about memory processes and representations (Brown, 1997), such claims are not always implemented in the models derived from the theory. Thus, levels of analysis vary among models (see Marr's, 1982, distinction between computational, algorithmic, and implementational levels of analysis).

The quality and success of a model depend on several criteria. First, it should be possible to evaluate whether the model parameters respond to experimental manipulations in ways consistent with theoretical predictions (model validation). It is also desirable, though not always possible, to statistically test the goodness-of-fit of a model to empirical data. We will refer to models that permit parameter estimation and goodness-of-fit analysis as measurement models. Another desirable property is parsimony; a model that can account for the same data with fewer parameters than its competitors is generally considered superior. Finally, good models generate new predictions, which in turn can be empirically tested.

Formal models have clear advantages over verbal theories. First, cognitive psychology uses empirical data to draw inferences about unobservable, hypothetical constructs, such as memory and attention. Therefore, cognitive theories are theories of unobservable mechanisms, computations, and representations, not of overt behavior. Formal models state explicitly how overt behavior is thought to arise from the interplay of multiple latent influences. Verbal models can also describe such relationships, but formal models usually possess a higher degree of specificity, and are consequently easier to test and falsify.

Second, in the absence of a formal process model, researchers typically rely on standard statistical tests such as ANOVA to draw inferences from experimental data. This is often problematic, because the assumptions underlying standard statistical tests are routinely violated. For example, nonlinear relationships between variables are often obscured by analyses that are based on the assumption that the variables relate in a linear fashion.

Third, formalization frequently leads to new predictions the researcher would not otherwise have thought of (Hintzman, 1991). And fourth, formal models can be particularly helpful in drawing comparisons across experimental tasks or paradigms, or across different populations, as in cross-sectional cognitive-aging studies (e.g., Ratcliff & McKoon, 2000).

What are the advantages of formal modeling in the specific case of research on episodic memory and aging? We believe that the advantages come into play when dealing with several specific challenges of memory-and-aging research. These challenges include the interpretation of age-by-task interactions and of age differences in baseline performance, and the

separation of latent processes that contribute jointly to overt performance. More generally, these issues involve uncertainty about the relationship between observed variables and the latent constructs of interest, and about potential age differences in these relationships. In the following paragraphs, we will consider these challenges in more detail.

With regard to age-by-task interactions, it has been pointed out repeatedly (e.g., Loftus, 1978; Perfect & Maylor, 2000) that the choice of measurement scale, while often arbitrary, can significantly affect outcomes. For example, a researcher might be interested in the effects of age and another variable on response time in a memory test. Whether the researcher chooses raw response time or, alternatively, a monotonic transformation of response time as dependent variable can determine whether or not the two independent variables interact on the dependent variable (Baron, 1985). For a discussion of this issue in the context of accuracy measures, see Loftus (1978). "Drawing nonmeaningful conclusions about scale-dependent interactions" (Nelson, 2000, p. 254) can be avoided with formal models that specify the combination rule for the independent variables (e.g., monotonic, linear, nonlinear, etc.), as well as the scaling properties of the dependent variable.

Baseline differences are a related issue. Whenever researchers compare multiple participant groups in a quasi-experiment, they have to be wary of differences in baseline performance between the groups. This is a particularly important issue in cognitive-aging research, because young adults often outperform older adults in the baseline condition. For example, say a researcher is interested in the effects of divided attention at encoding versus at retrieval on younger and older adults' reaction times at retrieval. Younger adults' reaction times can be expected to be shorter even in the full-attention condition. Even when there are no obvious floor or ceiling effects, interpreting age by task interactions can be difficult in these cases. "Nonmeaningful conclusions" will be drawn if the dependent variable is not on a linear scale, as is the case for reaction time, or if the effects of age on the dependent variable are nonlinear (see also Perfect & Maylor, 2000, for an analysis of this issue and an example). A popular solution is to equate age groups experimentally at baseline. For example, some researchers adjust presentation times to allow each individual to meet a certain accuracy criterion at baseline (e.g., Kliegl, 1995). Although this approach can be helpful, there always remains some doubt as to the interpretability of the results, because a basic principle of experimental design - equal treatment in all but the independent variables of interest - is violated. As a consequence, results can be attributed to the experimental manipulation, the differential treatment at baseline, or both. Again, it would be preferable to address the scaling problem by obtaining scale-independent model parameters in each age group (e.g., see Verhaeghen, 2000).

Finally, formal measurement models permit the estimation of model parameters from observed data. These parameters measure cognitive processes or states that are not directly observable. Thus, measurement models allow researchers to identify the locus of age-related differences in tasks that are believed to tap multiple cognitive processes. For example, to determine whether older and younger adults differ in their ability to discriminate between old and new items in a recognition task, or whether they differ instead in their response biases, a measurement model is needed that permits the separation of these two influences (e.g., Harkins, Chapman, & Eisdorfer, 1979).

Salthouse (1988) was among the first to call for a formalization of theories of cognitive aging. In his words, theories should be "rigorous, precise, and at least potentially quantitative" (p. 3). In Salthouse's view, one of the most important challenges of cognitive-aging

research is to explain why some tasks are spared by aging while others are not, a finding that he characterizes as a "product-process" difference. According to this view, cognitive "products" (knowledge) remain intact in old age, but the ability to engage in active cognitive processing is negatively affected by age. Salthouse (1988) presented a connectionist network model to simulate the interactions of cognitive products (knowledge, represented by nodes and connections) and processes (properties of the activation-spreading mechanisms). Salthouse's model was intended to illustrate the idea that differential age-related cognitive decline should be studied within a well-specified theoretical framework. Although Salthouse's proposal to use connectionist models did not immediately resonate in the cognitive-aging literature, applications of network models have become more common since the late 1990s. For example, research on changes in the dopaminergic neurotransmitter system has utilized connectionist models to simulate age-related cognitive deficits (e.g., Braver & Barch, 2002; Braver et al., 2001; Li & Lindenberger, 1999). However, the specific case of age-related change in episodic memory has not yet been addressed widely in this literature, which has mostly focused on working memory processes. One notable exception is a study by Li, Lindenberger, and Frensch (2000), who proposed a causal relationship between age-related decline in dopaminergic neuromodulation, particularly in the prefrontal cortex, and age-related decline in episodic memory. Li and colleagues tested this hypothesis in a series of simulations with a connectionist neural-network model. The age-related neuromodulatory deficit was modeled as a reduction in the value of a single parameter of the activation function ("gain parameter") of the network units, resulting in less distinctive neural representations. The outcomes of the model simulations mimicked several aspects of behavioral age differences in paired-associate learning data, including age deficits in learning rate, asymptotic performance, susceptibility to interference, and increased intra- and inter-individual variability. Together with other recent neurocomputational work, Li et al.'s study suggests fascinating opportunities for neuroscientific research on memory and aging. However, because of the general focus on non-episodic memory functions, we refrain from a fuller discussion of connectionist approaches in this review.[3]

Overview

The remainder of this article addresses three of the major theoretical issues concerning age-related differences in episodic memory: age-related deficits at encoding versus retrieval, age-related deficits in the processing of contextual information, and age differences in judgments and decisions that are related to episodic memory. Formal models have proven very useful in these areas. We discuss how models have advanced theoretical development, and we point out opportunities for future work. Table 1 provides an overview of the models we discuss in this article. This table is organized around the three research themes listed above.

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[3] MacKay and Burke (1990) pointed out that another connectionist theory, MacKay's (1982; 1987) Node Structure Theory (NST), could explain existing findings of age differences in context effects in episodic memory (e.g., Rabinowitz, Craik, & Ackerman, 1982). However, to our knowledge, subsequent tests of predictions derived from NST, in the cognitive aging literature, have been limited to non-episodic domains such as semantic memory and language production (e.g., Burke, MacKay, Worthley, & Wade, 1991; Taylor & Burke, 2002).

