

Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>

Contents lists available at [SciVerse ScienceDirect](http://www.sciencedirect.com)

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review

Memory encoding and aging: A neurocognitive perspective

Fergus I.M. Craik*, Nathan S. Rose

Rotman Research Institute at Baycrest, Toronto, Canada

ARTICLE INFO

Article history:

Received 3 September 2011

Received in revised form

19 November 2011

Accepted 24 November 2011

Keywords:

Memory

Encoding

Aging

Attention

Processing resources

Self-initiated activities

Environmental support

ABSTRACT

This review article surveys the evidence for age-related changes in memory from cognitive and neuroimaging studies. It is probable that the observed declines in episodic memory with increasing age are a consequence of impairments in both acquisition (encoding) and retrieval – possibly for similar reasons – but the present review focuses on the former set of processes. An additional emphasis is on a processing approach to understanding age-related encoding deficiencies; we suggest that many problems stem from a decline in the ability to self-initiate deeper semantic processing operations. The article briefly discusses the role of declining sensory and perceptual abilities, but focuses primarily on the nature of processing resources, their consequences for memory acquisition, and on age-related changes in cognition and neural functioning. We also survey the evidence for neuroplasticity in the older brain, and how compensatory activities at behavioral and neural levels can reduce age-related problems. Finally, we review recent studies of brain and cognitive training procedures. Age-related memory problems are real, but there are also grounds for optimism.

© 2011 Elsevier Ltd. All rights reserved.

Contents

1. The roles of sensory impairments and age-related slowing	1730
2. The problem of inadequate processing resources	1731
3. Age-related changes in brain structure and function	1731
4. Encoding of nonverbal materials	1733
5. Characteristics of encoding: binding and distinctiveness	1733
6. Overcoming the deficit: environmental support	1734
7. Encoding strategies and training studies	1736
8. Conclusions	1737
References	1737

One of the commonest complaints of older adults is a reduction in their ability to learn and remember new information. This age-related decline starts surprisingly early in fact, as early as the mid-20s for some forms of memory (Park et al., 2002). The anecdotal reports of mild memory failures are also borne out by the experimental literature (see reviews by McDaniel et al., 2008; Zacks et al., 2000) although it is also clear that the age-related drops in performance are substantial for some memory tasks, yet virtually absent for others. One purpose of the present article is thus to shed some light on the factors governing this pattern of strengths and

weaknesses; a second purpose is to review the current literature for evidence on the neural location of age-related processing inefficiencies. Information on the second point would both contribute to our scientific understanding of brain aging, and also point the way to the development of adequate remedial procedures.

Overall memory performance is traditionally ascribed to the efficient functioning of three stages – encoding, storage and retrieval. This review will focus on the encoding stage, but it may be helpful to preface the discussion with a brief overview of how we view relations among the three stages. One of the most important things to realize about encoding is that how well something has been encoded can only be measured by administering some specific test of retrieval, either an implicit test such as word fragment completion or an explicit test such as cued recall. Moreover, the failure to retrieve an event does not necessarily mean that a memory was not encoded or that a memory has been forever forgotten – it only

* Corresponding author at: Rotman Research Institute, Baycrest Centre for Geriatric Care, 3560 Bathurst Street, Toronto, Ontario, Canada M6A 2E1.
Tel.: +1 416 785 2500x3526; fax: +1 416 785 2862.

E-mail address: fcraik@rotman-baycrest.on.ca (F.I.M. Craik).

shows that the administered test failed to elicit the wanted item. In some senses then it is impossible to fully understand encoding without also considering retrieval. A further important point is that whereas memory *storage* must obviously reflect structural and functional changes in the nervous system, these changes have no counterparts in conscious experience and have no clear cognitive attributes. That is, whereas encoding and retrieval processes have correlates in both brain functions and in conscious awareness, memory storage characteristics can be described in neurological and biochemical terms, but we have no conscious awareness of these neural changes. Storage is therefore different from both encoding and retrieval in this respect, and may therefore exist at a different explanatory level. Third, it is usually assumed that 'consolidation' processes form part of the acquisition phase when new information is learned or a new experience is encoded, but the nature of such processes is still very poorly understood, at the human level at least, so they are not considered in this review.

Cognitive studies have therefore focused on the nature of encoding and retrieval processes, the factors that modulate them, and the relations between them. At a recent meeting of memory researchers, a group analyzing various concepts of memory defined encoding as 'The set of processes involved in transforming external events and internal thoughts into both temporary and long-lasting neural representations.' These processes obviously have both cognitive (i.e. experiential) and neural aspects; this review will focus mainly on the former, but will also deal to some extent with relations between the two levels of description and explanation. Finally, with regard to retrieval processes, one point of view that is gaining credibility from recent neuroimaging results is that retrieval is not so much a 'search' for a wanted trace, as an attempt of the cognitive system to recapitulate the original encoding operations (Craik, 1983). This idea follows from the cognitive notion known variously as the encoding specificity principle (Tulving and Thomson, 1973), repetition of operations (Kolers, 1973), and transfer-appropriate processing (Morris et al., 1977), and has more recently received support from neuroimaging studies showing that successful retrieval is associated with patterns of activation in the same cortical regions as were activated during initial encoding (e.g., Köhler et al., 1998; Nyberg et al., 2000; Vaidya et al., 2002).

