

Modeling Age-Related Memory Deficits: A Two-Parameter Solution

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Recent research and meta-analytic reviews suggest that 1 observed pattern of impaired and intact memory performance with advancing age is a deficit in measures of episodic but not semantic memory. The authors used computational modeling to explore a number of age-related parameters to account for this pattern. A 2-parameter solution based on lifelong experience successfully fit the pattern of results in 5 published studies of the word-frequency mirror effect and paired-associate recognition. Lifelong experience increases the strength (resting level of activation) of concepts in the network but also saturates the network with an increasing number of episodic associations to each concept. More episodic associations to each concept mean that activation spreads more diffusely, making retrieval of any newly established memory trace less likely; however, the greater strength of a concept makes recognition based on familiarity more likely. The simulations provide good quantitative fits to the extant age-related memory literature and support the plausibility of this mechanistic account.

Keywords: memory and aging, item recognition, associative recognition, recollection, meta-modeling

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Prominent researchers have called for formalized models of cognitive aging processes for the purpose of organizing and integrating this sizeable research literature in a rigorous and testable manner (e.g., Charness, 1988; Salthouse, 1988). In that regard, computational modeling can be quite useful in establishing the formal computational principles and mechanisms that underlie and distinguish a certain theoretical perspective. The particular theoretical perspective undertaken here is that much of the course of normal age-related effects on memory can be characterized by changes to the memory representation that occur as a function of experience. Surprisingly, experience is absent as a causal factor in most models of cognitive aging. As a theory of age-related change, a computational mechanism predicated on lifelong experience is a proximal one.

Memory impairments are a salient characteristic of aging, yet not all memories are equally subject to decline. Longitudinal studies have demonstrated separate trajectories for measures of episodic and semantic memory (Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Schaie, 1996). This article introduces a computational model of cognitive aging that attempts to capture this pattern of normal age-related change in memory performance. This model

posits two changes to memory that occur simply as a result of lifelong experience. That is, lifelong experience reaffirms and strengthens semantic knowledge, which increases the general familiarity of concepts. However, episodic deficits also arise because memory concepts are experienced over a lifetime in a multitude of different contexts, which makes the recollection of any specific episode more difficult. Although there are undoubtedly biological changes that occur with age that affect performance, this article examines the extent to which certain patterns of well-known age deficits can be explained without appealing to neurodegeneration.

The Pattern of Age-Related Decline of Memory Function

A common focus in the cognitive psychology of adult development has been to establish patterns of impaired and intact performance with advancing age. A number of meta-analytic reviews of age-related changes in memory performance (LaVoie & Light, 1994; Spencer & Raz, 1995; Verhaeghen, Marcoen, & Goossens, 1993) suggest that one pattern of age-related change in memory functioning corresponds quite well to the episodic versus semantic distinction proposed by Tulving (1972).¹ LaVoie and Light's (1994) meta-analysis demonstrated that age-related decrements in memory are more often observed in episodic memory tasks, such as recall and recognition, than in implicit memory tasks, such as priming.

Across a variety of experimental paradigms and over 100 published studies, there are few, if any, age differences for indirect

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¹ Our view is based on the process distinction proposed by Reder (1999) of procedural (skills) and nonprocedural (semantic, priming, episodic) memory processes. As nonprocedural memory processes, the dual processes of familiarity and recollection operate in the source of activation confusion model on a common representation of semantic and episodic nodes. This differs from the modular view of declarative (semantic, episodic) and nondeclarative (skills, priming) memory (Squire, 1994).

tests of memory, such as priming (for reviews, see Light, Prull, LaVoie, & Healy, 2000; Prull, Gabrieli, & Bunge, 2000; Salt-house, 1991; see also Balota & Duchek, 1991). This suggests that the accessibility of common knowledge residing in long-term memory is robust with advancing age (for knowledge maintenance across the life span, see Bahrck, 1984; Bahrck & Hall, 1991). In another meta-analytic review, Verhaeghen et al. (1993) estimated the size of the episodic memory impairment for older adults to be about one standard deviation below that of young adults' performance. This age-related episodic deficit applies to many types of event details, such as the case or color of word fonts, the modality of presentation of words, and the gender of voice (for a meta-analytic review, see Spencer & Raz, 1995).

A particularly elegant demonstration of this dissociation is offered by Light and Singh's (1987, Experiment 2) study, in which word-stem completion was examined in young and older adults in two conditions that differed only in the instructions given. In the implicit task, subjects were asked to fill out the word stems with the first word that came to mind, whereas in the explicit task, subjects were asked to fill out the word stems with previously presented study words. Older adults had pronounced difficulty, compared with young adults, explicitly recalling the previously presented study words using the word stems as cues; however, there was little difference between the two age groups in implicitly completing the word stems, both groups frequently completing the word stems from the studied word.

Experience-Based Changes to Memory

Aging is a rich area for testing general cognitive theory and the effects of experience on human information processing. The lexical domain is well suited for our modeling purposes. First, the lexical domain is intriguing from an age-related perspective. Several researchers have demonstrated that the lexical domain is particularly resilient to age-related change (see Hale & Myerson, 1996), as it embodies lifelong learning. Second, the lexical domain affords us a unique metric, normative word frequency (e.g., Kucera & Francis, 1967), a quantification of experience with a particular word stimulus. In particular, computational principles, such as the base level of activation and the structure of the network (i.e., number of episodic associations), for different classes of stimuli (e.g., low- and high-frequency words) can be estimated on the basis of their reported normative frequency of occurrence (per million) in the lexicon. Word frequency has played an important role in theories of memory, and the explanation of the word-frequency mirror effect provides a good analog to our theory of how memory changes with age–experience.

The *word-frequency mirror effect* refers to the phenomenon that high-frequency words are recognized less often but produce more false alarms than low-frequency words (Brown, Lewis, & Monk, 1977; Glanzer & Adams, 1985). A number of dual-process models of memory have successfully accounted for this phenomenon (Balota, Burgess, Cortese, & Adams, 2002; Reder et al., 2000; Reder, Angstadt, Cary, Erickson & Avers, 2002). A dual-process model postulates that there are two ways to recognize something: (a) the recollection of the episode–event when the information was acquired (see Jacoby, 1991; Mandler, 1980; Reder et al., 2000; Yonelinas, 1997) and (b) a familiarity-driven process based on underlying memory strength that is not dependent on the retrieval of any contextual (episodic) details. According to dual-process

models of the mirror effect (Joordens & Hockley, 2000; Reder et al., 2000), the hit rate portion of the mirror effect is largely determined by the process of recollection, whereas the false-alarm portion is determined by familiarity. According to the dual-process model of Reder et al. (2000), recollection of a specific episodic trace is less likely for a high-frequency word because of interference generated from a greater number of previous episodes. Low-frequency words have less of this interference and, as a class of stimuli, are also less likely to trigger spurious familiarity judgments (i.e., false alarms) because nonstudied low-frequency words are (by definition) less familiar than nonstudied high-frequency words.

We hypothesized that the underlying changes to memory representation that occur as a result of stimulus experience in accounting for the word-frequency mirror effect are magnified by lifelong experience and can account for the differential pattern of age-related change to episodic memory and semantic memory function. On behavioral measures, we observed that the pattern of hit and false-alarm rates for low- and high-frequency words (stimulus experience) is similar to the age-related comparison between young and older adult performance (lifelong experience). With advanced age, older adults exhibit decreased hit rates and more false alarms than young adults for a given class of word-frequency-matched stimuli (Balota et al., 2002; Bowles & Poon, 1982; Ratcliff, Thapar, & McKoon, 2004). Below, we present the two computational principles underlying our hypothesis that greater experience leads to a decrease in hit rate and an increase in false alarms. These predictions are based on our previous models that generate fewer recollections when there are more episodes associated with a concept and give more familiarity judgments when concepts are stronger. For instance, a compelling data set and successful model implementation of these principles are given by Reder, Angstadt, et al. (2002), who were able to artificially recreate the hit rate and false-alarm rate mirror effect pattern using pseudowords (e.g., *bist*, *clow*, *nime*, *treg*) by varying the amount of exposure to two separate lists of pseudowords (i.e., artificial low frequency and high frequency) over an intensive 5-week acquisition period.

Contextual Fan

The fan factor (Anderson & Bower, 1973) is based on an established principle rooted in the associative memory literature. It refers to both an increase in response latency and error rate as a function of the number of associations linked to a concept that is the source of spreading activation. As more competitors share the activation that is sent by a concept, each fact will receive less activation, thereby affecting both the probability and speed with which it is accessed. The amount of activation that a fact receives is affected by the number of competing associations fanning out of that source node. The fan effect has even been shown to affect verification times for semantic factual knowledge with the introduction of fantasy facts (e.g., “Napoleon Bonaparte gave the Gettysburg Address”) associated with that semantic knowledge (Lewis & Anderson, 1976; Marsh, Meade, & Roediger, 2003; Peterson & Potts, 1982).

Although the fan effect has been studied extensively in the literature (Anderson & Lebiere, 1998; Anderson & Reder, 1979, 1999; Reder & Anderson, 1980; Reder & Ross, 1983; Sohn, Anderson, Reder, & Goode, 2004; for age-related accounts, see

Cohen, 1990; Gerard, Zacks, Hasher, & Radvansky, 1991; for an alternative account, see Radvansky & Zacks, 1991), it has only recently been extended to include contextual fan effects. Experimental manipulations of contextual fan have been shown to decrease the success of recollection of the episodic context (Diana, Peterson, & Reder, 2004; Reder, Donavos, & Erickson, 2002; Reder et al., 2000). Most fan experiments have manipulated the number of associations in the laboratory, but Reder et al. (2000) demonstrated the viability of this construct in accounting for stimulus experience, namely the word-frequency mirror effect.