Table 1:
Overview of Formal Models of Episodic Memory

Purpose in Cognitive-Aging Research	Name of Model(s) and/or Author(s)	Type of Model	Experimental Tasks	Measurement model with goodness-of-fit test?	Experimental Validation Studies	Applications in Research on Episodic Memory and Aging
Locating age differences at encoding and retrieval	Two-stage model (Greeno, 1968)	Markov	Repeated recall	Yes	Greeno (1968, 1974)	Howe (1988), Howe & Hunter (1985, 1986)
	Wilkinson and Koestler (1983)	Markov	Repeated recall following a single presentation	Yes	Wilkinson & Koestler (1983)	Wilkinson & Koestler (1983)
	Batchelder and Riefer (1980, 1986)	Multinomial processing tree	Free recall	Yes	Batchelder & Riefer (1980)	Erdfelder & Bayen (1991), Riefer & Batchelder (1991)
	Glanzer & Bowles (1976)	Stimulus sampling	Forced-choice recognition	Yes	Bowles (1980) Glanzer & Bowles (1976)	Bowles & Poon (1982)
Analysis of age differences in context processing	Multinomial models of source monitoring (Batchelder & Riefer, 1990; Bayen et al., 1996)	Multinomial processing tree	Source monitoring	Yes	Bayen et al. (1996)	Bayen & Murnane (1996), Henkel et al. (1998), Light et al. (1992), Spaniol & Bayen (2000)
	Model for proactive interference in cued recall (Kliegl & Lindenberger, 1993)	Markov	Cued recall	Yes	--	Kliegl & Lindenberger (1993)
	Stimulus fluctuation model (Estes, 1955)	Stimulus sampling	Cued recall	Yes	--	Balota et al. (1989)

	Temporal Context Model (Howard & Kahana, 2002; Howard et al., under review)	Single-store distributed-context model	Free recall	No	Howard & Kahana (2002)	Howard et al. (under review)
	OSCAR (Brown et al., 2000)	Dynamic learning context	Serial-order memory	Yes	Brown et al. (2000)	--
	Process-dissociation model (Jacoby, 1991, 1998)	Dual process	Inclusion-exclusion procedure	Yes	Jacoby (1991, 1998)	Caldwell & Masson (2000), Hay & Jacoby (1999), Jacoby (1999), Jennings & Jacoby (1993, 1997), Rybash & Hoyer (1996), Schmitter-Edgecombe (1999), Titov & Knight (1997)
	Dual-process model (Yonelinas, 1994, 1997, 1999)	Combined threshold / signal-detection dual process	Old-new recognition, associative recognition, source monitoring	Yes	Yonelinas (1994; 1997; 1999; 2001)	Light et al. (2000), Light & Healy (2001)
	SAC (Reder et al., 2000)	Dual-process semantic network	Remember-Know	Yes	Reder et al. (2000)	--
	ICE (Murnane et al., 1999)	Global matching	Old-new recognition	No	Murnane et al. (1999)	Bayen et al. (2000)
	SAM (Gillund & Shiffrin, 1984)	Global matching	Old-new recognition, recall	No	Gillund & Shiffrin (1984)	--
	Diffusion Model (Ratcliff, 1978)	Sequential sampling	Old-new recognition, lexical decision	Yes	Voss, Rothermund, & Voss (in press)	Ratcliff, Thapar, & McKoon (2004)
Analysis of age differences in judgment processes	Minerva-DM (Dougherty et al., 1999)	Global matching	Conditional-probability judgments, frequency judgments	No	Dougherty (2001), Dougherty et al. (1999)	Spaniol & Bayen (accepted)
	Hindsight Model (Erdfelder & Buchner, 1998)	Multinomial	Hindsight paradigm	Yes	Erdfelder & Buchner (1998)	Bayen et al. (under review)

Note: Measurement models are models that permit the estimation of model parameters from observed data.

In the table, we list the name of each model and its author(s), the model family to which it belongs, and the experimental tasks used to collect data that can be analyzed with the respective model. We note whether or not a model is a measurement model. We also provide references for studies that have experimentally validated a model or at least one of the model parameters. Finally, we list published studies that have applied the model to address issues of memory and aging.

It should be noted that we limit this review to the experimental literature. Sophisticated formal models have been used to analyze correlational data to relate individual differences in episodic-memory performance to various possibly underlying theoretical constructs. Most of these models are structural equation models (e.g., Hultsch, Hertzog, Small, & Dixon, 1999; Park et al., 1996). However, a detailed discussion of models for correlational data is beyond the scope of this paper.

Age-Related Encoding Versus Retrieval Deficit

The *storage-retrieval debate* in the cognitive-aging literature has focused on the locus of age differences in episodic memory: Do older adults have a deficit in encoding or storage of information, or is their deficit located at the retrieval end? This controversy became a focal issue in the field following a seminal study by Schonfield and Robertson (1966), who found greater age differences in recall than in recognition and concluded that age differences in episodic memory were due to age differences in retrieval processes. This conclusion was based on the generate-recognize theory of recall (e.g., Kintsch, 1970), according to which recall involves the generation of candidate responses, followed by the recognition of previously studied items among the generated responses. However, this theory had problems explaining encoding-specificity effects and failures to recognize recallable items (Tulving & Thomson, 1973), and it was pointed out that the age differences could also be located at earlier processing stages, since retrieval is dependent on encoding strategy (A. D. Smith, 1980). Researchers have chosen both design-based approaches and modeling approaches to study storage and retrieval processes. Design-based approaches attempt to disentangle age effects on encoding versus retrieval via experimental design. However, it is often unclear whether an experimental manipulation affects encoding, retrieval, or both. This issue is most pronounced with experimental manipulations at the time of encoding because it can be argued that these manipulations also affect retrieval processes. Empirical measures of memory, such as recall or recognition performance, do not allow us to determine to what extent manipulations affect processes in different phases of a memory study. Moreover, as Brainerd (1985) pointed out, design-based approaches are flawed because of response-scaling problems. First, these approaches do not specify how encoding and retrieval contribute to memory strength. Even assuming monotonic relationships, any number of combination rules are possible, including nonlinear ones. Secondly, the underlying measurement models are unspecified, that is, assumptions regarding the functions that characterize the relationship between memory performance and memory strength are not explicit and can therefore not be tested. Again, various scaling functions are possible. Brainerd demonstrated that it is impossible to draw conclusions about encoding and retrieval processes or memory strength from empirical measures of task performance without making scaling assumptions.

The encoding versus retrieval issue in memory research has led to the development of formal models that offer solutions to the problems inherent in design-based approaches (see Brainerd, 1985, and Bayen, 1990, for reviews). Although the bulk of the modeling work on encoding versus retrieval was geared towards explaining memory development in children (e.g., Chechile, Richman, Topinka, & Ehrensbeck, 1981; Wilkinson, De Marinis, & Riley, 1983), several articles have addressed the effects of aging on encoding and retrieval. Some of the models used in these studies are tailored to repeated-recall paradigms, in which a list of items is studied and recalled repeatedly until a performance criterion is met. The reason for the use of this design is the assumption that learning occurs in stages, and to observe these, one must measure recall on multiple successive occasions (e.g., Howe & Hunter, 1985).

The data from recall experiments are of categorical nature (e.g., an item is or is not recalled). Most of the mathematical models for categorical data that have been applied in research on recall memory in older adults belong to two classes: finite-state Markov models and multinomial processing tree models. In addition to models for recall, we also discuss a model by Bowles and Poon (1982) designed to measure contributions of encoding and retrieval processes to performance in recognition tasks.

Markov Models

Finite-state Markov models of recall assume that recall is probabilistic and that, at any time during a recall test, participants are in one of several discrete memory states with regard to each to-be-recalled item. For example, in a three-state Markov model, an item can be in an unlearned state, a partially learned state, or a learned state. Learning and forgetting are conceptualized as probabilities of moving from one cognitive state to the next. In addition to these assumptions, finite-state Markov models assume that the number of cognitive states is finite, and that "how the process gets to a particular state is not important – all information about the past is embodied in the current state" ("Markov property"; Wickens, 1982, p. 10). Since state changes cannot be observed directly, the parameters capturing transition probabilities have to be estimated on the basis of the trial-by-trial protocols from recall experiments. The models encompass a latent-state space, an observed-response space, transition probabilities between the latent states, and response mappings between the state space and the response space.

Five published articles have targeted age-related differences in adults' recall with a Markov modeling approach. Three of these papers used a model for a recall paradigm in which study items are presented and tested repeatedly until the participant reaches a performance criterion in free or cued recall (Howe, 1988; Howe & Hunter, 1985, 1986). The other two articles described models for recall paradigms in which each item list is presented only once, and participants are asked to recall the list multiple times, either in a free-recall or a cued-recall format (Kliegl & Lindenberger, 1993; Wilkinson & Koestler, 1983). Of the latter two papers, only the one by Wilkinson and Koestler directly addressed the issue of age differences at encoding versus at retrieval, while Kliegl and Lindenberger's article focused primarily on comparing younger and older adults in their ability to process context information. We therefore postpone a discussion of Kliegl and Lindenberger's study to the section on age differences in context processing. A sixth study (Batchelder, Chosak-Reiter, Shankle, & Dick, 1997) used a Markov model to assess storage and retrieval in dementia patients and

a healthy control group, but the authors did not compare different age groups, and we therefore will not discuss it here.