A further point, noted by several investigators, is that retrieval processes also serve as encoding operations. We do remember what we retrieve, and if retrieval processing is rich and meaningful we will remember the retrieval event better. This approach has been illustrated in a series of ingenious experiments by Jacoby et al. (e.g., Jacoby et al., 2005). In their paradigm, different groups of young adults studied words under either deep (meaningful) or shallow processing conditions and were then given a recognition memory test in which the studied words were mingled with new distracter words. A second recognition test was then given for the *distracter* words in the first test, with the finding that words that had served as distracters for deeply-encoded words were now better recognized than distracters for the shallow-encoded words. Arguably, participants in the 'deep' condition maintained this processing attitude into their first recognition test, resulting in semantic processing of distracter items as well as targets. This 'depth of retrieval effect' was not found in older adults, however, possibly because they relied on general familiarity rather than recollection to perform the first recognition test.

In general, then, encoding and retrieval operations share many features, and this similarity suggests that age-related memory decrements may reflect inefficiencies of both encoding and retrieval operations for the same underlying reasons. So what are these inefficiencies of processing that may underlie age-related memory impairments? A number of candidates have been proposed and championed in the cognitive aging literature. One is the

indisputable fact that mental operations are slower in older than in younger adults, and Salthouse (1991, 1996) has suggested that age-related slowing leads to less effective working memory operations and thus to less efficient cognitive processing, including memory encoding. As a second point, it is generally agreed that working memory processes are key to understanding cognitive successes and failures in many domains, including memory encoding and retrieval; both Park and Salthouse have illustrated this point (e.g., Park et al., 1996; Salthouse, 1990). A third prominent point of view is that older adults are less able to inhibit unwanted or irrelevant information and this in turn leads to inefficiencies of encoding and other cognitive activities (Hasher and Zacks, 1988; Hasher et al., 1999). On the one hand, this processing inefficiency is associated with greater vulnerability to distraction, but by the same token the age-related difficulty in inhibition can sometimes result in benefits to older adults; for example if the 'irrelevant' information turns out to be useful in a subsequent task. This pattern has been demonstrated in priming studies by Hasher et al. (reviewed by Healey et al., 2008). As a fourth type of explanation underlying age-related memory problems, Craik (1983, 1986, 2002) proposed that aging is associated with a reduction in available processing resources, and that this reduction results in the formation of less deep and elaborate encoding operations. Complementary ideas include the notion that the age-related reduction in processing resources results in a failure to carry out 'self-initiated' mental operations, but that appropriate operations (at both encoding and retrieval) may be carried out if they are induced or supported by environmental stimuli and contexts. Finally, an important idea of a somewhat different sort has been proposed by Baltes and Lindenberger (1997) as the 'common cause hypothesis.' These authors found remarkably high correlations between sensory functioning and higher cognitive processing abilities; their suggestion was that widespread physiological deterioration of neural systems with increasing age is associated with parallel decrements in many cognitive abilities.

One dominant idea in current memory research is that human memory is not one monolithic entity but is composed of different systems that obey different rules. Tulving (1983) identifies five different systems; sensory memories, working memory, episodic memory, semantic memory and procedural memory; and this classification is relevant to the present discussion in that age differences in memory performance vary depending on the system used. Thus age-related differences in sensory memory are apparently slight provided that the sensory system in question (e.g., vision, hearing) is functioning well. Age differences in procedural memory (e.g., memory for activities such as driving, playing an instrument or reading) are also minimal provided the activity is maintained. Semantic memory refers to representations of accumulated knowledge, and this type of memory is also relatively unaffected by aging, again provided the information is accessed and utilized on a regular basis. One obvious exception to this general rule is the common age-related difficulty found in retrieving names and other highly specific forms of information. Working memory and episodic memory *do* show substantial age-related losses, however. Thus older adults have trouble manipulating material held in mind (working memory) and also have trouble recollecting specific events that occurred in the past (episodic memory). We now go on to consider these last two types of memory, and to what extent the age-related problems reflect difficulties of acquisition.

1. The roles of sensory impairments and age-related slowing

One factor that seems likely to affect the adequacy of memory encoding in older adults is the quality of sensory information presented to the cognitive system. Declines in both vision and hearing are well established in the elderly, and it seems probable

that degraded sensory inputs will reduce the richness or specificity of the encoded record. One early study was conducted by Rabbitt (1968) who showed that when the stimulus representation was degraded by noise in young adults, subsequent memory was poorer, even when the initial stimulus had been clearly identified. The effects of aging were compared to the effects of noise on younger adults' memory by Murphy et al. (2000). They found that the patterns of word recall in a short-term memory task were essentially identical between older adults in quiet and younger adults in noise. That is, the effects of aging on memory encoding can be mimicked by presenting stimuli to younger adults in noisy conditions. Importantly, these effects occurred even when the words were correctly identified at the time of encoding. Two possible explanations put forward by Murphy et al. were first that if older adults have fewer processing resources, a substantial part of their resources may be taken up in identifying the stimulus word, thereby leaving inadequate resources for processing the item. This interpretation has been referred to as the 'effortfulness hypothesis' by McCoy et al. (2005); the idea that individuals with perceptual deficits have to expend greater effort on perception and comprehension, thereby impairing memory formation. A second, related account is simply that the perceptual record is less adequate in both older individuals and young adults working in noise, and that this initial inadequacy cascades through subsequent higher-level processing operations resulting in an impoverished memory trace (Schneider and Pichora-Fuller, 2000).