We propose a quasi-experimental variable, the contextual fan factor, that is derived from lifelong experience, varies with age, and is analogous to laboratory manipulations of fan such that the amount of fan affects the spread of activation. Theoretically, this means that an older person's memory should have more contextual fan and therefore the spread of activation should be more diffuse. This results in less activation arriving at any one memory trace, making retrieval more difficult.²

Increased Familiarity: A Strengthening of Concepts

It can be argued that there are positive, generative components to aging as well as liabilities, especially to general semantic knowledge. The lexicon has been demonstrated to be well preserved across the life span (see Light, 1992). For instance, the Seattle Longitudinal Study (Schaie, 1996) has found that vocabulary scores continue to increase to age 81. It may be because lexical information is continually reexperienced across the life span. This is true even for unrehearsed knowledge, which has been found to be remarkably stable across extremely long retention intervals (Bahrick, 1984; Bahrick, Bahrick, & Wittlinger, 1975; Bahrick & Hall, 1991).

In our aging simulation, the positive effect of experience was modeled by increasing the base-level activation of concept nodes residing in long-term memory by a multiplicative factor, the base factor parameter. Lifelong learning results from repeated exposures to concepts. This was modeled as a general strengthening of the base level of activation of all concepts residing in the long-term memory of older adults. This higher base level can also result in an increased tendency to false alarm to items on the basis of familiarity judgments. Our aging simulation implemented both the fan factor and base factor parameters in the source of activation confusion (SAC) model of memory (Reder, Angstadt, et al., 2002; Reder et al., 2000).

Computational Model: Implementation of the Age-Related Parameters

SAC was used in our model as a test bed for evaluating the adequacy of a number of aging parameters. As a dual-process model, the SAC model was selected because it can offer precise estimates of how different age-related information-processing assumptions affect the familiarity (e.g., semantic) and/or recollection (e.g., episodic) memory processes. A full account of the SAC model, including a table of modeling equations and constants, is available as an online supplement (or at http://www.andrew.cmu.edu/user/reder/model_fits/BuchlerReder.html; see also Reder et al., 2000). A brief overview of the computational model and how it accounts for the mirror effect and aging results is provided below.

The SAC model representation consists of a network of both semantic (concept) nodes and associated episodic (context) nodes. Node activations are governed by the computational principles of spreading activation and the strengthening and decay of activation. Episode nodes are new memory traces formed during the study phase, which binds the concept presented with the experimental context. In a recognition test, the presented probe activates a word concept and activation spreads from it (the source) to all its associated contexts. The activation spread to any given node depends on the strength of that link and its strength relative to all competing links; the more competing links, the less activation that is sent down any one link. Recollection occurs when there is sufficient activation at the episode node to pass threshold. The amount of activation accrued at the episode node depends on how active it was before receiving the spread and how much activation it receives from the concept. According to SAC, a word may still be judged "old" when recollection fails if the concept is judged as sufficiently familiar to pass the familiarity threshold.

An illustration of the memory representation used in SAC models is shown in Figure 1. "Coffee" and "grass" are shown with thicker circles to represent a higher base level of activation caused by more exposures to those words over a person's lifetime than the low-frequency words "stoic" and "abbey." Likewise, there are fewer links fanning out of the low-frequency words because they are associated with fewer prior contexts. Base or resting levels of activation for words of different frequency are estimated by transforming established frequency norms, specifically, taking the Kucera and Francis (1967) value and raising it to the 0.4 power. Likewise, we estimated the amount of preexisting³ contextual fan by raising it to the 0.7 power. Again, the assumption of the model is that more activation will spread back to an episode node associated with a concept with fewer competing contexts and that more familiarity judgments (both valid and spurious) will occur for words experienced more often. The reader is advised to consult Reder et al. (2000) or the online supplements (listed above) for the equations and more specific assumptions.

Our approach was to first fit the young adult data and then fit the older adult data by assuming that only the two computational principles were affected by age: the strength of the words in memory (base factor) and the number of prior episodic associations to the words (fan factor). Our model simply applied a scalar to the values derived from the Kucera and Francis (1967) norms because the exponents used in previous SAC models were based on young adult experience. The scalar allows us to simulate the increase in lifelong experience. In other words, we tested the adequacy of the two age-related processing assumptions to uniquely account for the age-related variance in memory performance. An age-related data set allows us to test the implications of these two experience-based computational principles, taking the

² It is important to note that there is an alternative account for increased fan effects with age other than an increased number of contextual associations in the network. Fan effects could also be conceived of as an interference phenomenon alternatively arising out of a weakened inhibitory mechanism with age (see Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999).

³ The term "preexisting" is used to distinguish inherent differences (quasi-experimental variables) from direct experimental manipulations for which the fan effect was named (Anderson, 1974).

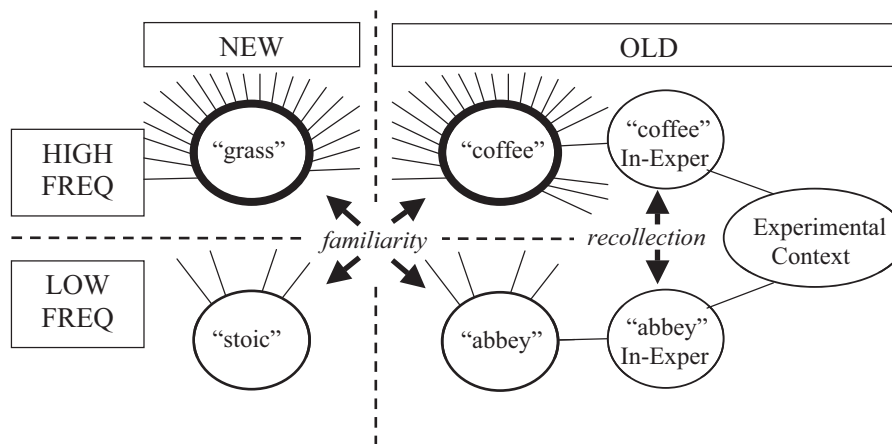


Figure 1. Schematic illustration of memory representation of words of different frequencies tested in a recognition memory experiment. Base-level strength is denoted by the thickness of the circle; contextual fan is denoted by the number of line projections. FREQ = frequency; Exper = experiment. Adapted from “A Mechanistic Account of the Mirror Effect for Word Frequency: A Computational Model of Remember—Know Judgments in a Continuous Recognition Paradigm,” by L. M. Reder, A. Nhouyvanisvong, C. D. Schunn, M. S. Ayers, P. Angstadt, and K. Hiraki, 2000, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, p. 296. Copyright 2000 by the American Psychological Association.

account of the word-frequency mirror effect to its logical extreme—lifelong aging.

It is worth noting that our goal is not to argue that SAC is the correct model of cognitive aging or any model of cognition. Like all models, it is an approximation to the truth and will ultimately be modified or discarded as new findings emerge. We aspire to delineate a narrow set of computational principles that can account for a relatively broad range of data.

Modeling Data Sets From the Literature

We modeled the data from five published studies involving young and older adults. Those studies fall into one of two paradigms: single word recognition and word pair recognition. Three of the studies (Balota et al., 2002; Bowles & Poon, 1982; Ratcliff et al., 2004) fall into the first category. They examine how the word-frequency mirror effect changes with age. The other two studies (Castel & Craik, 2003; Light, Patterson, Chung, & Healy, 2004) examine how paired-associate recognition varies with age. Each study reported the normative frequency of occurrence (per million) for their word stimuli, making all studies directly comparable. The results of these studies bear on the dual-process interpretation that age-related memory deficits are due to a loss in ability to recollect and result in a greater reliance on familiarity.

Our approach involved using the SAC equations to calculate average activation values for young adults. We estimated base-level activation values for stimuli, such as low- and high-frequency words, from the norms as described above. The four free parameters for the young data are the threshold for responding and the variance of the activation values for both concepts (i.e., words) and context (i.e., episodes). These values affect the probability of recollecting that a word was studied (i.e., episode node is active enough) and the probability of judging that the stimulus seems sufficiently familiar (i.e., word node is active enough) that an old response is generated when the recollective process fails. Once the young adult data are fit with standard SAC parameter values, then

the older adult data are fit with the scaling values of the two parameters that represent lifelong experience, base-level activation and contextual fan. The particular patterns of results, model implementation, and parameterized aging model fits for the single word frequency studies and word-paired-associate studies are given below.

Word-Frequency Mirror Effect and Age

Three studies were modeled, each of which assessed recognition memory for single words of varying word frequency using the study–test procedure: Balota et al. (2002), Bowles and Poon (1982), and Ratcliff et al. (2004). The data and model fits are presented in Figures 2, 3, and 4, respectively. In each case, the accuracy data demonstrated the classic mirror effect pattern—opposite trends were observed for the hit rate and false-alarm rate of low- and high-frequency words. With advanced age, older adults exhibit decreased hit rates and more false alarms than young adults for a given class of word-frequency matched stimuli. Details about each study and special considerations in generating the model fit are given below.