Howe (1988) and Howe and Hunter (1985, 1986) performed *stages of learning* analyses with a version of Greeno's (1968) two-stage Markov model. According to this model, at any given point in time each item is in one of three states: an unmemorized state, a partially memorized state, or a memorized state. In the memorized state, retrieval is always successful ("algorithmic retrieval"); in the partially memorized state, it can be unsuccessful some of the time ("heuristic retrieval"). The model includes several parameters, estimated with a maximum-likelihood algorithm, to measure various aspects of encoding and storage over time, as well as heuristic and algorithmic retrieval. Parameters responded appropriately to experimental manipulations confirming the validity of the model (for a review, see Brainerd, 1985). A series of experiments with younger and older adults (Howe, 1988; Howe & Hunter, 1985) yielded age differences in encoding, but not in storage over time. Moreover, an age-related retrieval impairment was present in algorithmic, but not in heuristic retrieval (Howe, 1988).

Wilkinson and Koestler (1983) used an experimental paradigm in which repeated recall followed a single presentation. The authors proposed a model to account for relative frequencies of recalls and forgets in this paradigm. The model makes assumptions about the role of contextual associations and inter-item associations in recall. According to the model, recall depends on contextual associations of items in memory, with context fluctuating continually. Every time an item is successfully retrieved, its associative pathways are strengthened. The probability that an item is recalled increases with the number of context and inter-item associations and equals the proportion of all currently available paths through memory that include the item. In addition to these assumptions about associative pathways in memory, Wilkinson and Koestler postulated one parameter to measure initial encoding and four retrieval parameters ("functions") that relate changes in recall probability to changes in retrieval context, previous successful recalls, and trial number. The authors mathematically derived predictions about the shapes of these functions and found these predictions supported after fitting the model to the observed frequencies of recall patterns in a sample of younger adults. Using the same parameter values, the model also fit recall data from children, another younger adult sample, and older adults. In this analysis, adult age differences were found only in initial encoding. Wilkinson's and Koestler's findings thus did not lend support to the age-related retrieval deficit proposed by Howe and colleagues. However, this discrepancy could be due to the differences in model assumptions and parameter definitions.

Erdfelder and Bayen (1991) noted that some of the rigid assumptions of Markov models (e.g., homogeneity of state transition probabilities across participants and across trials in an experiment) may render these models overly cumbersome, and may hinder the goal of explaining age differences in episodic memory. A possible solution may come in the form of multinomial processing tree models, which we discuss next.

Multinomial Processing-Tree Models

Multinomial processing tree (MPT) models are less restrictive than finite-state Markov models, in that they do not require assumptions about trial-to-trial changes in cognitive states. Like Markov models, they assume that processing is discrete, and that transitions between states are probabilistic (Riefer & Batchelder, 1988). They are commonly represented as tree

structures in which each branch represents the probability of attaining a certain hypothetical psychological state. These probabilities are estimated from observed response frequencies via maximum-likelihood parameter estimation (for reviews of MPT models in psychology, see Batchelder & Riefer, 1999, and Erdfelder, in press). Parameter-estimation techniques, goodness-of-fit measures, and strategies for power analysis are readily available (Hu & Batchelder, 1994; Riefer & Batchelder, 1988). The only applications of multinomial processing-tree models in the context of the encoding versus retrieval debate in the aging literature are studies by Erdfelder and Bayen (1991), and by Riefer and Batchelder (1991). These authors used Batchelder and Riefer's (1980, 1986) multinomial encoding-retrieval model to address the encoding-retrieval controversy. The model is designed to measure encoding/storage and retrieval contributions to performance in a task in which participants free-recall a list of words containing category pairs and singletons. The recall data are classified into six response categories (e.g., "category pair recalled adjacently"). The observed response category frequencies are used to estimate three parameters: c, the probability of forming and storing a cluster consisting of two items from the same category; r, the probability of retrieving a cluster if stored; and u, the probability of recalling a nonclustered item as a singleton. Riefer and Batchelder (1991) found age differences in cluster retrieval only, whereas Erdfelder and Bayen (1991) found age differences in both encoding and retrieval of clusters. There have been no other applications of multinomial models designed to separate storage and retrieval influences in older adults, although in addition to Riefer and Batchelder's (1991) storage-retrieval model there are at least two other models that would allow researchers to test relevant hypotheses (Bäuml, 1996; Riefer & Batchelder, 1995). A Markovian version of Riefer and Batchelder's model (Bäuml, 1996) allows the measurement of storage loss and forgetting rates, as well as retrieval failure, to retroactive inhibition. Bäuml's model might offer a useful framework for studying the question why older adults are more susceptible to interference in long-term memory tasks. A multinomial model by Riefer and Batchelder (1995), designed to model data from the recognition-failure paradigm (Tulving & Thomson, 1973), is another possible candidate. This model estimates independent parameters to measure storage of a word pair over time, retrieval of a word pair during the recognition task, and retrieval of a word pair in the recall task, as well as guessing during the recognition task. The model would allow researchers to test hypotheses of age differences in any of these parameters.

Stimulus-Sampling Model

To our knowledge, a study in the encoding-retrieval tradition by Bowles and Poon (1982) represents the first model-based analysis of adult age-related differences in recognition memory. These authors used a stimulus-sampling model (Glanzer & Bowles, 1976) that assumes that each word is represented in memory as a set of features, and that a random subset of these features is sampled and marked at encoding. At retrieval, another random subset of features is sampled. In a two-alternative forced-choice recognition test, the word that has more marked features is judged old. The model contains two parameters, α and $p(N)$. Parameter α ("encoding effectiveness") represents the proportion of the features of a stimulus that are encoded at study. Parameter $p(N)$ is an index of susceptibility to interference and can thus be considered a retrieval parameter. It depends on the amount of overlap between the

features for a test item and the studied items. Model parameters were validated experimentally, that is, they showed expected effects of manipulations of word frequency (Glanzer & Bowles, 1976) and list length (Bowles, 1980). There is some similarity between this model and the one used by Balota, Duchek, and Paullin (1989), which we discuss in detail in the section on age differences in context processing.

Bowles and Poon fit the stimulus-sampling model to forced-choice recognition data from younger and older adults. They estimated separate sets of parameters for low and high performers in each age group, and found that low-performing older adults differed significantly from the other participant groups in encoding effectiveness (parameter α). No differences in the retrieval parameter $p(N)$ were found. The authors thus conclude that a recognition deficit in older adults can be attributed to encoding, not retrieval difficulties. Glanzer and Bowles' (1976) stimulus-sampling model is a good example of what Raaijmakers and Shiffrin (1992) refer to as models aimed at "precise fitting of single experiments." The model has only two parameters, and although stimulus-sampling theory is a theory with a broader scope, this specific model is limited to forced-choice recognition. Perhaps this is why Bowles and Poon's article failed to inspire further modeling work in a mostly design-based gerontological literature. Nevertheless, the authors made an important contribution by demonstrating that model-based analyses can provide fine-grained information about age-related differences in performance measures such as percentage correct.

Encoding versus Retrieval: Discussion

The mathematical models of encoding and retrieval reviewed in this section differ greatly in scope. Some models make explicit assumptions about the nature of representations in memory, their associations with one another, and specifically about the role of context in episodic memory (Wilkinson & Koestler, 1983). Others draw inferences about a set of discrete hypothetical cognitive stages or states that are thought to drive performance, without making explicit assumptions about basic information-processing mechanisms (Batchelder & Riefer, 1980, 1986; Howe, 1988). Models targeting such different levels of analysis are naturally difficult to compare. Results are also difficult to compare, because the parameters in the various models measure different aspects of encoding and retrieval. Rather than addressing a general encoding or retrieval deficit, the precision of mathematical models allows for a more differentiated view of various aspects of encoding and retrieval. For example, while the model used by Howe and the one used by Wilkinson and Koestler measure encoding of single items, the model by Batchelder and Riefer measures the encoding of associations between items. It is, therefore, not surprising that the results of model-based research do not always concur with regard to the locus of age differences. Some studies found such differences in encoding only (Wilkinson & Koestler, 1983), or retrieval only (Riefer & Batchelder, 1991); others found differences in both (Erdfelder & Bayen, 1991; Howe, 1988). It is striking that the studies reviewed in this section each present different models, and use different experimental paradigms. Identifying a model apt to explain performance across *multiple* experimental tasks, and applying this model to the encoding-retrieval question in cognitive-aging research, remains a challenge for future research. This observation is particularly timely, because interest in the encoding-retrieval question has recently been revived by cognitive neuroscientists studying the brain systems involved in different memory functions (e.g.,

Cabeza, 2002; Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003). A 'combined strategy' – pairing a neuroscience approach with formal-model-based analyses of behavioral data – has the potential to yield powerful converging evidence.