2. The problem of inadequate processing resources

From the perspective of a processing view of memory (Craik and Lockhart, 1972; Craik and Tulving, 1975), good subsequent memory performance depends on the depth and elaboration of the initial encoding processes. That is, perceived stimuli and events must be processed in terms of their meaning and significance; they should also be processed in a rich elaborate manner. Such extensive processing operations require adequate attentional resources, and these resources are available to young adults but less available to older adults, with the consequence that their initial processing is less deep and elaborate, and the subsequent memory less well represented. This argument, with supporting data, is presented more fully in previous publications (Craik, 1983, 1986, 2002) but one line of evidence concerns the similarity between the effects of aging and the effects of divided attention in younger adults on memory performance (Anderson et al., 1998; Jennings and Jacoby, 1993). If aging is associated with fewer processing resources, then perhaps patterns seen in older adults may be mimicked in young adults whose available resources have been reduced by giving them a second task to perform concurrently with the memory task. Table 1 (from Anderson et al., 1998) shows the results of free recall and cued recall tests carried out by younger and older adults under

conditions of either full or divided attention (DA). Participants studied lists of unrelated words for later free recall or word pairs for later cued recall, either under full attention conditions or while also performing a concurrent reaction time (RT) task. The data shown in Table 1 are the proportions of words recalled and also average RTs for each task performed on its own (full attention), or under dual-task conditions when participants were instructed to emphasize performance of the *other* task. The results show that both memory performance and RTs are quite similar between older adults under full attention and younger adults under DA conditions. We argue that the withdrawal of attentional resources from young adults during the encoding process yields a pattern of results that closely mimics the pattern found in older adults working under normal conditions, and that one consequence of the aging process is a reduction in available processing resources.

Results from other labs are also in line with the notion of an age-related reduction in processing resources. A study by Lindenberger et al. (2000) asked young (20s), middle-aged (40s) and older (60s) adults to encode a list of 16 unrelated words either while standing or while walking along an unpredictable 'aperiodic' track. The latter condition requires more attentional control and was associated with reductions in words subsequently recalled by all three age groups. The drop in performance was greatest in the older group however (losses were 21%, 35% and 40% for young, middle and old, respectively). Again, the numbers of words recalled were similar in the older participants when simply standing (i.e. 'full attention') and the younger adults when walking along the aperiodic track – 9.6 and 10.5 words, respectively.

The notion of processing resources was originally conceptualized in our lab in terms of available 'mental energy' (e.g., Craik and Byrd, 1982). In this sense, it is essentially equivalent to 'amount of attention' with the idea that there is a limited resource that can be allocated to a small number of concurrent activities, and also similar to the concept of 'working memory capacity' (e.g., Cowan, 2010; Kane et al., 2004). The same pattern of effects may also be attributed to cognitive control processes, and this alternative formulation may be more palatable to cognitive neuroscientists. Other candidates for the resource concept include the linked notions of processing speed and available time to complete cognitive operations (Salthouse, 1996), and there is evidence that restricting time in younger adults also reduces performance in a way that resembles the behavior of older adults (Benjamin and Craik, 2001).

Are there real differences among explanatory accounts couched in terms of processing resources, cognitive control, processing speed and processing efficiency – or will these descriptive labels ultimately map onto the same underlying age-related changes in brain function? We argue that a decrease in available attentional resources (or perhaps in cognitive control) is more basic, and that reductions in processing speed and overall efficiency are the *consequences* of this fundamental change. This argument is supported by the similarity of the effects of aging to those of divided attention (DA) in young adults. That is, DA in young adults clearly slows performance and reduces the efficiency of memory processing (Table 1; Anderson et al., 1998). The remaining question is whether 'resources' and 'control' are essentially identical, or whether a reduction of resources also results in an apparent reduction in the efficiency of cognitive control.

3. Age-related changes in brain structure and function

Age-related changes in the neural underpinnings of cognitive processes are well documented and largely reflect deterioration from young adulthood (Raz, 2000; Raz et al., 2005). Changes include volumetric declines in hippocampus and frontal cortex, thinning of white matter tracts, reductions in dopamine production and receptors; these age-related changes are especially prominent in

Table 1
Proportions recalled from two memory tasks and reaction times (RT, in ms) on a secondary task performed either singly or concurrently (data from Anderson et al., 1998).

Experimental condition	Memory		RT	
	Young	Old	Young	Old
Free recall				
Full attention	0.82	0.53	408	570
Divided attention	0.51	0.28	530	815
Cued recall				
Full attention	0.85	0.49	404	510
Divided attention	0.50	0.25	502	745

Note: 1. Divided attention scores are for conditions in which the *other* task was emphasized. 2. Some numbers are in bold to highlight young-old similarities.

frontal cortex and some medial-temporal areas – regions intimately associated with memory encoding processes (Giorgio et al., 2010). It seems likely that both the ‘resources’ and ‘control’ concepts described above are localized in the frontal lobes, and a large number of neuroimaging studies provide converging results that support this suggestion. In particular, an area of the left inferior frontal gyrus has been implicated in studies of acquisition, with the general result that activity in this area reflects ‘good’ encoding processes that result in high levels of subsequent memory (Buckner et al., 1999). It follows from this view that age-related memory impairments might reflect inefficient functioning in this region, at least in part, and there is now good evidence to support this suggestion. More specifically, Tulving et al. (1994) proposed the influential idea that encoding processes are located (or at least controlled) primarily in left frontal regions whereas retrieval processes are located primarily in the right frontal lobes; the so-called Hemispheric Encoding Retrieval Asymmetry (or HERA) model. In a study of face encoding and recognition, Grady et al. (1995) found that younger adults showed activation in the anterior cingulate, left prefrontal cortex (PFC) and left temporal cortex whereas older adults had no significant activation in the inferior frontal cortex or medial temporal cortex during encoding. This initial observation has been confirmed in further studies. In a study of paired-associate learning using word pairs, Anderson et al. (2000) found that only the young adults activated regions of the left inferior PFC (Brodmann areas, BA 44, 45, 46, 47) but older adults showed relatively more activation (than younger adults) in the inferior parietal lobe (BA 40) bilaterally. This second result may reflect the possibility that older adults relied more on relatively shallow phonological encoding, as opposed to the semantic encoding effects associated with the left inferior PFC (Buckner et al., 1999; Kapur et al., 1994). Similar findings of reduced activation of left inferior PFC regions have also been reported by Cabeza et al. (1997) using verbal paired associates, and by Stebbins et al. (2002) whose subjects made semantic/non-semantic judgments about words during encoding. These latter authors concluded that “these results suggest that age-associated decreases in memory ability may be due to decreased frontal-lobe contributions to the initial encoding of experience.” Cabeza (2002) followed these findings and conclusions with the more general idea that aging is associated with a reduction in the contrast of functions between the right and left frontal regions; the notion of Hemispheric Asymmetry Reduction in Older Adults (or ‘HAROLD’).