Balota et al. (2002). Balota et al.’s (2002) study involved three age groups: young (19 years), older (71 years), and still older (85 years) adults. For the model to account for both older adult age groups without introducing any additional free parameters, the authors assumed a priori that age-related differences in the old age range are a continuous function of age. Specifically, a multiplicative constant based on the relative ratio of the age difference between the two older adult groups, aged 71.4 years and 85.0 years, was used to simulate the effects of advancing age between the aged groups. A scalar was used to determine the old-old age group (85.0 years) parameter values based on the old age group (71.4 years) parameter values. The scalar applied was 1.19 higher (i.e., $85.0 / 71.4$) for both the fan factor and base factor parameters. The initial base-level strengths and pre-existing fan effect for the low- and high-frequency words were set (by convention; see Reder

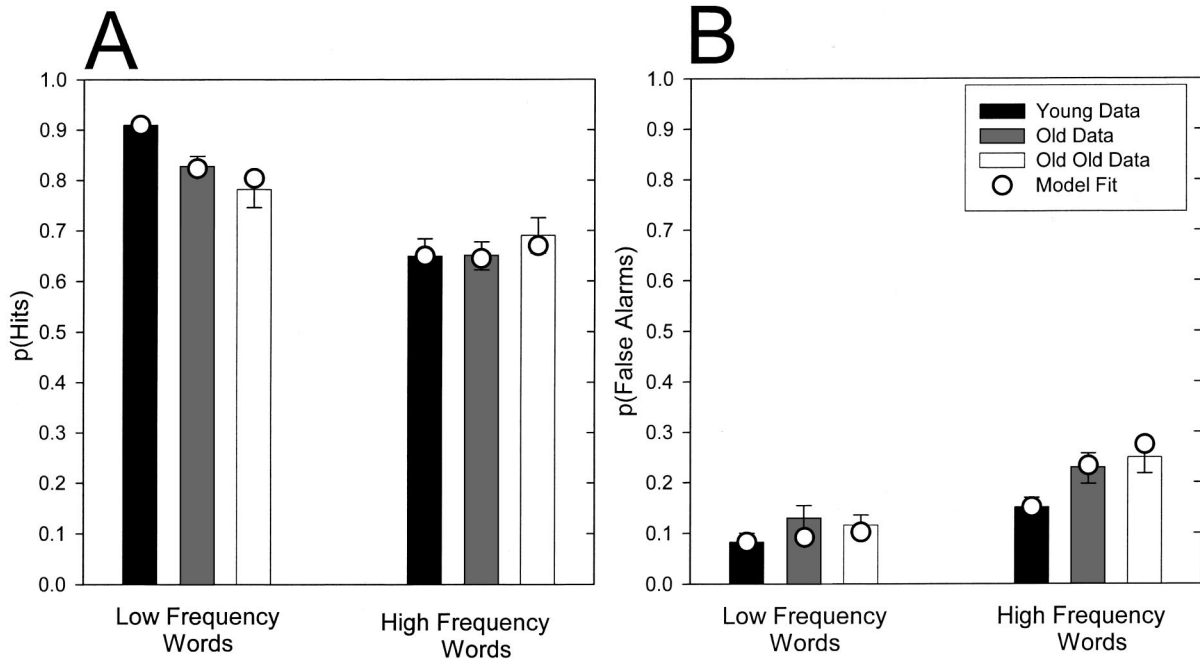


Figure 2. Source of activation confusion model fit (open circles) of Balota, Burgess, Cortese, and Adams's (2002) low- and high-frequency word hit rate (A) and false-alarm rate (B) data for young, old, and old-old age groups. The error bars represent the standard error of the mean.

et al., 2000) to their respective Kucera and Francis (1967) word frequency raised to the 0.4 power for strength and 0.7 power for fan. In this data set, high- and low-frequency nouns had norms of 77.4 and 2.2 (per million).

Figure 2 presents the model fit that shows how well the two-

parameter model does at capturing the pattern of results. The results of the model fitting procedure are summarized in Table 1. Listed at the top of Table 1 are the four free parameters (word and episodic node thresholds and standard deviations) used to fit the young adult data. The fit statistics listed at the top of Table 1

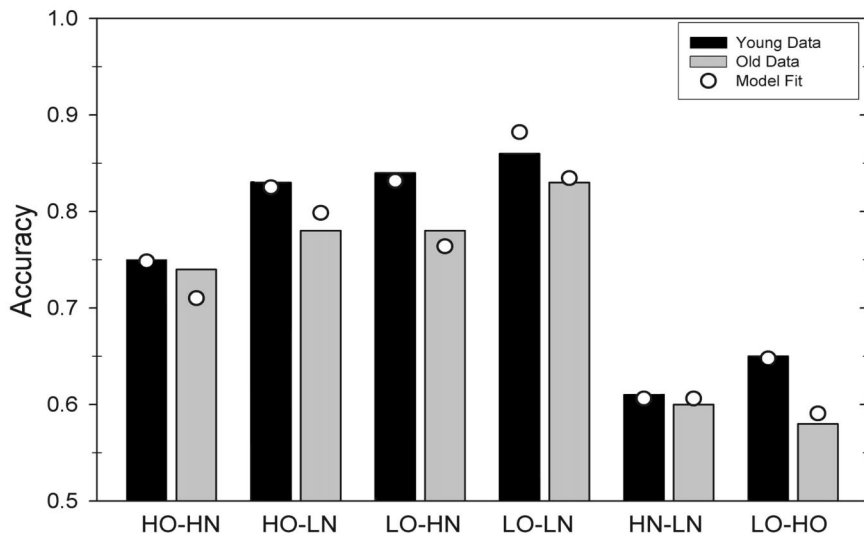


Figure 3. Source of activation confusion model fit (open circles) to the young and older adult recognition memory data of Bowles and Poon (1982), where HO is a high-frequency old word, HN is a high-frequency new word, LO is a low-frequency old word, and LN is a low-frequency new word. The labels represent the two-alternative forced-choice procedure. The reported accuracy is that for the first word type in the pair (the dominant one; accuracy above 50% chance).

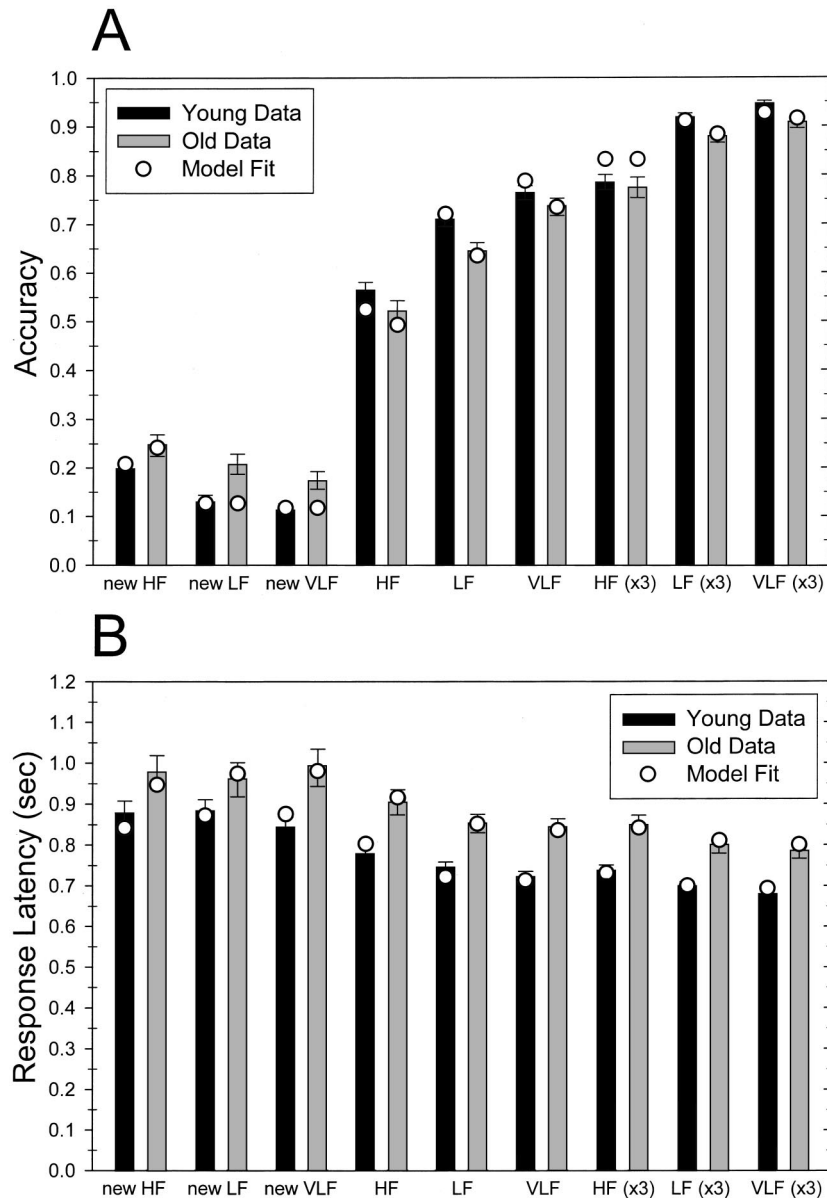


Figure 4. A: Source of activation confusion (SAC) model of the accuracy data of Ratcliff, Thapar, and McKoon (2004). B: SAC model of the response latency data (in seconds) of Ratcliff et al. A transform (see Equation 1 in the text) was used to convert activation values from the accuracy model fit (Panel A) into response latencies. New = novel word (false alarm); HF = high-frequency words; LF = low-frequency words; VLF = very-low-frequency words; $\times 3$ = the repetition of stimuli three times during the study phase. The error bars represent the standard error of the mean.

compare the young and older adult data with the young adult model fit. The older adult data are included in this statistic so that we have a reference for assessing the improvement in model fit captured by simulating the older adults. We then assessed the sufficiency of the base factor and fan factor parameters to account for the aging data, listed in the lower half of Table 1. Any improvement in the model fit statistics reflects the ability of the parameter(s) to capture unique age-related data. The data were fit by just using one of the two parameters, and we report how much variability is captured by each parameter alone. The best-fitting

model involved both parameters, as each parameter captured a different source of variability in memory performance. It is noteworthy that the parameters lend themselves to a dual-process interpretation such that the fan factor parameter adversely affects recollection and the base factor parameter increases familiarity-based responding.