Age-Related Deficits in Context Processing

An episode is defined by the context in which information is encoded. Remembering information from an episode thus requires the encoding and retrieval of contextual information in order to determine whether or not particular information was part of the relevant episode. For example, when participants in an experiment try to recall or recognize items from a list that was presented earlier in the experiment, they must remember whether a particular item occurred in the context of the study phase of the experiment, or whether it occurred in a different context. The importance of context memory for performance in episodic-memory tasks led to the hypothesis that age differences in such tasks might result from age-related deficits in the processing of contextual information. This hypothesis was first formulated in the early 1980s (e.g., Burke & Light, 1981; Rabinowitz et al., 1982) and continues to be influential (e.g., Braver et al., 2001). Several authors have used formal models to investigate context memory in older adults. There is a multitude of theoretical approaches, models, and experimental tasks. The latter include recall, recognition, frequency judgments, serial-order memory tasks, the process-dissociation procedure (Jacoby, 1991), and source-memory tasks. Context memory is sometimes tested directly, by asking participants in which context an item was presented (by which source, in which list position, etc.). Indirect tests of context memory suggest that contextual information influences performance even when participants are never explicitly instructed to use context information at study or at test. For example, recall performance is usually better when encoding and retrieval occur in the same as opposed to different contexts (e.g., S. M. Smith, 1994).

Some formal models of context memory make explicit assumptions about the nature of contextual information and contextual change over time (e.g., Balota et al., 1989; OSCAR by Brown, Preece, & Hulme, 2000; Howard & Kahana, 2002). Other models are less specific in this respect (e.g., Kliegl & Lindenberger, 1993). The majority of models are tailored to a particular experimental task, but some make predictions regarding performance in several different tasks (e.g., OSCAR by Brown et al., 2000; SAM by Gillund & Shiffrin, 1984).

Finally, some modeling approaches are attempts to disentangle familiarity and recollection in item and context memory (e.g., the dual-process model by Yonelinas, 1994, 1999), while others model familiarity processes in item and context memory only (e.g., the ICE model of recognition memory by Murnane, Phelps, & Malmberg, 1999). We emphasize these different themes in our review of this literature.

Multinomial Models of Source Monitoring

Source monitoring is "the set of processes involved in making attributions about the origins of memories, knowledge, and beliefs" (Johnson, Hashtroudi, & Lindsay, 1993, p. 3). Some of these processes involve source memory, that is, memory for the origin of information, or for the context in which an event was experienced. In the typical source-monitoring paradigm, participants are presented with a series of items, each of which is paired with one of several sources (speakers, presentation modalities, backgrounds, etc.). During a subsequent test phase, a mixed list of study items and new items is presented. Participants are asked to indicate whether a given test item was presented by Source A, by Source B (etc.), or is new. Source-monitoring tasks include direct tests of memory for context and are, therefore,

an obvious way to test the hypothesis that older adults have difficulties in remembering the context in which information occurred.

Older adults are typically reported to show poorer source memory than do younger adults (for reviews, see Spencer & Raz, 1995; Light, 2000). To measure source memory, researchers have traditionally used empirical performance measures, such as the proportion of hits (i.e., test items identified as old) attributed to the correct source. However, these measures confound the contributions of item memory (i.e., discrimination between old and new items) and guessing biases with the contributions of source memory to performance (Murnane & Bayen, 1996). For example, if a participant correctly attributes a test item to Source A, this may be because he or she remembers that the item was presented at study, and that it was presented by Source A, or, alternatively, the correct answer may be the result of guessing.

The challenge of separating the different cognitive processes (item recognition, source memory, response biases) that contribute to performance in source-monitoring tasks has been met with the development of multinomial processing-tree (MPT) models designed for these tasks (Batchelder & Riefer, 1990; Bayen, Murnane, & Erdfelder, 1996). We have introduced MPT models in the section on the encoding-retrieval debate. MPT models of source monitoring permit the separate estimation of item-recognition parameters, source-memory parameters, and response-bias parameters from empirical data gained in a source-monitoring experiment. Bayen et al. (1996) have shown that their two-high threshold (2HT) model of source monitoring provides valid measures of both old-new item recognition and source memory.

Multinomial models of source monitoring have successfully been applied in several empirical studies of the effects of aging on source memory (Bayen, 1999; Bayen & Murnane, 1996; Henkel, Johnson, & De Leonardis, 1998; Light et al., 1992; Spaniol & Bayen, 2000). In studies of aging, it is particularly important that source memory be measured independent of response biases, because Multhaup's (1995) research suggests that there are age differences in response biases in source-monitoring tasks. These age differences should not be confounded with age differences in source memory.

The Process Dissociation Procedure for Recognition Memory

Dual-process models of episodic memory distinguish between familiarity-based and recollection-based processes (e.g., Mandler, 1980). Familiarity is thought of as a fast, automatic process that does not require cognitive resources. Recollection, on the other hand, is characterized as a slow and deliberate process that is conscious and resource-dependent. Dual-process models postulate that recollection involves remembering contextual details of an episode. Some authors believe that direct tests of context memory require more recollective processing than do tests of memory for item information (e.g., Yonelinas, 1999), and item and context memory have dissociated in retrieval time-course studies (e.g., Hintzman, Caulton, & Levitin, 1998). Recollective processes are of particular interest to cognitive aging researchers, because resource-deficit theories of cognitive aging postulate that older adults have difficulties with episodic-memory tasks because of limited processing resources (e.g., Craik, 1986). Since recollective processes require more resources than familiarity processes, age differences should be larger in recollection than in familiarity.

Results from several lines of research in the area of aging and episodic memory have been interpreted in terms of an age-related deficit in recollection with little or no age differences in familiarity (Light, Prull, LaVoie, & Healy, 2000). The three prominent paradigms that have been used to investigate this issue are a) comparisons of performance on implicit and explicit-memory tasks (LaVoie & Light, 1994), b) the Remember-Know paradigm (e.g., Parkin & Walter, 1992), and c) the process-dissociation procedure (e.g., Jacoby, 1999). The first two have brought forth a sizable empirical literature (reviewed by Light et al., 2000), but no modeling work. By contrast, the process-dissociation approach is often considered a formal-modeling approach, and we therefore discuss it next.

The process-dissociation procedure for recognition memory (introduced by Jacoby, 1991) was designed to estimate the contributions of recollection and familiarity to recognition with a quantitative model. In this procedure, participants study two lists of items and later receive two different kinds of instructions for the memory test. In the inclusion condition, participants are instructed to respond *yes* to all studied items, regardless of the list in which they were shown. In the exclusion condition, participants are instructed to respond *yes* only to the items from one study list, and to respond *no* to the items from the other study list and to new items. In Jacoby's original model for the analysis of data gained with the inclusion-exclusion paradigm, *Yes* responses on the inclusion test are assumed to reflect independent contributions of recollection (R) and familiarity (F), such that $p(yes|\text{inclusion}) = R + F\,(1\text{-}R)$. *Yes* responses on the exclusion test, however, are assumed to reflect only familiarity: $p(yes|\text{exclusion}) = F\,(1\text{-}R)$.