Further advances were made in an interesting fMRI study by Morcom et al. (2003), building on the results of Logan et al. (2002). These latter authors had noted that under-recruitment of left prefrontal areas by older subjects occurred during intentional learning of verbal material, but that this age-related under-recruitment was eliminated when both age groups were instructed to perform a simple semantic task (abstract/concrete judgment) on each word during the ‘incidental learning’ encoding phase. Logan et al. therefore showed that inducing older adults to engage in effective encoding strategies resulted in participants activating this region to the level of younger adults, thereby reducing bilateral recruitment and facilitating subsequent memory. Thus, the capacity to engage in effective encoding processes that minimize age-related differences in subsequent memory is apparently preserved, despite the fact that older adults often fail to self-initiate these processes. The finding that age differences in memory can be ‘repaired’ by asking participants to perform a semantic task was also reported by Craik and Byrd (1982) and by Troyer et al. (2006); the significance of this finding is discussed later in the article. Morcom et al. had younger and older adults perform an animacy judgment on presented words, thereby ensuring semantic processing. They examined ‘subsequent memory’ effects, that is, the pattern of cortical activation associated with words later recognized successfully, and found such effects in the left inferior frontal cortex for both age

groups. These frontal activations were left lateralized in the young group, but located bilaterally in the older group, a finding that may reflect compensation in older learners (additional recruitment of homologous areas in the other hemisphere; see also Cabeza, 2002) or possibly ‘dedifferentiation’ – a reversion to the less focused pattern of activation often found in children. It seems then that activation of left prefrontal areas (and sometimes also right prefrontal areas in older adults) is associated with semantic processing of verbal materials, which in turn predicts successful later memory of the materials (Craik and Tulving, 1975). The further implication is that when simply instructed to learn verbal materials for a later memory test, older adults fail to process the information sufficiently deeply, do not activate prefrontal areas to the same extent, and remember the material less well.

A second age-related difference reported by Morcom et al. (2003) was the finding of a subsequent memory effect in the left anterior temporal cortex for younger subjects only. Activations in this region have been linked to specific (as opposed to general) semantic processing, so this finding may reflect the fact that younger adults tend to process information in a more differentiated or semantically elaborate way – a processing style associated with higher levels of subsequent memory. Behavioral evidence for a more general style of processing in older adults was presented by Craik and Simon (1980); relevant neuroimaging evidence was reported by Stebbins et al. (2002).

If DA in younger adults during encoding results in a pattern of later memory performance that resembles the pattern found in older adults under full attention conditions, it might be expected that younger adults in DA conditions should also show neuroimaging patterns found in older subjects. Evidence in favor of this outcome was reported by Shallice et al. (1994) who conducted a PET study in which young adults learned auditorily-presented verbal paired associates while simultaneously performing an easy or difficult visual-motor task. Memory performance decreased from 83% in the easy task condition to 68% in the difficult condition, and an area of left dorsolateral PFC (BA 46) was activated only during the easy task. Thus, DA in younger adults, like the effects of aging, reduced left PFC activity during the encoding of verbal material. Similar results were reported by Anderson et al. (2000) and by Iidaka et al. (2000). In the latter study (on young adults), Iidaka et al. found that a DA task reduced encoding-related activity for visually-presented word pairs in several areas of the left prefrontal cortex, and in the uncinate fasciculus connecting the frontal and temporal lobes. They also reported significant correlations between activity in left inferior frontal gyrus (BA 47) and subsequent memory performance under full attention conditions, and between activity in left inferior PFC (BA 45/46) and memory under DA conditions. The effects of DA were attributed to impaired semantic encoding. The study by Anderson et al. (2000) directly compared the effects of aging to those of DA (in young adults) in an experiment using PET; they concluded that “left inferior prefrontal activity was reduced similarly by aging and by DA during encoding, suggesting that the behavioral correspondence between these effects is the result of a reduced ability to engage in elaborate encoding operations” (p. 775).

Subsequent studies using fMRI technology have found similar results to those using PET. For example, Kensinger et al. (2003) again found that a difficult concurrent task reduced both subsequent memory and the level of activation in the left PFC. They also reported that whereas an easy concurrent task was associated with later memory retrieval judged to be ‘recalled’ by subjects, the hard concurrent task was associated with later retrieval of items judged to be merely ‘familiar.’ This shift from recollection to familiarity had been reported previously in cognitive studies of aging (e.g., Jennings and Jacoby, 1997). Uncapher and Rugg (2005) also reported that activations in the left PFC and right lateral parietal

cortex (BA 40) were attenuated while performing a hard relative to an easy concurrent task. Subsequent memory effects were related to activity in the inferior frontal gyrus and the anterior hippocampus. To sum up, a number of studies have shown similarities between the effects of aging and the effects of DA on later memory performance and on the patterns of brain activity associated with successful encoding. One way to interpret this similarity is to suggest that both DA and aging reduce the participant's ability to engage in the type of deep, semantic, elaborate encoding operations that have been shown to support good levels of subsequent memory.