The single- and two-parameter aging model fits (Table 1, bottom) are judged against the standard young adult model fit (Table 1, top), which we explain below. Following the recommendation of Schunn and Wallach (2004), two goodness-of-fit statistics are

Table 1
Results of the Model-Fitting Procedure

Study	Threshold (and standard deviation)		Fit statistics	
	τ_{word} (σ_{word})	τ_{episode} (σ_{episode})	RMSSD	r^2
Balota et al. (2002)	4.26 (0.23)	3.09 (0.71)	2.12	.98
Bowles & Poon (1982)	3.92 (0.10)	3.67 (0.87)	0.63	.93
Ratcliff et al. (2004)	4.46 (0.45)	3.35 (1.13)	2.33	.99
Castel & Craik (2003)	4.23 (0.22)	3.27 (0.17)	2.84	.89
Light et al. (2004)	4.68 (0.86)	3.05 (1.50)	1.99	.96

Study and model	Age-related parameters		Fit statistics	
	Base factor	Fan factor	RMSSD	r^2
Balota et al. (2002)				
Single parameter (base)	1.41 (1.68) ^a		1.82	.99
Single parameter (fan)		1.91 (2.27) ^a	1.89	.98
Two parameter	1.70 (2.02) ^a	2.62 (3.12) ^a	0.57	.999
Bowles & Poon (1982)				
Single parameter (base)	1.32		0.58	.94
Single parameter (fan)		2.84	0.24	.98
Two parameter	1.00	2.84	0.24	.98
Ratcliff et al. (2004)				
Single parameter (base)	1.00		2.33	.99
Single parameter (fan)		2.17	1.76	.99
Two parameter	1.30	2.27	1.70	.99
Castel & Craik (2003)				
Single parameter (base)	1.77		2.06	.93
Single parameter (fan)		1.05	2.82	.90
Two parameter	1.96	1.31	1.57	.96
Light et al. (2004)				
Single parameter (base)	3.64		1.51	.97
Single parameter (fan)		1.69	1.91	.97
Two parameter	4.04	2.61	1.19	.98

Note. The top portion of the table presents the four free parameters (word and episodic node thresholds and standard deviations) used to fit the young adult data. The bottom portion of the table presents the single- and two-parameter aging model fits judged against the standard young adult model fit. RMSSD = root-mean-squared scaled deviation.

^a For the Balota et al. (2002) data, base and fan factor values are for old adults (with old-old adult values in parentheses).

reported: r^2 for trend relative magnitude and root-mean-squared scaled deviation (RMSSD) for deviation from exact data location. RMSSD is a calculation of the square root of the mean squared value of the standardized model residuals.

In Balota et al.'s (2002) data set, the standard young adult model had an r^2 of .98 and an RMSSD of 2.12, so further improvements in fit because of the application of the aging parameters captures unique age-related variance. In other words, the standard young adult model is the starting point when the older adult model is the young adult model. First, the single base factor parameter value was 1.41 (1.68 for old-old adults), with a relative trend statistic r^2 of .99 and an RMSSD deviation from data statistic of 1.82. Second, the fan factor parameter was 1.91 (2.27 for old-old adults), with an r^2 of .98 and an RMSSD of 1.89. Thus, applied as single parameters, the base factor parameter captured slightly more age-related variance. A two-parameter model with a base factor parameter value of 1.70 (2.02) and a fan factor parameter value of 2.62 (3.12) provided an excellent fit, with an r^2 of .999 and an RMSSD of 0.57. The two-parameter computational model of Balota et al. reaffirms the dual-process interpretation that older adult performance is characterized by a decrease in recollection but an increase in familiarity-based responding.

Bowles and Poon (1982). Bowles and Poon (1982) assessed young (22 years) and older (74 years) adult recognition memory using the study–test procedure with two-alternative forced-choice (2-AFC) methodology at test, seen in Figure 3.⁴ The study list consisted of a randomized arrangement of low- and high-frequency words studied one at a time. At test, subjects were required to make a 2-AFC choice between two types of words: (a) HO–HN, (b) HO–LN, (c) LO–HN, (d) LO–LN, (e) HN–LN, and (f) LO–HO, where HO is a high-frequency old word, HN is a high-frequency new word, LN is a low-frequency new word, and LO is a low-frequency old word. As listed in Figure 3, the first word in each pairing is the dominant one, chosen in proportions greater than chance 50%. The first four pairings denote a studied old word paired with an unstudied new word, and in each case, older adults demonstrate a decrease in hit rate for the studied word in comparison with young adults. The last two pairings are “null pairs” first introduced by Glanzer and Bowles (1976). For the HN–LN pairing, there is no correct choice but subjects tend to

⁴ Variability was not reported by the study authors and is absent in Figure 3.

choose the high-frequency word. In the LO–HO pairing, both are correct and subjects favor the low-frequency word.

Bowles and Poon's (1982) data set had mean high and low word frequencies of 40 and 5, which we used to set base-level activations and preexperimental contextual fan. The 2-AFC methodology of Bowles and Poon was implemented using conditional probabilities. For instance, in the first HO–HN pairing, if HO was recollected then the subject selected HO as the studied alternative. If HO was not recollected, then the probability of choosing HO was contingent on the conditional probability of the HO word node being over the familiarity threshold given that the HN word node was not. If both or neither word was over the familiarity threshold, then selection was determined with 50–50 probability. An alternative model in which the selection process was instead weighted as a proportion by the underlying probabilities for each stimulus did not improve the model fit. In the LO–HO null pair, there is also the chance that both words are recollected. In such cases, as with the familiarity process, either word could be selected with equal probability.

Bowles and Poon's (1982) data set was unique because it was modeled using only one age-related parameter, fan factor. Addition of the base factor parameter did not improve the model fit. The fit of the model to the data is shown in Figure 3. The best-fitting model solution specified a fan factor parameter value of 2.84, with fit statistics of $\text{RMSSD} = 0.24$ and $r^2 = .98$.

Ratcliff *et al.* (2004). The third simulation modeled the accuracy and latency data of Ratcliff *et al.* (2004). The fits are presented in Figures 4A and 4B, respectively. This study differed from the previous two in that the effect of repetition (one or three presentations) was assessed in the recognition of very-low-, low-, and high-frequency words. Furthermore, this was the only data set that reported response latencies as well as accuracy. The effect of repetition increased the hit rate. The accuracy data exhibit the mirror effect pattern, with decreased hit rates and increased false-alarm rates as a function of increasing word frequency. This pattern was especially pronounced for older adults. Response latencies decreased as a function of repetition and decreasing word frequency. The response latencies of older adults were consistently about 100 to 125 ms longer across all of the conditions.

In the computational model, a given study word presented three times received the input activation three times within the study period, which also strengthened the contextual link and the episode node. The three stimulus classes, high-frequency, low-frequency, and very-low-frequency words, had normative frequencies of 325.0, 4.4, and 0.4, respectively, which were used to assign initial base-level strengths and preexisting fan.⁵

In Ratcliff *et al.*'s (2004) data set, the fan factor parameter best captured age-related variance with a value of 2.17 and RMSSD and r^2 fit statistics of 1.76 and .99, respectively. Applied as a single parameter, the base factor parameter did not capture any age-related data and, when paired with the fan factor parameter, resulted in a slightly improved model fit. The best-fitting two-parameter model is depicted in Figure 4A, with a fan factor of 2.27, a base factor of 1.30, and RMSSD and r^2 fit statistics of 1.70 and .99.

Ratcliff *et al.* (2004) also reported response latencies, although the instructions to subjects stressed accuracy. Using the convention from another computational model, atomic components of thought–rational (Anderson & Lebiere, 1998), we converted activation values A_i into response latencies by the following relation:

$$\text{RT}(s) = \text{Intercept} + F \cdot e^{-A_i}, \quad (1)$$

where RT represents response latencies and F is a scaling factor for a fitted intercept. This equation was used to transform the activation values specified by the best-fitting two-parameter model for the accuracy data into response latencies. The best-fitting solution, displayed in Figure 4B, involved separate intercepts for young and older adults with respective values (in seconds) of 0.67 and 0.77, as well as separate F scaling factors for the familiarity and recollection processes of 10.48 and 1.75. The fit statistics for this model were $\text{RMSSD} = 0.89$ and $r^2 = .96$.