Several studies have used the process-dissociation procedure for recognition memory with younger and older adults (Caldwell & Masson, 2000; Jacoby, 1999; Jennings & Jacoby, 1993, 1997; Rybash & Hoyer, 1996; Schmitter-Edgecombe, 1999; Titov & Knight, 1997). Generally, in these studies, age-related differences were found in R, but not in F (for a review, see Light et al., 2000). These findings have been interpreted in terms of age-related deficits in recollection but not familiarity. However, there is evidence to suggest that the process-dissociation procedure may not yield valid measures of recollection and familiarity. As pointed out by Buchner, Erdfelder, Steffens, and Martensen (1997), the process-dissociation procedure for recognition is a source-monitoring task (i.e., it requires old-new discrimination as well as distinction between two list contexts). Parameters based on multinomial models of source monitoring (see above) estimated from process-dissociation data pass experimental validity tests, whereas parameters based on Jacoby's process-dissociation model do not (Yu & Bellezza, 2000; see also Mulligan & Hirshman, 1997). As Yu and Bellezza (2000) report, decreasing *both* old-new recognition and source memory simultaneously via experimental manipulations can decrease parameter R, but may not affect parameter F. A pattern of age differences in R and not F can thus be explained with the common finding that, in comparison to young adults, older adults have lower ability to distinguish between old and new items as well as lower source memory. Thus, an interpretation of patterns of age differences in the R and F parameters in terms of age differences in recollection and familiarity must be considered with caution. Other issues that require careful consideration when analyzing data from the inclusion-exclusion paradigm are response biases, and the assumption of independence of recollection and familiarity. For a discussion of these issues and a review of possible solutions that have been suggested in the literature see Erdfelder and Buchner (2003).

Yonelinas' Dual-Process Model

Light et al. (2000) attempted to disentangle the contributions of recollection and familiarity via analyses of the shape of receiver operating characteristics curves (ROC curves). The ROC is a plot of hit rates against false-alarm rates in old-new recognition or other two-choice tasks (see our section on decision models of recognition below). To construct an ROC, multiple pairs of hit rates and false alarm rates are obtained from each participant, either with a confidence-rating procedure, or with payoffs or instructions to use different response criteria. Light et al. (2000) reanalyzed ROCs published by Harkins et al. (1979) that were based on confidence ratings of young and older participants in an old-new recognition task. In their analyses, the authors adopted the assumptions of Yonelinas' (1994, 1999) dual-process model. These assumptions are that familiarity is a continuous signal-detection process and that recollection is an all-or-none threshold process by which contextual elements of an episode are identified (for explanations of signal-detection theory and threshold theory, see our section on decision models of recognition below). Yonelinas further assumes that confidence-rating ROCs predicted by SDT are curvilinear, while confidence-rating ROCs predicted by threshold theory are rectilinear. Based on these assumptions, Light et al. (2000) estimated familiarity and recollection in young and older adults from Harkins et al.'s empirical confidence-rating ROC curves (see Light & Healy, 2001, for an application to associative-recognition data). Compared to younger adults, older adults in the Harkins et al. (1979) study showed declines in both familiarity and recollection, as measured by Yonelinas' model. However, rating ROCs are difficult to interpret, because one of Yonelinas' core assumptions, namely the assumption that the shape of confidence-rating ROCs is diagnostic of the type of underlying memory process, is questionable. According to Malmberg (2002) and earlier work by other authors (e.g., Erdfelder & Buchner, 1998; Larkin, 1965; Lockhart & Murdock, 1970), a threshold process can yield *either* rectilinear or curvilinear rating ROCs, depending on the participant's response strategy. Specifically, a threshold process yields a rectilinear rating ROC only under the assumption that in detect states (e.g., detect-as-old), extreme ratings (e.g., the highest point on a rating scale) are always used. If, however, in detect states, less extreme ratings are sometimes used, then a curvilinear ROC curve results. Thus, curvilinear rating ROCs cannot unequivocally distinguish between threshold and continuous processes. Rating ROCs are, therefore, of limited value for the distinction of both types of processes and of possible age differences therein. Further, Yonelinas' assumption that recollection is an all-or-none process has been challenged (e.g., Kelley & Wixted, 2001; Qin, Raye, Johnson, & Mitchell, 2001). Several models with alternative assumptions have been proposed (Banks, 2000; DeCarlo, in press; Glanzer, Kim, Hilford, & Adams, 1999; Hilford, Glanzer, Kim, & DeCarlo, 2002; Kelley & Wixted, 2001; Macho, 2003; Rotello et al., 2004) and await application to resolve the issue of a possible dissociation in effects of aging on familiarity versus recollection.

The SAC Model

Another formal dual-process theory of human memory, SAC (Source of Activation Confusion; Reder et al., 2000), was created to account for mirror effects (e.g., Glanzer & Adams, 1985) in Remember-Know judgments (e.g., Gardiner & Java, 1990). As a semantic-network model, SAC makes explicit assumptions about representations and memory mechanisms. Specifically, it assumes that each study word has a dual representation in memory: as a *word node* (with lexical, semantic, and graphemic associations) and as an *event node* (i.e., a memory of the word as having occurred in the study list). Familiarity is a function of the activation level of the word node, which in turn depends on the recency and frequency of exposures. By contrast, recollection is a function of the activation level of the event node, which depends on the number of associated contexts. The more contexts a word is associated with, the more difficult it is to recollect the word as having been part of the study list. Predictions derived from SAC can be tested through computer simulations as well as quantitative model fits. As shown by Reder et al. (2000), the model predicts empirical patterns of mirror effects (e.g., Glanzer & Adams, 1985) in Remember-Know judgments (e.g., Gardiner & Java, 1990). SAC may be useful in studying age differences in familiarity or recollection, and in pinpointing the causes of such differences (e.g., in terms of age differences in activation functions).

List Context and Proactive Interference in Recall

Another approach towards modeling age differences in the ability to discriminate between list contexts is Kliegl and Lindenberger's (1993) Markov model. This model is geared towards explaining proactive interference in cued recall of word lists when participants learn multiple lists. The task paradigm used by Kliegl and Lindenberger did not involve direct tests of context memory; rather context memory is assessed indirectly via errors of intrusion from prior lists. The authors reported that older adults committed more intrusion errors even when they correctly recalled as many items did the younger adults. Kliegl and Lindenberger's modeling work aimed at specifying the source of these age differences. In their model, intrusions represent failures to distinguish between different list contexts. The authors, therefore, designed a model in which a critical role is given to context, represented in the model in the form of list tags.

Similar to Howe's model discussed above (Howe, 1988; Howe & Hunter, 1985, 1986), Kliegl and Lindenberger's model postulates two stages. Items are either stored with a list tag (i.e., with a contextual marker indicating the list origin of the item), stored without a list tag, or not stored at all. There are two encoding parameters: the probability that an item is encoded with a tag, and the probability that an item is encoded without a tag. Further, there are two storage parameters: the probability that the item is intact at retrieval, and the probability that the tag is intact at retrieval. The model has no retrieval parameters, because retrieval is assumed to depend entirely on the encoding and storage parameters. Fitting this four-parameter model to data from two experiments with younger and older adults indicated that the older adults' increased rate of intrusion errors could be attributed to age differences in the encoding parameters. More specifically, the probability of constructing traces without list tags was greater for older than for younger adults, while the probability of constructing traces with list tags was greater for younger than for older adults. Thus, according to Kliegl and

Lindenberger's model-based analyses, there were age-related differences in the integration of items and context at encoding. No age differences were observed in storage parameters. However, it should be noted that Kliegl and Lindenberger's model has received independent experimental validation. Therefore, any conclusions drawn from applications of the model must be considered preliminary.

Stimulus Fluctuation Model

Balota et al. (1989) were the first to use a formal model to address the hypothesis of an age-related deficiency in context processing. Young adults' recall performance is positively related to the degree of match between encoding and retrieval contexts (see S. M. Smith, 1988, for a review). If older adults have difficulties processing context information, their recall performance should be less enhanced than that of younger adults when there is a match between encoding and retrieval contexts as opposed to a mismatch. To test this hypothesis, Balota and colleagues examined a well-known experimental effect: the crossover interaction of lag and retention interval in recall. As the number of items presented between the first and second presentation of a repeated item in a list increases, delayed recall performance increases, but immediate recall performance decreases. According to Crowder's (1976) and Glenberg's (1976) encoding variability framework, recall performance is a function of the overlap between the encoded context and the retrieval context. At short retention intervals, recall performance is high for items with short lags between presentations, because participants have two opportunities to encode a context that is similar to the retrieval context. At long retention intervals, recall performance is higher in the long-lag condition because this condition results in more unique contexts being encoded, making it more likely that one of the encoding contexts matches the retrieval context. The encoding variability framework attributes the crossover interaction to the interplay of three processes: encoding of contextual information, the use of context at retrieval, and the rate of change in the available contextual information across time.