4. Encoding of nonverbal materials

Verbal materials, whether they are single words, sentences or text passages, are rather idiosyncratic in that it is possible to process them in a variety of ways, running from a superficial visual scan to a deeply integrative reading involving previous knowledge and inferential reasoning. These various 'levels' of processing have substantial effects on later memory for the material, but this variety of different types of processing is typically not available for other materials. We can perceive snowflake and kaleidoscope patterns perfectly well, but typically they are poorly remembered because they lack deep meaning. On the other hand, pictures of objects and scenes are highly meaningful to us, and because we are all in a sense experts at object and scene perception, such stimuli tend to drive deep encodings in people of all ages, regardless of processing attitude. The consequence is that pictures are typically better remembered than words for both young and older adults, and in fact performance levels were found to be higher and age differences minimal in several studies of memory for pictorial materials (e.g., Craik and Byrd, 1982; Craik and Schloerscheidt, 2011; Grady et al., 1999). At the other end of the semantic scale, age decrements in working memory for *meaningless* visuo-spatial patterns are substantially larger than for verbal material (Hale et al., 2011; Rose et al., 2009), possibly because younger adults are better able to construct meaning from stimuli that lack obvious semantic characteristics. The main point is that age-related differences in memory encoding will depend on the materials used, and the extent to which deep, elaborate encoding operations are available to younger and older adults for these materials. Some brief examples follow.

Craik and Byrd (1982) reported an experiment in which objects were presented to be remembered either as the name of the object or as line drawings. Later recognition tests showed a 10% age difference for words (0.73 and 0.63 for young and old, respectively) but only a 1% difference for pictures (0.84 and 0.83, respectively). This same pattern was observed in a later study by Luo et al. (2007); in this case word recognition levels were 0.55 and 0.42 for younger and older adults, respectively, but picture recognition levels were 0.70 and 0.72, respectively. The slight age-related superiority for pictorial materials was also found in some conditions by Craik and Schloerscheidt (2011).

A PET study by Grady et al. (1999) also found a reliable age-related decrement in word recognition, but not in picture recognition. Word encoding was again associated with activations in left prefrontal and temporal cortices, whereas picture encoding activated regions of extrastriate and medial temporal cortex, with older adults showing these patterns to a lesser degree. The authors concluded that age-related memory changes were more negative for words than for pictures, and that age-related dysfunctions in encoding networks were generally present but were spared for networks involved in the elaborate encoding of pictorial material. Another study of age differences in picture encoding was reported by Gutchess et al. (2005). These researchers also found no age differences in subsequent recognition of pictures, but the fMRI results showed that the older adults had less activation than their

younger counterparts in the hippocampus bilaterally, but more activation in the middle frontal cortex. The authors speculated that prefrontal regions might perform a compensatory function for age-related declines in medial-temporal activity. In the present article we argue rather that rich meaningful stimuli such as pictures tend to 'drive' good encodings automatically, without much need for effortful elaborations on the subject's part.

5. Characteristics of encoding: binding and distinctiveness

In many cases, components of an event, utterance or statement must be bound together to form a coherent unit, which is then remembered as such. Laboratory examples include paired-associate learning (of unrelated word pairs), and everyday examples might include the necessity to remember the person you lent a book to, or the people present at a meeting. A particularly important aspect of this need to bind components together is 'source memory' – remembering where and when a specific event occurred, or the source of some known information. A profound inability to remember source is referred to as 'source amnesia,' and was demonstrated in patients with frontal lobe problems by Schacter et al. (1984); a milder form of the same impairment was shown to be typical of older adults by McIntyre and Craik (1987). The general difficulty of integrating components into a holistic representation, or more simply of associating one item with another or with its context of occurrence, appears to be a general problem for older adults. An age-related deficit in binding was reported by Chalfonte and Johnson (1996) and the problem was further illustrated and named the 'associative deficit hypothesis' (ADH) by Naveh-Benjamin (2000).

As one example of the ADH, Naveh-Benjamin et al. (2004) studied face-name associations in younger and older adults. Age-related decrements in later face recognition and name recognition were relatively slight (4% and 2%, respectively), but the name-face associative recognition deficit was substantially greater (14%). Naveh-Benjamin has also made the interesting point that the effects of aging are *not* entirely mimicked by dividing attention in young adults when associative deficits are considered (e.g., Naveh-Benjamin et al., 2004). His basic finding is that whereas divided attention in young adults reduces item and associative recollection to the same extent, aging is associated with a disproportionate drop in associative information. He therefore concluded that the ADH in older adults is not caused by depleted attentional resources. Given the similarities between young divided-attention subjects and older adults in many respects (Table 1), one way of reconciling the differences is the suggestion that DA in younger adults impairs frontal lobe functioning (and therefore resembles aging in this respect) but that older adults have an additional associative impairment as a consequence of poor hippocampal functioning (e.g., Davachi and Wagner, 2002; Raz et al., 2005; Shing et al., 2010), which is not mimicked by DA in younger adults.

It is well established that deeper semantic processing is the primary key to successful encoding and subsequent memory, but the exact reasons for this 'levels of processing' effect are less clear. One aspect of the effect is probably the differentiation of the encoded record that is a consequence of deeper processing, resulting in a distinctive trace that may be specified more precisely and so retrieved successfully. To describe a wanted book in a large library simply as having "a blue cover and around 300 pages" is unlikely to be successful; it requires further specification of date, title and content. This connection between elaboration of encoding and trace distinctiveness was discussed by Craik and Jacoby (1979) among others. Craik and Simon (1980) made the further suggestion that older adults are less likely than their younger counterparts to encode information deeply and elaborately, with a consequent loss of trace distinctiveness. Their suggestion was that the older brain

tends to encode similar repeated events 'in the same old way' from one occasion to the next, whereas the younger brain is more apt to modulate each event in terms of the current context, thereby conferring distinctiveness and a higher probability of retrieval on each episodic record. This type of thinking has been developed and made much more precise by the distinction between familiarity and recollection (e.g., [Jacoby, 1991](#); [Mandler, 1980](#); [Yonelinas, 2002](#)); episodic traces that contain aspects of the encoded context allow later retrieval that specifies the where and when aspects of the original event. The well-established finding of a disproportionate age-related drop in recollection compared to familiarity (e.g., [Jennings and Jacoby, 1997](#)) is in line with the idea that older adults encode details of the current context less well.