The ratio of the intercepts between the age groups is 1.15, which conforms to established peripheral slowing estimates reported in the cognitive aging literature of about 1.25 on control tasks (Cerella, 1985). The separate F scaling factors for the familiarity and recollection processes specify that familiarity is a more time-consuming and variable process than recollection. This initially appears to be inconsistent with research using response deadlines that show that the rise time for recollection is longer than familiarity (see Jacoby, 1999; Light *et al.*, 2004). However, we assume familiarity and recollection are alternative processes that are executed sequentially, the former tending to be adopted only when the latter process fails. Familiarity processes can be used first for quick rejections of unfamiliar items under deadline procedure conditions (e.g., Reder & Ritter, 1992). Without speed constraints, people prefer to rely on the slower and more accurate process of recollection and only use familiarity as a back up. Familiarity is more variable because it is sometimes executed without bothering to try recollection, for example, when items are very unfamiliar or subjects are unmotivated to execute the more effortful process.

Word-Paired-Associate Recognition

Two studies involving word pair recognition by Castel and Craik (2003) and Light *et al.* (2004) were included as our fourth and fifth simulation. Both studies compared young and older adult associative memory for word pairs and did not manipulate word frequency; however, both varied how the items were tested, as explained below.

Castel and Craik (2003). Castel and Craik's (2003) data set contrasted memory for single words with memory for associations between words in a pair. Subjects were instructed to either (a) recognize whether the word pair had been presented together during study (the associative test) or (b) recognize whether just the second word had been presented during study (the item test). There were four classes of stimuli at test: previously studied pairs (denoted $A-B$, $C-D$), rearranged or "conjunction pairs" ($A-D$), single items ($A-X$), and novel items ($Y-Z$), where X , Y , and Z are new words. That is, in the associative test there are two sources of activation, whereas in the item test there is only one, the second word. The data and best-fitting two-parameter model are presented in Figure 5. False-alarm rates are higher and hit rates are lower for the associative test than the item test, a result that is magnified by

⁵ However, for very-low-frequency words, the calculated amount of contextual fan was less than 1, which was problematic because as a term in the denominator (see online supplement Equation 4 or Reder *et al.*, 2000, Equation 3), a value less than 1 multiplies rather than spreads activation. For this reason, the contextual fan for very-low-frequency words was set to a minimum value of 1.

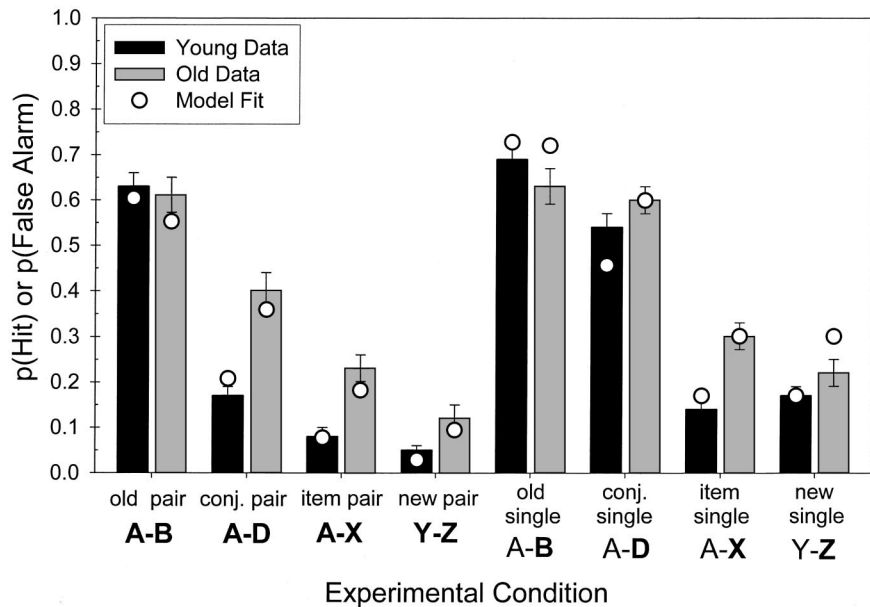


Figure 5. Source of activation confusion model of Castel and Craik's (2003) paired-associate recognition memory data, given $A-B$ and $C-D$ as study word pairs and $X, Y,$ and Z as new words. Accuracy values are listed by type of recognition probe. The associative test is signified by the word *pair* and the item test (second word) is signified by the word *single*. The error bars represent the standard error of the mean. Conj. = conjunction.

advanced age. Older adults exhibited increased false-alarm rates and decreased hit rates for both the item and associative tests.

A schematic of the paired-associates model is shown in Figure 6. The success of the recollection process was determined by the probability of the episode node passing threshold, which for reinstated word pairs ($A-B$) involved two sources of activation. Both active concept (i.e., word) nodes conferred activation to the same episode node (that binds the word to the experimental context). During the experimental procedure prior to the associative test, subjects were informed of the presence of lures on the test list. In the associative test, each of the four classes of probes shown in Figure 6 test for pair recognition and the success of the familiarity process was modeled as a conditional probability of both concept nodes being over threshold. Studied concepts had a higher level of activation and were more likely to be judged familiar. In the case of item test recognition, subjects judged whether they had previously seen the second word in the pair. For familiarity to be successful, only the second word had to be above the word threshold.

The majority of data points in Castel and Craik (2003) were false alarms, so it is not surprising that the base factor parameter captured a sizeable amount of variance associated with an age-related increase in false-alarm rate. The fan factor parameter captured a small amount of age-related variance associated with a slight decrease in the older adult hit rate for reinstated pairs. The two-parameter model, displayed in Figure 5, with a base factor of 1.96 and a fan factor of 1.31, best captured the fidelity of the data, trend, and deviation from data, with an r^2 of .96 and an RMSSD of 1.57.

Light et al. (2004). Light et al. (2004) investigated the effects of repetition on word-pair-associate recognition memory in young and older adults. During the study phase, word paired associates were presented either once or four times. During the test phase,

one of three stimulus types was presented: intact pairs ($A-B$), rearranged conjunction pairs ($A-D$), or new pairs ($Y-Z$). Figure 7 shows our fit to their data. The major results involved slight age-related decreases in hit rate to single and repeated presentations of reinstated pairs and a large age-related increase in false-alarm rate to the four-fold repetition of conjunction pairs.

The fan factor parameter captured the observed age-related decrease in hit rate to single and repeated presentations of reinstated pairs, whereas the base factor parameter captured the observed age-related increase in false-alarm rate to the fourfold repetition of conjunction pairs. Both parameters provided a good fit to the data. The model solution presented in Figure 7 is defined by a base factor of 4.04 and fan factor of 2.61, with fit statistics RMSSD and r^2 equaling 1.19 and .98, respectively.

Specific Considerations for Improving Model Fits

There are a number of areas in which the model fits could be improved. For one, our models did not have unanimous consistency. Bowles and Poon's (1982) study was the exception in that the model fit suggested an age-related recollection deficit without any age-related increase in familiarity-based responding or false-alarm rate. It is possible that the use of 2-AFC methodology biased subjects to largely base response decisions on recollection. Consider the forced-choice null pairing of a high-frequency and low-frequency new word (HN-LN). There is a slight bias to choose the high-frequency word ($\sim .60$) over the low-frequency word, which is equivalent in young and older adults—there are no age differences. This condition reflects a pure measure of familiarity because there is no context to recollect. In contrast, for all of the four types of forced-choice pairing of studied and novel words of varying word frequency, older adults demonstrated an age-related deficit in hit rate for all four studied words, modeled as a deficit in