Balota et al. (1989) were interested in the question whether older and younger adults differ in context encoding or in contextual fluctuation, and conducted a cued-recall experiment with younger and older adults in which presentation lags and retention intervals were varied. An ANOVA on percentage correct recall showed no interactions of age with the experimental variables, although older adults' cued-recall performance was lower than that of younger adults overall. To obtain measures of context encoding and contextual fluctuations over time, Balota and coworkers fitted Estes' (1955) stimulus fluctuation model to the cued-recall data for younger and older adults. In this model, each stimulus is represented as a population of elements. At the time of encoding, only a subset of these elements is available, and only some elements of this subset will be encoded. The model also assumes that across time, there is a random exchange of elements in the available and unavailable sets. That is, the available elements fluctuate, and at different points in time, different elements are available for encoding. There are two model parameters: the probability that an available element is encoded (B), and the rate of fluctuation across time (F).

Using a least-squares method the authors estimated the B and F parameter values that provided the best fit to the data from each age group. The modeling results suggested that age-related differences in cued-recall performance could be predicted on the assumption that

older adults encoded less contextual information and had a slower rate of contextual fluctuation across time. As the authors pointed out, a superficial inspection of the data would not have led to the discovery of age differences in two different cognitive processes. Balota et al. suggested experimental manipulations that should differentially affect the model parameters, but to our knowledge no such validation has been performed to date.

The Temporal Context Model

The Temporal Context Model (TCM) by Howard and Kahana (2002) builds on Estes' (1955) stimulus fluctuation theory, but adds important assumptions. TCM is a single-store distributed model of item-context processing in episodic recall that can account for the order of item recall in immediate and delayed free-recall tasks. The model stands in contrast to traditional dual-store models that assume separate short-term and episodic long-term memory stores (Atkinson & Shiffrin, 1968). During list presentation, TCM stores associations between items and gradually changing context. While in Estes' (1955) model context fluctuates randomly over time, the TCM adds a contextual retrieval process to the random context model. Contextual drift in the TCM is determined by the retrieval of context associated with the currently active item. At the time of recall, a recalled item cues previously stored contextual states (via item-context associations) which in turn cue other items that are associated with similar contexts as the recalled item. Nearby list items share many temporal context features. Therefore, storage and retrieval of item-context associations give rise to contiguity effects: recall of an item tends to be followed by recall of items that were nearby on the study list (the so called lag-recency effect).

Howard, Kahana, and Wingfield (under review) used the TCM to model free recall data from normal young and older adults that showed a dissociation between recency and lag-recency effects. In a study by Kahana, Howard, Zaromb, and Wingfield (2002), young and older adults exposed same levels of the recency effect. That is, rate of recall was increased for the last items on a list in immediate recall, but not in delayed recall. Moreover, in immediate recall, older as well as young participants recalled end-of-list items first. By contrast, older adults showed less of a lag-recency effect than young adults which went along with a lower overall recall rate in older in comparison with young adults. According to TCM, this dissociation between recency and lag-recency points to age-related deficiencies in the process of contextual retrieval. Age differences in contextual drift cannot account for the dissociation, because they would result in age differences in both the recency and the lag-recency effects. Howard et al. (under review) succeeded in simulating the age-related dissociation of the recency and the lag-recency effects with an extension of TCM that includes a parameter for noise in contextual retrieval. The authors interpret this noise as interference from item-context associations that were not formed during list encoding. As the authors point out, this interpretation is in accord with Hasher and Zacks' (1988) inhibitory deficit theory of cognitive aging. That is, older adults inhibit irrelevant alternative associations less effectively than their young counterparts.

TCM thus yields conclusions that differ from those drawn by Balota et al. (1989) who used Estes' (1955) simple random context model. As explained above, Balota et al. concluded that age differences in contextual encoding and in rate of contextual fluctuation over time were responsible for observed age differences in recall. They did not consider a retrieval

parameter. The inclusion of both recency as well as contiguity effects in the data modeled with the TCM, however, demonstrated that neither encoding of context, nor rate of contextual change during study can account for the complete pattern of observed age differences in recall. Instead, the age-related deficiency appears to lie in the process of retrieving the temporal context of list items.

Estes' stimulus fluctuation model has also influenced modeling work in the area of serial-order memory, where the notion of changes in context over time has been a central theoretical theme. We next turn to models of serial-order memory.

Context Models of Serial-Order Memory

Serial-order memory is memory for the order in which a set of events has occurred. Context here is defined as the temporal position of a specific event. In laboratory experiments, three paradigms have been used to study serial-order memory: list discrimination, recency judgments, and serial-order reconstruction tests. In list-discrimination experiments, participants are presented lists of items and are later tested for their memory of the list membership of the items. This task requires only relatively coarse temporal discrimination and resembles the tasks used in source-monitoring and process-dissociation experiments described above. In recency-judgment tasks, participants are presented with two test items at a time and have to indicate which one was seen more recently. The test items may include lures, which have to be rejected as new. In this case, the test taps old-new recognition and serial-order memory. In serial-order reconstruction tests, participants are asked to re-arrange sets of test items in the order in which they were previously seen or actions in the order in which they were previously carried out. The traditional measures of serial order memory are accuracy scores derived directly from the observed responses.

Most theories of cognitive aging predict age differences in serial-order memory. This is most clearly the case for theories that attribute age-related declines in memory performance to age-related deficits in the processing of contextual information. While there is some evidence that age differences exist in serial-order memory, the findings are mixed and seem to depend in part on factors such as instructions, test format, and test materials (Dumas & Hartman, 2003). One problem with interpreting the pattern of age differences in serial-order memory tasks is that performance measures of serial-order memory are not process-pure. Formal models have the potential to remedy this problem. However, to our knowledge, none of the existing formal models have been applied in gerontological research on episodic serial-order memory.

Overviews of existing models of serial-order memory can be found in the literature (e.g., Brown, 1997; Brown et al., 2000), so we only provide a listing here. Important models include so-called slot-based models (e.g., Conrad, 1965), Estes' perturbation model (e.g., Estes, 1972), associative chaining models (e.g., Lewandowsky & Murdock, 1989), distinctiveness models (e.g., Murdock, 1960), and dynamic-context models (e.g., Estes, 1972). These models have influenced more recent formal theoretical developments, the most successful of which is a computational model named Oscillator-based Associative Recall (OSCAR; Brown et al., 2000). In this model, a dynamic learning context signal is created by multiple internal oscillators with different periodicities, which jointly contribute to each element of the context. Items and context are represented as separate feature vectors. To recall a sequence of items, their

associated contexts have to be reinstated. This requires remembering the initial state of the learning-context signal. Because the periodicities of the oscillators are known, any states of the context signal following its initial state can be reconstructed. The model accounts for different error patterns in serial-order memory tasks in younger adults: movement errors (confusions of adjacent list items), omission errors, and intrusion errors (Brown et al., 2000; see Maylor, Vousden, & Brown, 1999, for a concise explanation of how these errors arise in the model).

Simulating older-adult data in this model may provide clues about potential effects of aging on the ability to form item-context associations, the ability to reinstate the learning context at retrieval, and the nature of the oscillator-based context signal. Maylor et al. (1999) used the model to simulate adult age-related differences in serial-order short-term memory. It seems that an extension to the effects of aging on performance in tests of episodic serial-order memory would be straightforward and provide an opportunity to test specific hypotheses derived from some of the currently dominant cognitive-aging theories. One specific possible avenue for further research would be a replication and extension of the cued-recall findings reported by Balota et al. (1989) with cued recall to serial-order memory with OSCAR. As mentioned above, Balota et al.'s research suggested the presence of age differences both in the rate of contextual fluctuation and in the encoding of context information. Within the OSCAR model, these age differences might translate to differences in the speed of the oscillators and in learning rate.

Global-Matching Models

The family of global-matching models includes SAM (Gillund & Shiffrin, 1984), REM (Shiffrin & Steyvers, 1997), MINERVA2 (Hintzman, 1988), TODAM2 (Murdock, 1993), and the Matrix model (Humphreys, Bain, & Pike, 1989). For an overview of global-matching models see Clark and Gronlund (1996). Unlike most of the models reviewed so far, global-matching models are designed to explain human memory performance across a range of experimental tasks, most notably recognition tasks. These models share the assumption that a memory probe is matched against all information in memory ("global match") to produce a familiarity signal. This signal is then evaluated in a signal-detection process to determine whether or not to respond to a test item with "old" or with "new". Important differences between the models concern the representation of information in memory (vector representation vs. item representation; separate vs. composite storage), the computation of the global match, and the contributions of context information to the global match.