The related notions of specificity and distinctiveness of neural representations have received some recent research attention, with the additional implications that such specificity declines in the course of normal aging. One line of investigation concerns the age-related loss of dopaminergic receptors, with the suggestion that the loss of these receptors reduces the brain's ability to modulate incoming stimuli with respect to their specific contexts of occurrence, thereby resulting in less distinctive cortical representations of the event ([Bäckman et al., 2000](#); [Li et al., 2001](#)). A study by [Park et al. \(2004\)](#) investigated the specificity of activations to categories of perceptual inputs. It is known that young adults have areas in the ventral visual cortex that react specifically to face stimuli, and that other areas (e.g., parahippocampus) react to pictures of houses and outdoor scenes. The study by [Park et al.](#) found that whereas pictures of faces and places evoked substantially different patterns of activation in young adults, the differentiation was much less in older adults. The finding of decreased specificity in older adults' encoded representations was further bolstered by [Chee et al. \(2006\)](#) who demonstrated decreased specificity for object recognition in the lateral occipital cortex for older adults. In their scaffolding theory of aging and cognition [Park and Reuter-Lorenz \(2009\)](#) make the further suggestion that increased activation of the frontal cortex in older adults may represent the system's attempt to compensate for such age-related impairments in differentiation. In general, this line of work is providing plausible neural mechanisms for the earlier behavioral observations. Additionally, there has been some debate in the recent cognitive aging literature as to whether age-related over-recruitment of particular brain areas represents compensatory activity or dedifferentiation. A reasonable compromise is struck by the suggestion that both may occur, and that some degree of compensatory activity (e.g., in frontal cortex) may mitigate the age-related losses due to less distinctive representations ([Park and Reuter-Lorenz, 2009](#)).

6. Overcoming the deficit: environmental support

This review has largely been concerned with age-related losses in encoding efficiency, resulting in poorer later memory performance. There is also a substantial literature on compensatory mechanisms, however, at both behavioral and neural levels. One cognitive idea is that older adults are less able than their younger counterparts to self-initiate appropriate mental operations, owing perhaps to reduced attentional resources or to a decrease in frontally-based control mechanisms ([Craik, 1983, 1986](#)). This author's further suggestion was that mental operations are partly initiated 'top-down' by existing habitual procedures and current intentions, and partly driven 'bottom-up' by external stimulation. Putting these ideas together it follows that at least some age-related impairments in top-down self-initiated processing may be reduced by increasing the externally driven bottom-up component in the form of enhanced 'environmental support.' The advantages of this type of support are most obvious during retrieval – by providing a recognition test as opposed to a recall test ([Craik and McDowd,](#)

[1987](#)) or by reinstating the original encoding context (e.g., [Craik and Schloerscheidt, 2011](#)), but encoding processes can also be 'repaired' in the same manner. The suggestion is that older adults are less likely (or less able) to process incoming perceived events so deeply and elaborately in a spontaneous fashion, yet they *can* perform such useful operations – and so enhance encoding and later memory performance – when adequate environmental supports are provided.

One enduring puzzle in this area concerns the relative benefits of enhanced environmental support to younger and older adults. In some cases older adults benefit disproportionately, in many cases the two groups improve to the same extent, and in other cases young adults benefit more than older adults. One example of equivalent benefits is the provision of pictorial stimuli as opposed to words (e.g., pictures of the objects 'basket, apple, lion' as opposed to the words themselves). In a study reported by [Craik and Byrd \(1982\)](#) subsequent recall was boosted from 17% to 36% by the provision of pictures to older adults, but the corresponding figures for young adults were 33% to 52%; a 19% improvement for both groups. A second example involves the use of "subject-performed tasks" (SPTs), simply asking subjects to carry out a simple action ("point to the ceiling," "pick up the book") as opposed to learning a list of such commands. In a study by [Rönnlund et al. \(2003\)](#), 10 groups of subjects ranging in age from 35 to 80 years all showed a remarkably uniform increase in recall (about 20%) when carrying out SPTs, as compared to list learning. As illustrated below, it seems necessary to repair retrieval processes as well as encoding processes before older adults' memory performance catches up with that of their younger counterparts.

A study by [Luo et al. \(2007\)](#) attempted to find a principled reason for the various patterns of enhanced benefits to younger and older adults. Their conclusion was that greater benefits to older adults are found in situations where the enhanced operations are already carried out spontaneously by younger but not by older adults; equivalent benefits are seen in cases (such as SPTs) where neither age group performs the additional operations spontaneously; and young adults benefit disproportionately when the enhancing operations are too difficult for older learners.