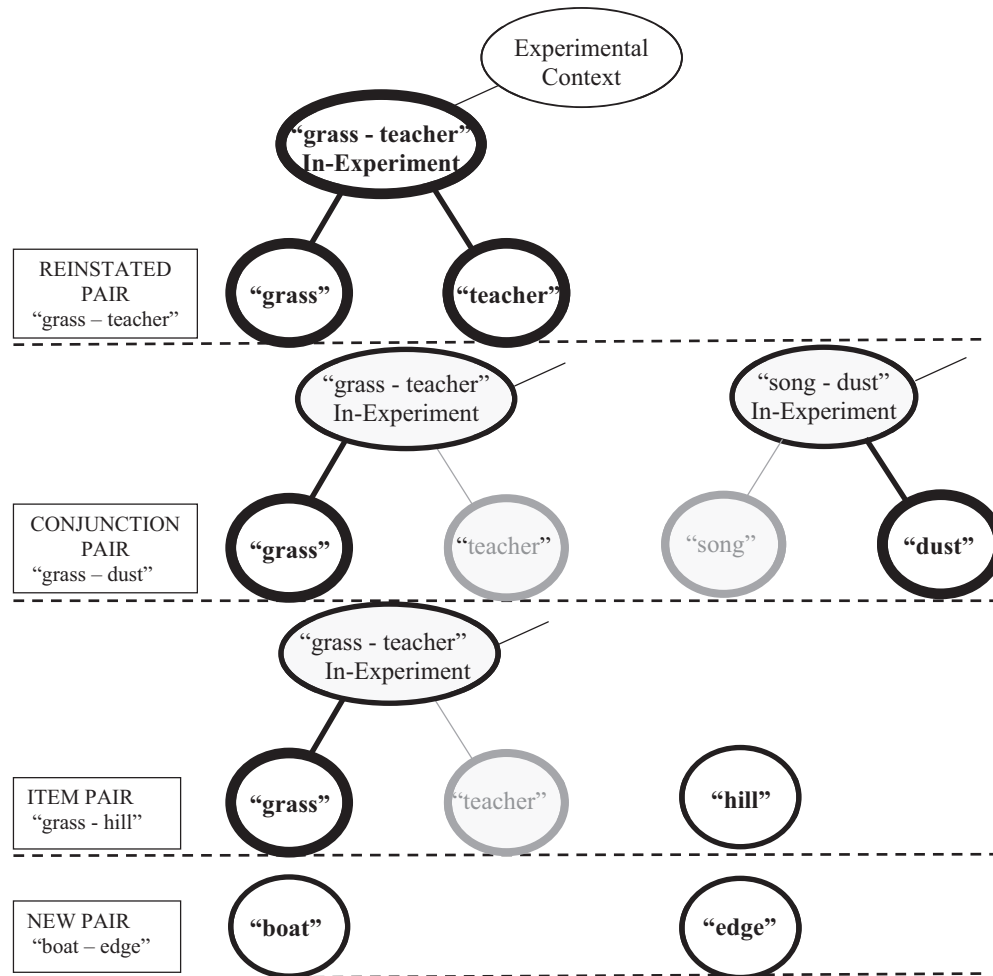


Figure 6. Schematic illustration of the memory representation of word paired associates in a recognition memory experiment for each of four classes of recognition test probes: (a) reinstated pair ($A-B$), (b) conjunction pair ($A-D$), (c) item pair ($A-X$), and (d) new pair ($Y-Z$), where $A-B$ and $C-D$ are studied word pairs and X , Y , and Z are novel, previously unstudied words.

recollection. Our model fit suggests that older adults are disadvantaged in using familiarity when presented with a forced-choice word-recognition task, perhaps because they resort to guessing rather than making a decision based on relative familiarity. This modeling result can be examined further experimentally.

Our simulation of Ratcliff et al.'s (2004) data set yielded an age-related recollection deficit and a small increase in familiarity-based responding. Although the base factor parameter helps the model capture the false-alarm data (see novel very-low-frequency, low-frequency, and high-frequency words in Figure 4A), the disparity in word frequency values is too great between high-frequency words (325.0) and low-frequency (4.4) and very-low-frequency (0.4) words. The base factor parameter is oversensitive to the high-frequency words and not large enough to affect low-frequency and very-low-frequency word false-alarm rates. Further, the high-frequency word hit rates are overestimated in the model prediction. These two modeling results may have to do with an inflated mean normative word frequency reported by the authors for high-frequency words. The range reported for the high-frequency words was between 78 and 10,600. The reported mean

frequency of 325.0, used for estimating base-level strength and contextual fan, is inflated by at least one outlier. A post hoc analysis fit the data using the median. The median value of 161 slightly reduced the disparity between high-frequency words and the low-frequency and very-low-frequency words, as well as the contribution of familiarity in inflating the model prediction of the high-frequency word hit rate. The median value allowed the base factor parameter to capture additional data with a value of 1.75, and the overall model fit was improved, with an RMSSD of 1.65 and an r^2 of .99.

As a final consideration, in the item test of Castel and Craik (2003), the model specifies equivalent predictions for the probability of responding "old" for the single item ($A-X$) and single new ($Y-Z$) because the second word in both cases is novel. However, this does not quite match the older adult data from Castel and Craik. It is possible that older adults were not properly performing the task as instructed and used information from the first word in the word pair to bias performance, evident in lower $A-X$ false alarms than $Y-Z$ false alarms. For example, they might sometimes retrieve the word associated with the A word and conclude that

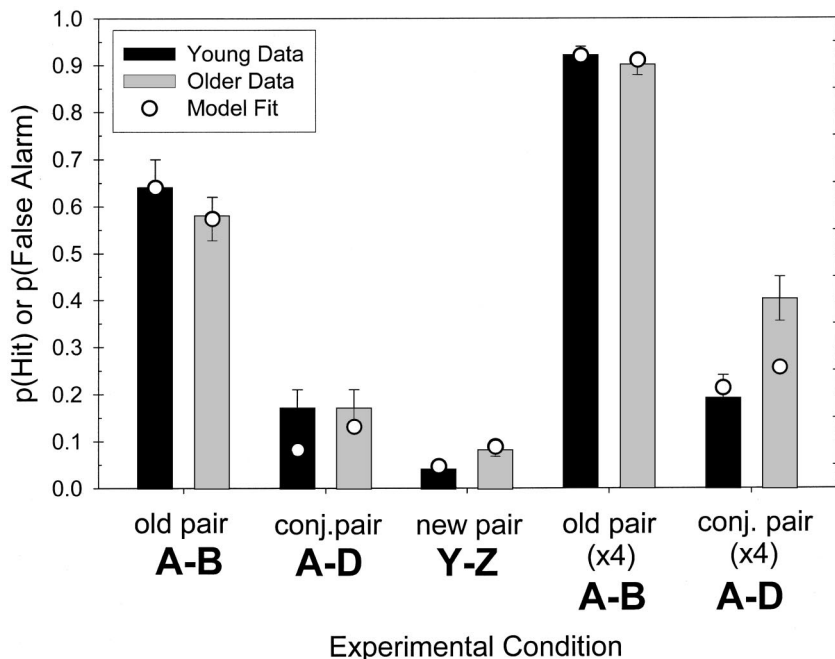


Figure 7. Source of activation confusion model of Light, Patterson, Chung, and Healy's (2004) paired-associate repetition recognition memory data, given *A-B* and *C-D* as study word pairs and *Y* and *Z* as new words. Accuracy values are listed by type of recognition probe. A class of old pairs and conjunction (conj.) pairs were repeated four times during the study phase, as denoted by $\times 4$. The error bars represent the standard error of the mean.

because *X* did not match the binding of *A*, it was likely not to be studied. For the sake of model parsimony, we did not explore such possibilities.

Discussion

The results of our model contribute to the successful explanation that SAC provides in simulating a range of memory phenomena. Although previous SAC models of the word-frequency mirror effect highlighted the role of experience in recognition memory, the aging domain offered a natural test of a model of experience-based change. The model characterized experience-related change as a double-edged sword, having both pros and cons. Lifelong experience reaffirms and strengthens semantic knowledge, increasing the general familiarity of concepts; however, strong concepts also make false alarms more prevalent. In contrast, episodic memory deficits arise with experience because there are more episodic associations to a concept, which makes the recollection of any specific episode more difficult. So, episodic deficits and false alarms increase when concepts are experienced more often, such as for high-frequency words and for older subjects.

The two-parameter model of SAC is a proximal theory of age-related change that is predicated on lifelong experience. It is clear, however, that additional processes are necessary to fully capture age-related change. For instance, our model predicts a continuous memory decline with age and that is discrepant with terminal drops in semantic memory function in very old adults (Rönnlund et al., 2005; Schaie, 1996). From our perspective, such discontinuities signal the engagement of other processes on top of experienced-based change, such as age-related neurodegeneration (Raz, 2004; Raz et al., 1997), neuropathology, or the impact of

reduced processing resources (D. C. Park et al., 2002). In other words, to capture terminal decline on semantic memory measures or specific age-related deficits in working-memory intensive tasks (i.e., Age \times Complexity interaction; see Salthouse, 1991), a third parameter is necessary. Our model could serve as a benchmark prediction of normal age-related change in general memory performance that can be expected from experience alone.

Comparison to Single-Process Models

The SAC model did a good job accounting for the various cognitive aging patterns described above; however, one might ask why another computational model was not used as the basis for an aging simulation. The SAC model is not alone, as there are a number of other computational models that also account for the word-frequency mirror effect, such as the subjective likelihood model (SLiM; McClelland & Chappell, 1998) and the retrieving effectively from memory (REM; Shiffrin & Steyvers, 1997) model. Both SLiM and REM are single-process models of memory that successfully account for the word-frequency mirror effect. However, both models assume different representations for low- and high-frequency words without an explicit experience-based process for arriving at those different representations. Both models are inspired by Bayesian principles and use likelihood ratios of feature matches as the basis for decision making, such as judging a test item on a recognition memory list as old or new.

In SLiM (McClelland & Chappell, 1998), features are encoded in a binary fashion and some occur so rarely that they are of great diagnostic value. False alarms occur more often for high-frequency words because of the high degree of overlapping features. In REM, as an item is strengthened it becomes more similar to itself and

therefore more distinctive from other items. This accounts for the word-frequency mirror effect by assuming that the feature weights encoding low-frequency words are more distinct (have higher values) than high-frequency words (Malmberg, Holden, & Shiffrin, 2004). As a result of the distinctiveness of low-frequency words, the hit rate is higher and the false-alarm rate lower.

The SAC account is preferred to that of SLiM and REM because no ad hoc assumptions need to be made regarding overlapping features or diagnosticity. Rather, the assumption that concepts strengthen with exposure and are linked to contexts each time experienced is self-evident. Neither SLiM nor REM have been extended to account for age-related data, and it is unclear how these models could accommodate age-related results. Moreover, the SAC models resulting from our aging simulation clearly support a dual-process interpretation of age-related change to memory function.