A general global-matching model: ICE. A study by Bayen et al. (2000) illustrates some of the general features of global matching models and provides an example of how these types of models can be used to test hypotheses about age differences in the use of contextual information in episodic-memory tasks. Bayen et al. used Murnane, Phelps, and Malmberg's (1999) Item, Context, and Ensemble (ICE) general global matching theory of recognition memory to study age-related differences in the processing of contextual information in recognition. According to ICE, three types of information contribute to the global match: item (I), context (C), and ensemble information (E). The ensemble is an integrated representation of item and context.

Bayen et al. (Experiment 2) presented young and older adults with word items in rich visual contexts (i.e., within pictures of scenes on a computer screen) and later tested these items as well as distractor items in either the same context that appeared at study, or in a different context. The main dependent variables in these experiments are context effects. A context effect is present if performance is higher when memory is tested in the same context versus different contexts. ICE predicts context effects on hit rates (HR) and false alarms rates (FAR), but not d' (a discrimination measure based on signal detection theory) if item and context information (I and C) only contribute to the global match. Context effects on d', on the other hand, are predicted when in addition to item and context information, an ensemble match contributes to the global match (for formal derivations of these predictions, see Murnane et al., 1999).

Bayen et al. (2000) hypothesized that older adults have difficulties forming and using an integration of item and context information. According to this hypothesis, older adults use ensemble information to a lesser extent than young adults. Thus, the authors predicted that under conditions where young adults show context effects on d', older adults show context effects on HR and FAR only. Empirical patterns of context effects confirmed these predictions and suggested that older adults do encode and retrieve context information, but they do not integrate item and context information into an ensemble as effectively as young adults do. This finding supports the view that older adults have a specific, rather than a general deficit in processing contextual information in recognition.

Global-matching models: SAM. SAM (Search of Associative Memory; Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1981) makes the assumption that information is represented in separate "memory images". Images that were formed as the result of episodic experiences contain item information, contextual information, and inter-item associative information. A limited-capacity short-term buffer determines the strength and the type of information stored. Recall is modeled as a sequential search process, in which an item is recalled if its image is sampled and subsequently recovered. The probabilities of sampling an item and of recovering it each depend in part on the strength of association of memory cues to the target image in memory. Old-new recognition decisions, on the other hand, are based on a single retrieval step. A global match between item and context information in the memory probe and all information in memory is computed, and if the global match exceeds a decision criterion, an *old* response is given. Despite some limitations (e.g., Ratcliff, Sheu, & Gronlund, 1992), SAM and its descendants (e.g., REM, Shiffrin & Steyvers, 1997) could serve as effective tools for cognitive-aging researchers interested in age differences in the use of context information in recall and recognition tasks. For example, by allowing for age differences either in single or in multiple parameters of the model, it would be possible to test a single-factor aging hypothesis (e.g., the hypothesis that age differences in the processing of contextual information alone can account for age differences in memory) against more complex, multifactor hypotheses.

Age-Related Deficits in Context Processing: Discussion

The notion that aging is accompanied by a differential decline in the ability to process contextual information has been put to the test in a wide variety of experimental paradigms, and a number of formal models have been used to guide that empirical research. We believe

that some of these models are better suited than others to help answer questions about age differences in context processing. In particular, our review of the literature suggests to us that some of the extant models claiming to assess the contributions of familiarity and recollection may fall short of this promise. Careful consideration of model assumptions and issues of construct validity are called for before applying these models in cognitive aging research. Unfortunately, Kliegl and Lindenberger's (1993) Markovian approach and Balota et al.'s (1989) work with the stimulus-fluctuation model have remained isolated attempts to localize and quantify age difference in context processing, and their models still await independent experimental validation.

We believe that context models of serial-order memory (e.g., the OSCAR model by Brown et al., 1999) and global-matching models (e.g., SAM by Gillund & Shiffrin, 1984, and REM by Shiffrin & Steyvers, 1997), none of which have been broadly applied in research on aging and episodic memory (for an exception, see Bayen et al., 2000), offer intriguing opportunities for cognitive-aging research, as they permit a "molecular" analysis of the mechanisms that contribute to age differences in context processing.

The Interplay of Episodic-Memory with Judgment and Decision Processes

Performing in episodic-memory tasks involves decisions. For example, old-new recognition tasks require a decision to respond 'old' or 'new', based on output from memory in response to a memory probe. Conversely, episodic memory is believed to play a crucial role in many of the laboratory tasks used in research on judgment and decision-making. For instance, judgments of the probability of an event are informed by a person's memory for previous occurrences of the same event. In this section, we therefore focus on two types of models, namely models of decisions in recognition tasks, and memory-based models of judgment and decision-making.

Models of Decisions in Recognition Tasks

Threshold Theory. In early research on aging and recognition memory, researchers employing old-new recognition tasks used the number of hits (i.e., items correctly identified as old) or hit rates as measures of recognition (e.g., Arenberg & Robertson-Tchabo, 1985; Fullerton & Smith, 1980). Eventually, researchers realized that a measure is needed that corrects for response biases. A popular "corrected recognition" measure is hit rate minus false alarm rate (e.g., Mitchell, 1989; Vakil, Melamed, & Even, 1996). This is the old-new discrimination measure based on two-high threshold (2HT) theory, although it is often used without explicit reference to its threshold-theoretical implications. Threshold theories (e.g., Krantz, 1969; Snodgrass & Corwin, 1988) state that the decision space in a detection task or an old-new recognition task is divided by thresholds into discrete states. In two-high-threshold theory, one threshold can be crossed by old items only. An old item that crosses this threshold will be in a detect-as-old state. The other threshold can be crossed by new items only, which are then known to be new. Items that do not cross either threshold are in an undetected state and their status must be guessed. Note that the 2HT model of source monitoring (Bayen et

al., 1996) discussed earlier, makes 2HT assumptions for old-new discrimination as well as for source memory.

Signal-Detection Theory. In contrast to threshold theory, signal detection theory (Green & Swets, 1966) assumes that the output from memory is continuous. In signal-detection analysis, hit and false-alarm rates are transformed to yield separate estimates of old-new discrimination (memory), and of bias to respond "old" or "new". In aging research, the use of signal-detection theory became popular in the context of the encoding-retrieval debate in the 1970s, when researchers became interested in the question whether age differences in recognition performance might be due to age differences in response bias. For example, Harkins et al. (1979) found that, when inspecting hit rates and false-alarm rates in isolation, age-related differences in bias could obscure age-related differences in memory. White and Cunningham (1982) found that using corrections for response bias revealed similar-sized age differences in recognition as in recall.

However, the routine use of signal-detection measures comes at a cost, because the validity of sensitivity and bias parameters rests on assumptions about the distributions of memory strength for target and distractor items. Specifically, traditional signal-detection theory assumes that these distributions are normal and have equal variances. In addition, it is assumed that participants have reached asymptotic performance levels prior to the experiment (i.e., in practice trials), and that they engage in rational decision making with decision criteria that remain stable across experimental trials (Hertzog, 1980). These assumptions are easily violated, especially in research comparing younger and older adults. For example, older adults may need more practice than younger adults to reach asymptotic performance levels. Researchers can minimize the effects of such age differences by providing clear instructions and plenty of practice. However, the distributional assumptions of signal-detection theory can be tested only by deriving empirical ROCs (see Macmillan & Creelman, 1993).

Most cognitive-aging studies have based interpretations of parametric age differences on single point on the ROC. As Williams (1980) observed, interpreting between-group differences in sensitivity or bias based on single ROC points is not warranted if any one of the assumptions mentioned above is violated in at least one group. There are several alternatives to using single-point estimates in combination with parametric signal-detection measures: a) using a single-point nonparametric estimate of the area under the ROC curve (e.g., Macmillan & Creelman, 1991); however, these estimates are usually less precise; b) using forced-choice response formats; here, percentage correct is an unbiased estimate of the area under the ROC, but there is no estimate of response bias; or c) deriving empirical ROC curves. The latter method is perhaps the ideal but also the most labor-intensive way to use parametric analysis while testing parametric assumptions. To derive empirical ROCs, one needs multiple pairs of hit and false alarm rates per participant. To achieve this, one must bring participants to change their response biases, which is often done by varying the presentation probabilities of the stimuli, varying payoffs, instructing participants to shift their criteria, or by soliciting confidence ratings (e.g., Macmillan & Creelman, 1991).