The disproportionate benefit to older learners of providing support at both encoding and retrieval was shown in an experiment by [Troyer et al. \(2006\)](#). Participants were asked to learn eight surnames by saying them aloud at the time of presentation. They were also given three other sets of eight names ("as interfering material"); for the first set, participants were asked to state the first letter of each name, for the second set they were asked to generate a rhyme (e.g., Mr. Potter: "rhymes with daughter"), and for the third set they were asked to generate a meaningful association (e.g., Mrs. Page: "a page is part of a book"). The four types of encoding (letter, rhyme, associative and intentional learning) were intermingled in the complete list of 32 names, and this encoding phase was followed by unexpected recall test for all 32 names, and finally by a recognition test of the 32 names in a list containing the original 32 names plus 64 similar distracter names. The results are shown in [Fig. 1](#). Recall levels increased from physical processing (letter) to phonemic (rhyme) to semantic (associative) to intentional learning, with younger subjects generally outperforming the older group. All scores increased in the recognition test, with one dramatic result being the high performance levels achieved by older adults following semantic encoding – they score slightly higher than the younger group. Even though learning was 'incidental' and no memory test was expected, the combination of a semantic encoding task with a recognition test brought the older group (average age = 72 years) to the same level of performance as their younger counterparts (average age = 21 years).

Do these results mean that older adults' memory is "really" just as good as that of younger individuals? We argue not. In our view the age-related impairment lies principally in the inability of the

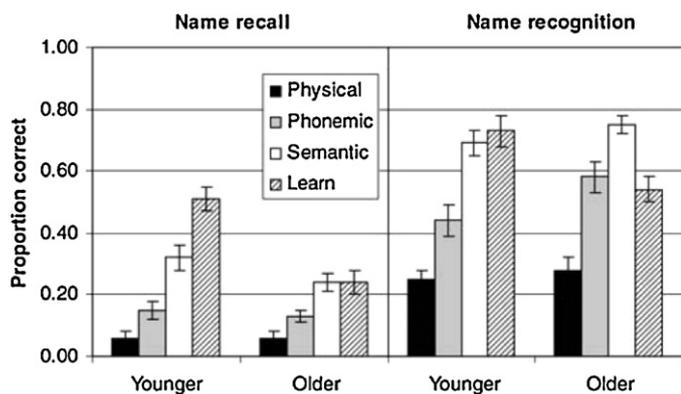


Fig. 1. Average proportions of names recalled (left panel) and recognized (right panel) by younger (mean age = 21.3 years) and older (mean age = 72.2 years) adults following incidental encoding of names as a function of levels of processing (physical: state the first letter of each name; phonemic: generate a rhyme; semantic: generate a meaningful association; learn: intentional learning). From Troyer et al. (2006); error bars represent one standard error of the mean.

older person to 'self-initiate' appropriate mental operations at the times of both encoding and retrieval. Such inefficiencies of processing can however be overcome by the provision of appropriate aids at both ends of recollective experience.

Age-related encoding impairments can also be reduced by using materials that are compatible with the expertise of specific older adults. As previously described, meaningfulness is crucial for good memory performance, and expertise in a particular topic or ability is a refinement of the same general principle. Both points were nicely illustrated by Castel (2007) who presented younger and older adults with phrases to learn for an upcoming memory test. Each phrase contained an arbitrary 2-digit number, an object and a location; the objects and locations were either related ('hotels in a city') or unrelated ('nails in a bowl'). At test, the location was presented as a cue, and participants attempted to recall the relevant number and object. Older adults recalled many fewer numbers correctly than younger adults; they also performed less well than younger adults when recalling unrelated objects, but were virtually equivalent to the young group in recalling related objects, thereby showing the generally beneficial effect of meaning. Castel also tested a small group of older adults who were retired bookkeepers or accountants, and this group actually outperformed the young adults when recalling numbers, illustrating the specific effects of expertise or 'schematic support.' In a previous study, Castel (2005) had shown that the typical age-related decrement in recall could be overcome by presenting grocery items with prices that were typical (compatible with the schema) as opposed to grossly atypical. Older adults recalled fewer atypical prices than younger adults (0.15 and 0.34, respectively), but the same older participants recalled slightly more typical prices than the young people (0.44 and 0.41, respectively). The behavioral literature thus shows clearly that encoding deficits can be overcome by the provision of appropriate environmental or schematic support.

Although the emphasis in this review is on cognitive studies of age differences in encoding processes, some brief comments are made on exciting developments in the study of age-related compensatory processes at the neural level. Several studies have found generally less activity in sensory areas (e.g., occipitotemporal cortex) during episodic encoding tasks, coupled with increased activity in frontal areas (bilaterally) in older adults relative to younger adults (Anderson et al., 2000; Cabeza et al., 2004; Davis et al., 2007; Gutchess et al., 2005; Morcom et al., 2003). Cabeza et al. have suggested that both the hemispheric asymmetry reduction in older adults (HAROLD) and the posterior to anterior shift in aging (PASA) reflects a compensatory response to age-related difficulties

in basic perceptual processing. Recently, Park and Reuter-Lorenz (2009) have proposed a 'scaffolding theory of aging and cognition' (STAC), which suggests that increased functional activity (typically in the form of bilateral recruitment of frontal areas or penumbral activation) in response to cognitive challenge is due to compensatory recruitment of additional circuitry to boost the performance of structures whose function has become noisy and inefficient with age. For example, when young and older adults encode pictures that are subsequently remembered, young adults have heightened parahippocampal activation compared to older adults, whereas older adults have heightened middle frontal activation for items that were subsequently remembered (Gutchess et al., 2005). Moreover, if rTMS is applied to either the left (dominant) or right (compensatory) dorsolateral prefrontal cortex of young and older adults while they encode pictures, recognition memory accuracy is impaired when applied to left DLPFC for young adults, but is impaired when applied to either left or right DLPFC for older adults (Rossi et al., 2004).