Dual-Process Interpretation

A number of dual-process accounts have stressed age-related deficits to recollection but not habitual or familiarity-based responding (Hay & Jacoby, 1999; Jacoby, 1999; Jennings & Jacoby, 1997; Light et al., 2004). Our base factor and fan factor parameters captured unique age-related variance associated with increased use of familiarity and decreased recollection, respectively. Age-related decreases in hit rate were observed in all five data sets, captured in our models with the fan factor parameter and corresponding decreases in recollection success. Age-related increases in false alarms were observed in all but one data set, which was captured in our models with the base factor parameter and corresponding increase in familiarity. The one exception to our two-parameter modeling solution was observed in Bowles and Poon's (1982) data set, which did not have an age-related increase in familiarity. This may be due to the use of a 2-AFC experimental paradigm by the researchers. One possibility is that subjects may have difficulty making comparative judgments of relative familiarity in a 2-AFC task.

The paired-associate empirical paradigm has proven useful in informing the distinction between item and associative memory. In particular, the contribution of associative information to a recognition judgment can be inferred by a comparison of intact and conjunction word pairs, as item information (i.e., familiarity) is of little diagnostic value because all of the words in both types of word pairs were studied before. Both of the studies of associative memory included such rearranged conjunction word pair lures. The increase in conjunction errors represents a dramatic age-related difference in both of the associative memory studies: Castel and Craik (2003) and Light et al. (2004). The computational models had the most difficulty fitting this condition, especially in Light et al.'s data set. Although it is clear that the familiarity of the word pair contributes to conjunction false alarms, it is an open question exactly how much recollection contributes to false acceptance or correct rejection of rearranged word pair lures (recollection to reject). The simplest possibility is that recollection is not involved, and, as postulated by Castel and Craik (see Jacoby, Jennings, & Hay, 1996), rearranged pairs are accepted based solely on the familiarity of both words. However, Light et al. contended that conjunction pairs reflect the operation of both processes in opposition to one another, such that recollection is a corrective influence on the false-alarm rate. In our models, allowing recol-

lection for rearranged conjunction pairs forced us to address the specificity of the episodic context. For instance, there is the possibility that the episodic context of only one of two words in the rearranged pair is retrieved. This could lead to a false acceptance with the knowledge that the first word was previously studied.⁶ The recollection-to-reject strategy involves using the word and the episodic context to correctly recall the associate for the word pair. This strategy resembles the common paired-associate paradigm in which one member of the study pair is presented and used to cue its pair (e.g., Salthouse, 1994). This seemingly rare case was omitted for the sake of model parsimony and also because its inclusion did not substantially improve the model fits. However, the model solution for the rearranged pairs is slightly off, which suggests that recollection may indeed play a role in conjunction word pairs, a topic that deserves further study.

Our modeling results support a broad literature arguing that older adults have a pronounced deficit in the recollection of associated information (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003; see also "binding," Chalfonte & Johnson, 1996). In one of our data sets, the item and associative paired-associates tasks of Castel and Craik (2003) were used to test the associative-deficit hypothesis of Naveh-Benjamin (2000) to attempt to explain why older adults have more difficulty remembering or forming new associations. The associative-deficit hypothesis makes salient the distinction between memory for single units and memory for associations among units. In Castel and Craik's data set, an age-related memory deficit in hit rate was more pronounced in the associative test than the item test. The SAC model of Castel and Craik fit the age-related deficits in the associative test as a deficit in recollection. In the SAC modeling framework, associations among memory units are encoded via the episode node; thus, from this perspective an associative deficit is effectively an episodic deficit (see Figure 6). Both involve retrieving a new association formed during the study period. For paired associates, the words are not linked directly but are bound together through an intermediary episode node that may also be bound to the general experimental context node.

Links play an important role in the SAC model memory representation, particularly in determining the success of the recollection process. In an aged network, a decrease in the amount of activation devoted to retrieving a particular episode can be achieved in one of three ways, as described by the following age-related computational parameters: (a) a proliferation of contextual links (fan factor), (b) an attenuation of link strengths, or (c) a lapse in attention so that links are not formed during encoding (failure to encode). Given the large role of recollection in the paired-associate tasks, the model also predicts that the age-related associative memory deficit is especially evident in tasks that preclude familiarity-based responding, for example by using less familiar stimuli (see Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin et al., 2003).

⁶ It is possible to constrain the model so that false recollection of conjunction pairs occurs only if both separate episodic contexts are retrieved. However, this raises the phenomenological question as to whether a participant can tell that each word was studied but with different associates, even if those associates are not explicitly recalled.

Table 2
Results of the Model-Fitting Procedure Using Other Cognitive Aging Accounts

Study	Threshold (and standard deviation)		Fit statistics	
	τ_{word} (σ_{word})	τ_{episode} (σ_{episode})	RMSSD	r^2
Balota et al. (2002)	4.26 (0.23)	3.09 (0.71)	2.12	.98
Bowles & Poon (1982)	3.92 (0.10)	3.67 (0.87)	0.63	.93
Ratcliff et al. (2004)	4.46 (0.45)	3.35 (1.13)	2.33	.99
Castel & Craik (2003)	4.23 (0.22)	3.27 (0.17)	2.84	.89
Light et al. (2004)	4.68 (0.86)	3.05 (1.50)	1.99	.96

Study and model	Age-related parameters					Fit statistics	
	Link strength	Fan factor	Encode fail	Base factor	Word τ	RMSSD	r^2
Balota et al. (2002)	One aging parameter					1.89	.98
	0.52 (0.44) ^a	1.91 (2.27) ^a	0.13 (0.15) ^a	1.41 (1.68) ^a	-0.17 (-0.20) ^a	1.89	.98
						1.59	.99
						1.82	.99
	Two aging parameters					1.85	.99
	0.38 (0.32) ^a			1.70 (2.02) ^a		0.57	1.00
	0.33 (0.26) ^a				-0.27 (-0.32) ^a	0.59	1.00
		2.62 (3.12) ^a		1.70 (2.02) ^a		0.57	1.00
		2.99 (3.56) ^a			-0.27 (-0.32) ^a	0.59	1.00
			0.16 (0.20) ^a	1.58 (1.88) ^a		0.59	1.00
		0.19 (0.23) ^a		-0.24 (-0.29) ^a	0.50	1.00	
Bowles & Poon (1982)	One aging parameter					0.22	.98
	0.53	2.84	0.36	1.32	-0.26	0.22	.98
						0.22	.98
						0.58	.94
	Two aging parameters					0.53	.94
	0.53			1.00		0.22	.98
	0.53				0.00	0.22	.98
		2.84		1.00		0.24	.98
		2.84			0.00	0.24	.98
			0.36	1.00		0.22	.98
		0.36		0.00	0.22	.98	
Ratcliff et al. (2004)	One aging parameter					1.76	.99
	0.46	2.17	0.13	1.00	0.00	1.76	.99
						1.91	.99
						2.33	.99
	Two aging parameters					2.33	.99
	0.44			1.77		1.70	.99
	0.36				-0.28	1.55	.99
		2.27		1.30		1.70	.99
		2.79			-0.15	1.55	.99
			0.14	1.26		1.87	.99
		0.17		-0.13	1.78	.99	
Castel & Craik (2003)	One aging parameter					2.83	.90
	0.96	1.05	0.11	1.77	-0.36	2.83	.90
						2.83	.90
						2.06	.93
	Two aging parameters					1.83	.95
	0.77			1.96		1.57	.96
	0.82				-0.40	1.55	.96
		1.31		1.96		1.57	.96
		1.23			-0.40	1.55	.96
			0.50	1.96		1.57	.96
		0.44		-0.40	1.55	.96	

Table 2 (continued)

Study and model	Age-related parameters					Fit statistics	
	Link strength	Fan factor	Encode fail	Base factor	Word τ	RMSSD	r^2
Light et al. (2004)							
One aging parameter	0.59	1.69	0.04	3.64	-0.25	1.91	.97
						1.91	.97
						1.93	.96
						1.51	.97
						1.27	.98
Two aging parameters	0.38			4.04		1.19	.98
	0.43				-0.26	1.01	.99
		2.61		4.04		1.19	.98
		2.31			-0.26	1.01	.99
			0.07	3.88		1.32	.97
			0.07		-0.26	1.01	.99

Note. The top portion of the table presents the four free parameters (word and episodic node thresholds and standard deviations) used to fit the young adult data. The bottom portion of the table presents the one- and two-parameter aging model fits using other cognitive aging accounts judged against the standard young adult model fit. RMSSD = root-mean-squared scaled deviation.

^a For the Balota et al. (2002) data, values are for old adults (with old-old adult values in parentheses).

Instantiation of Other Theoretical Accounts

A second question raised by our aging models is whether other theoretical perspectives might do just as well as the base factor–fan factor account. This question was addressed using competitive tests and comparing the fit of our preferred parameters to other plausible alternatives, each instantiated as a single parameter in the SAC model and held to account for the very same set of empirical findings. The other cognitive aging accounts examined within our model were (a) a decrease in associative link strength (see gain parameter, Li, Lindenberger, & Frensch, 2000; transmission-deficit hypothesis, MacKay & Burke, 1990), (b) a meta-cognitive strategy of lowering the word threshold (i.e., increased response bias) to familiarity-based responding (see response threshold parameter, Ratcliff et al., 2004; see also Touron & Hertzog, 2004), and (c) a probabilistic failure-to-encode context (see reduced processing resources, Craik, Govoni, Naveh-Benjamin, & Anderson, 1996).