Diffusion Model. Most of the models presented in this article were designed to explain episodic-memory accuracy, not reaction times. This reflects a bias in the field; episodic memory research has largely been treated as an "accuracy domain," whereas research on attention and perception, as well as semantic memory, has typically been a "reaction time domain." In fact, even in the area of episodic memory, the joint analysis of accuracy and reaction times can be highly informative with regard to the cognitive processes underlying

task performance. The advantages of reaction-time modeling are especially salient in the context of age-related cognitive slowing (for a review see Salthouse, 1996; see also Spieler, 2001). Are older adults' declines in episodic-memory performance due to a slowing of information-processing steps, or are they due to more stringent decision criteria? Ratcliff's (1978) diffusion model, designed to explain both accuracy and reaction-time patterns, is capable of addressing this question. It assumes that simple two-choice decisions are based on a random information-accumulation process that is constrained by two response criteria or boundaries (one for each response option). Important parameters in this model are the starting point of the information-accumulation process, the rate of information accumulation ("drift rate"), decision criteria or "boundaries", and a nondecisional factor that includes the motor and other peripheral contributions to reaction time. Independent experimental validation of the model parameters has recently been provided (Voss, Rothermund, & Voss, in press). Ratcliff, Thapar, and McKoon (2004) fit the model to old-new recognition data from younger and older adults. They reported age differences in decision criteria (older adults set stricter criteria than young, at least under speed instructions) and nondecisional components of reaction time (older adults were slower than younger adults), but not in the rate of information accumulation. Thus, Ratcliff et al.'s findings lend support to the so-called cautiousness hypothesis of aging (e.g., Botwinick, 1984), but suggest that cognitive slowing does not play a major role in explaining age differences in episodic-memory performance.

Memory-Based Models of Judgment and Decision-Making

Theoretically-based research on judgment and decision-making in older adults is scarce (Sanfey & Hastie, 1999). This is surprising given the close relationship between these phenomena and the extensively-researched area of episodic memory. In many choice tasks, for example, several alternatives, their features, as well as decision criteria must be accessed from memory. Judgments in everyday as well as laboratory situations also rely on information retrieved from memory. Yet, the implications of established findings in the memory-and-aging literature have not been applied to research on judgment and decision-making in older adults. Although judgment and decision-making are large research areas in mainstream cognitive psychology that include formal modeling approaches, these have thus far hardly been made fruitful for cognitive-aging research. Two examples of models developed in the younger-adult judgment literature that have potential to inform cognitive-aging theory are Minerva-DM (Dougherty, Gettys, & Ogden, 1999), and a multinomial model for judgments in a hindsight recall paradigm (Erdfelder & Buchner, 1998).

Minerva-DM. Minerva-DM (DM = decision-making; Dougherty et al., 1999) is an extended version of Minerva 2 (Hintzman, 1984, 1988), a global-matching model of memory designed to account for recognition, cued recall, and frequency judgments. In Minerva 2, items in memory are represented as feature vectors. Each feature of an item is independently encoded with a probability that is determined by a learning rate parameter. At retrieval, the global match between the memory probe and all items in memory is computed as a nonlinear function of the similarity of the test-item vector to all vectors stored in memory.

In Minerva-DM, a two-step conditional process is added to Minerva 2. All relevant traces in memory are identified first, and conditional likelihood judgments are then based on the global match between the test probe and those relevant traces. Minerva-DM can account for

conditional likelihood judgments, including phenomena such as the availability heuristic (Tversky & Kahneman, 1973), the representativeness heuristic (Kahneman & Tversky, 1973), base-rate neglect (Bar-Hillel, 1980), the conjunction error (Tversky & Kahneman, 1983), hindsight bias (Fischhoff, 1975), conservatism (Edwards, 1968), and many others. These heuristics and biases result from basic properties of the Minerva-DM memory system, that is, the nature of its memory representations and retrieval processes. The basic model has two parameters: a memory encoding parameter and a decision parameter. Spaniol and Bayen (accepted pending revisions) investigated age differences in these Minerva-DM model parameters indirectly by examining behavioral measures (frequency-judgment accuracy, conservatism, and overconfidence). The complex relationships between these measures and the two model parameters had been characterized previously in model simulations (Dougherty, 2001). Spaniol and Bayen's results did not lend support to the notion of an age-related change in decision criteria, thus contradicting the cautiousness hypothesis of aging (e.g., Botwinick, 1984). Rather, criterion setting – cautious or liberal – depended on the quality of memory for relevant information in both younger and older adults.

A multinomial model for hindsight judgments. Hindsight bias refers to the phenomenon that after people learn the outcome of an event, their recall of their own prior outcome prediction is biased toward the actual outcome (Fischhoff, 1975). In a typical hindsight research paradigm, participants are instructed to answer a series of general-knowledge questions. They are then presented with the correct answers to some of these questions. In a subsequent recall task, they are again presented with these same questions and instructed to recall their own prior judgments. Hindsight bias occurs when the response in the recall task is biased by the correct answer.

Obviously, episodic memory plays an important role in such a task. If participants do not remember their own original judgments they may be prone to hindsight bias. Also, according to some theories of hindsight, learning the correct answer may change the memory representation of one's own original judgment (e.g., Fischhoff, 1975). In research on aging, where age differences in memory for the original judgment are expected, it is particularly important to obtain separate measures of memory and bias. These measures are needed in order to investigate whether or not there are age differences in hindsight bias above and beyond performance differences caused by age differences in memory. Erdfelder and Buchner (1998) developed and experimentally validated a multinomial model to disentangle the contributions of memory and different forms of bias to the hindsight phenomenon. This model has proven most useful for an application to aging research. Bayen, Erdfelder, Bearden, and Lozito (under review) used the hindsight paradigm in experiments with young and older adult participants. Results based on the multinomial model suggested that hindsight bias can be larger or smaller in older adults than in young adults, depending on the availability of the correct answers in the environment and in working memory.

Memory, Judgment, and Decision-Making: Discussion

Remembering the past and making decisions are mutually dependent processes. If responses in a memory task depend on the evaluation of familiarity or memory strength, decision criteria are needed to make a response. Criterion setting, in turn, seems to be affected by aging (e.g., Ratcliff et al., 2004), or at least by episodic-memory differences that covary with

age (Spaniol & Bayen, accepted). Applications of formal-model approaches to explain age differences in judgment bias have yielded new insights (e.g., Bayen et al., under review), and the field is ripe for additional research.

General Discussion

In sum, we believe that theoretical advancement in the area of aging and episodic memory could be significantly facilitated by a more widespread embracement of formal-modeling approaches. As we have pointed out, memory-and-aging research faces several challenges that are not easily overcome in purely empirical-oriented research: interpreting age-by-task interactions and differences in baseline performance; and disentangling processes thought to contribute jointly to performance (see also Maylor et al., 2000; Salthouse, 1988).

We have reviewed several formal-modeling approaches that have informed theorizing in memory-and-aging research. These approaches address three major theoretical issues: age differences in encoding versus retrieval, memory for contextual information, and interactions between episodic memory and decision processes. Formal-modeling approaches in the encoding-versus-retrieval literature have yielded creative contributions (e.g., Riefer & Batchelder, 1991; Wilkinson & Koestler, 1983) but these have, unfortunately, remained isolated approaches lacking in theoretical integration. Research focusing on age differences in context-processing has not yet taken full advantage of models that have been developed in the cognitive literature. Specifically, we see great potential for memory-and-aging research in context-models of serial-order memory (e.g., OSCAR by Brown et al., 1999) and global-matching models such as SAM (Gillund & Shiffrin, 1984) and REM (Shiffrin & Steyvers, 1997). Finally, the interplay of memory and judgment is an area in which both empirical and formal-modeling contributions are scarce, but candidate models are available that could guide future work. Studying the effects of aging on memory is arguably one of the most important tasks for cognitive psychologists today. Sophisticated formal models of cognition are constantly being developed and improved in mainstream cognitive psychology. In our view, using these models in creative ways presents a unique challenge and a great opportunity for researchers in the area of memory and aging.

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