These parameters were selected as alternatives because they function to either impair episodic recollection or increase familiarity-based responding. To impair recollection, a decrease in the spread of associative activation can be achieved in one of three ways: (a) by increasing the number of links (fan factor), (b) by reducing existing link strengths, or (c) by sometimes failing to form links during encoding (failure to encode). Specifically, the link strength parameter was applied as a scalar to the numerator (see online supplement Equation 4, or Reder et al., 2000, Equation 3) and functioned to decrease by a fixed proportion the amount of activation sent from a given link. It is important to note that the link strength parameter is a parameterized equivalent to the fan factor parameter, although there are clear theoretical reasons to prefer the fan factor parameter. The two parameters are computationally isomorphic and achieve identical solutions. The link strength parameter operates on the numerator (see online supplement [Equation 4] or Reder et al., 2000 [Equation 3]), whereas the fan factor parameter operates on the denominator. The failure-to-encode parameter reflects the probability of an attentional lapse

during encoding. As a result, older adults are unable to recollect the episodic context on a proportion of trials.⁷

As an alternative parameter to an increase in base-level activation, we implemented a parameter that also functioned to increase familiarity-based responding, in this case by lowering the response threshold. The word threshold parameter was applied for older adults to the young adult word threshold fit and is expressed in standard deviation units. Negative values to the word threshold parameter signify strategic adaptivity, where older adults lower their threshold to familiarity-based responding.

The results of the aging models are provided in Table 2 and reinforce the assertion by Salthouse (1988; see also Charness, 1988) that any model of cognitive aging must capture both the positive and negative changes in cognitive performance with advanced age. The set of best-fitting models shown in Table 2 are all two-parameter solutions in which one parameter positively affects semantic memory (base factor, word threshold) and a second parameter negatively affects episodic memory (fan factor, link strength, failure to encode). In each data set, besides Bowles and Poon's (1982), each positive and negative two-parameter pairing achieved similar fits. The successful instantiation of alternative parameters in the model demonstrate that there are a number of ways in which the pattern of age-related change to semantic and episodic memory function can be realized computationally. However, judged from a theoretical perspective, there are clear reasons to prefer the fan factor and base factor model.

⁷ The failure-to-encode parameter is a proxy for research arguing that age-related memory deficits are due to poorer encoding by older adults, perhaps because of an age-related diminution of general processing resources (see Craik, 1986; Craik & Byrd, 1982). SAC is currently a retrieval model; however, L. M. Reder has been developing a revision to her model that also involves processes that operate at encoding. There are extant but unpublished models in L. M. Reder's lab that implement various types of manipulations on working memory that impact probability of encoding and account for a number of effects on memory.

First, the fan factor and base factor parameter pairing is predicated on arguably the most proximal causal age-related factor, lifelong experience. Second, the base factor–fan factor model requires only one assumption, whereas all of the other models require two. By using lifelong experience, it is unnecessary to posit additional processes to characterize normal aging other than age itself. For instance, in other cognitive aging accounts, the link strength parameter assumes neurodegeneration, the word threshold parameter assumes meta-cognitive strategic adaptivity, and the failure-to-encode parameter assumes that older adults have reduced processing resources. As all of the best-fitting solutions involve the pairing of a positive and negative parameter, we are forced to accept two different age-related assumptions in each case with the exception of the fan factor–base factor model, in which both parameters are derived from experience (one very plausible assumption). For instance, if we adopt the link strength–word threshold model, then we assume both neurodegeneration and meta-cognitive strategy adaptivity. A two-parameter solution is also evident in other extant models, such as the diffusion model of Ratcliff et al. (2004), in which older adult accuracy and response time data were captured in a random-walk model by varying both the drift rate of an information accumulator and adjusting the response threshold. Finally, the fan factor and base factor parameter pairing also has the virtue of consistency, both in accounting for the five data sets and as an outgrowth of prior research in the recognition memory literature. Our model was based on clear a priori computational assumptions regarding the role of experience on memory function.

Testable Model Predictions

Our SAC model offers several testable predictions. The paired-associate recognition paradigm offers perhaps the most direct test of the computational assumptions of the model. Simply repeating a stimulus was shown by our model of Light et al.'s (2004) data to increase both familiarity and recollection processes. A novel prediction generated from our SAC model involves the effects of associative interference that results from presenting multiple overlapping word paired associates (i.e., fan 2–2, fan 3–3, etc.). In theory, this manipulation should impair recollection; however, SAC also predicts that the presentation of multiple overlapping word pairs will increase the strength or familiarity of the underlying memory items with item repetition. There is some evidence to support our assumption that recollection is impaired and familiarity is strengthened as a result of a fan manipulation. Verde (2004) examined associative recognition using the remember–know paradigm (Gardiner & Java, 1991; Tulving, 1985; for a meta-analytic review, see Gardiner & Richardson-Klavehn, 2000). The remember–know paradigm facilitates the assessment of whether a memory judgment is based on recollection of specific associative information (i.e., remember response) or a familiarity-based inference of item memory strength (i.e., know response). As a result of a fan manipulation (fan 1–1, fan 2–2, fan 3–3, fan 4–4), Verde (Experiment 3) found that the remember responses decreased whereas the know responses increased. This suggests that the recollection of associative information decreases as a result of the associative interference generated by the fan manipulation, as predicted by our model. Furthermore, these results imply that the latter increase in know responses is due to increased familiarity as a result of the repetition of item information, even though the items

are presented on each occasion with a different associate, also as predicted by our model. Judged in terms of the hit rate (i.e., old–new judgments), the opposing trends of remember and know responses were shown by Verde to mask one another, which may explain why no effect of associative interference was found in the hit rates (fan 2–2) reported by Dyne, Humphreys, Bain, and Pike (1990).

Semantic Associations and Aging

Our model described an increase in the number of episodic associations as a function of experience. Word-association studies have shown that older adults also have a more elaborate semantic network (Burke & Peters, 1986; Perlmutter, 1979; Riegel & Birren, 1966; Riegel & Riegel, 1964; Tresselt & Mayzner, 1964; but see D. V. Howard, 1980), producing wider response distributions with age. This too could cause fan effects, a greater dispersion of activation from any source causing less to arrive at another concept.

The word-association research suggests a relation between word associations and verbal ability. Vocabulary, irrespective of age, was found to be the best predictor of single and second-most-popular responses (Burke & Peters, 1986; Lovelace & Cooley, 1982). Burke and Peters (1986) found that when young and old subjects are matched by vocabulary score, age-related differences disappear. Although it is somewhat unnatural to selectively match young and older adults in this manner, given that older adults usually outperform young adults on vocabulary measures (Schaie, 1996), these results suggest that age differences on the word-association task can be explained as vocabulary differences. This finding supports the basic assumptions of our model of experience-based change, as normative word frequency measures were used in our computational models to estimate stimulus experience and, by extension, to estimate lifelong experience. A large number of studies also point to the importance of verbal ability as a predictor of episodic memory (Hultsch, Hertzog, Dixon, & Small, 1998; Meyer, 1987). Thus, the word-association literature suggests that verbal ability results in a richly elaborated semantic network that may also contribute to fan effects.

Conclusion

The goal of this modeling exercise was to test an experience-based theory of age-related change to memory performance. The successful instantiation of alternative parameters in the model has demonstrated that there are a number of ways in which the pattern of age-related change to semantic and episodic memory can be realized computationally. Our view is that an experience-based model is the most plausible. Experience is underappreciated as a factor on cognitive performance and is absent in most models of cognitive aging. As a principle, experience can certainly be applied to other extant memory models of aging. For instance, the temporal context model (M. W. Howard & Kahana, 2002) posits that older adults are not as effective as young adults in using temporal codes to selectively retrieve episodic memories. Perhaps after a lifetime, the finding that temporal coding is a less effective retrieval cue (Kahana, Howard, Zaromb, & Wingfield, 2002; Kahana & Wingfield, 2000) is due to an oversaturation of the temporal codes in memory, analogous to increased fan. For instance, Steyvers and Malmberg (2003; see also Carroll, 1938) examined a

lexical database and found that words with low contextual variability (i.e., low contextual fan in our model), those occurring predominately in a small number rather than a wide range of different texts, resulted in better recognition memory performance, even when matched on frequency of occurrence.

Thus, our model can perhaps serve as a benchmark prediction of normal age-related change in recognition memory performance that can be expected from experience alone. A two-parameter solution best captured the fidelity of the data, containing both a positive and a negative parameter affecting familiarity and recollection respectively. Most theories of cognitive aging have focused on only one parameter, a negative one, which in our case involved an age-related saturation of the episodic context. A novel result of our modeling simulations is that a second positive parameter was necessary to capture age-related increases in familiarity-based responding. To capture specific effects beyond experience-based change, like terminal decline on measures of semantic memory or specific age-related deficits as observed in working-memory intensive tasks, a third parameter will be necessary. The significance of computational modeling is that these models are testable and can be usefully applied and held to account in a process of successive approximation. Our goal is to formalize theories of cognitive aging phenomena so that more focused tests can be applied to refine extant models. Computational modeling is useful both in hypothesis generation and in establishing coherence in the literature. Regarding the importance of formal models over verbal theorizing, Newell (1990) stated, "The theory gives answers, not the theorist" (p. 13). In our case, previous SAC models of the word-frequency mirror effect highlighted the role of experience on memory processes—to which lifelong aging is a natural extension.

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