The phenomenon of increased bilaterality with increasing age is now clearly established, although its significance is still a matter of debate. One possibility is that it reflects the aging brain's efforts to compensate for losses in volume and connectivity, a second possibility is that the pattern indicates a reversion to a less focused and less efficient mode of functioning – so-called 'dedifferentiation.' A critical difference between these competing hypotheses concerns the relation between the degree of bilateral involvement and cognitive performance; if the additional cortical recruitment is compensatory, those individuals who show it to the greatest extent should also perform best. This pattern has indeed been reported (Cabeza et al., 2002; Daselaar et al., 2003; Gutchess et al., 2005) and these optimistic findings have been incorporated into a number of recent models, each with its own trademark acronym, for example HAROLD (Cabeza, 2002) PASA (Dennis and Cabeza, 2008), STAC (Park and Reuter-Lorenz, 2009) and CRUNCH (Reuter-Lorenz and Cappell, 2008). On the other hand, Kramer et al. (e.g., Bherer et al., 2005; Erickson et al., 2007) have shown that intense training improved cognitive control (dual-task performance) in older adults, and that improvements were related to *reduced* bilaterality. Clearly this is an important point to clarify in future studies.

Another finding in line with the notion that bilaterality does signal compensation is that younger adults also show bilateral activations for difficult tasks (Reuter-Lorenz and Cappell, 2008). This finding suggests that recruitment of the 'other' hemisphere is a general compensatory reaction to task difficulty, with older adults switching in this mechanism at earlier stages of difficulty. However, Duverne et al. (2009) have shown that increased bilateral prefrontal activity for subsequently remembered items was only present for those older adults who performed poorly on the recognition test, and this low-performing group was also the only group to demonstrate statistically significant right prefrontal subsequent memory effects. Thus, the pattern of age-related "compensatory recruitment" may be driven by low performers, and reflects non-optimal performance. Duverne et al. argued that "the findings suggest that relative preservation of memory performance with increasing age does not depend upon right prefrontal 'over-recruitment' (p. 733). It should be noted, however, that Duverne et al. used an incidental encoding task, and this may be the source of differences between their and other studies, which used intentional learning procedures.

The topic of neural compensation in cognitive aging is interesting, exciting and fast-moving although many details remain to be worked out. It is somewhat paradoxical, for instance, that the frontal cortex is both the site of much compensatory adjustment yet also one of the main areas to show age-related atrophy (Raz, 2000; Raz et al., 2005). It is also unclear whether the increased frontal activation reflects an automatic adjustment at the neural level of

organization or whether it is secondary to the increased deliberate use of strategies by older adults. One particularly exciting possibility is that individual differences in frontal over-recruitment and enhanced white matter connectivity to hippocampus and other medial-temporal regions (e.g., Dennis et al., 2008) may relate to the notion of cognitive reserve suggested by Stern (2002) and others. That is, those older individuals who remain active socially, physically and intellectually may retain white matter connectivity and may develop new areas of frontal activity and function despite some generalized age-related losses. Exactly this pattern of retained white matter was reported by Luk et al. (2011) for older persons who had been bilingual for many years; the authors' suggestion is that the need to control two languages over a lifetime confers a degree of cognitive or brain reserve.

7. Encoding strategies and training studies

The observation that certain lifestyle factors promote cognitive reserve, coupled with research showing a preserved capacity for neuroplasticity and neurogenesis in later life, provides the basis for the idea that it may be possible to intervene and protect against age-related declines in memory. Various training approaches have been examined, but evidence for the utility, generalizability, and persistence of benefits from memory and cognitive training programs is mixed (for a review, see Reichman et al., 2010).

Because deep elaborative encoding is known to enhance subsequent memory, many training studies have instructed older adults to use strategies that promote this type of processing. Verhaeghen et al. (1992) conducted a meta-analysis of 49 independent experiments on the effectiveness of training older adults to use various elaborative encoding techniques (e.g., method of loci, Pegword method, imagery, organization). Verhaeghen et al. reported a large and significant benefit of memory encoding training for older adults on 'target' memory tasks (for which the learned mnemonic could be employed) but no significant benefit to 'non-target' untrained memory tasks. In addition, the authors suggested that the amount of benefit from memory training in an older group is mediated by individual differences in such cognitive variables as processing speed, working memory, reasoning, verbal ability, and general mental status, as well as by age itself. They also reported that within older adult groups the relatively younger participants obtain larger benefits from training than older participants. Ball et al. (2002) described one of the most ambitious training studies to date in which 711 participants (mean age = 74 years) performed a memory training program. The program consisted of ten 60–75 min. sessions in which participants learned encoding strategies (organization, visualization and association) for recalling word lists and texts, followed by practice in using those strategies. Assessments were conducted pre- and post-training and at 1, 2, 3 and 5 years follow-up. Assessment immediately following training demonstrated improved memory function, which was maintained through 2 years of follow-up, although no 'far transfer' to novel, untrained contexts was observed.

Restorative or process-based training studies attempt to train specific processes (e.g., working memory, controlled recollection) with the hope that improvements will transfer to new untrained domains (e.g., episodic memory) that rely on the trained processes. Many such studies attempt to 'repair' encoding processes in older learners, but others have explored the training of retrieval processes. For example, Jennings and Jacoby (1993, 2003) trained older adults to perform a complex list learning and recognition task in which non-studied lure items were presented twice during the recognition test. Both presentations of the lure items should be rejected because they were not from the studied list, but the second presentations are difficult to reject as these items feel highly familiar. Because performance on this task requires a great deal

of controlled retrieval processing associated with recollection, it was expected that improvements would result in transfer to non-trained tasks. Indeed, Jennings et al. (2005) showed that older adults did improve on an episodic memory task (source monitoring); also on processing speed (digit symbol substitution) and working memory (*n*-back and self-ordered pointing tasks). Lustig et al. examined a modified version of Jennings and Jacoby's recollection training procedure by allowing participants as long as they wished for encoding and retrieval (as opposed to 2 s/word) (Bissig and Lustig, 2007) or by instructing participants to use a deep encoding strategy (Lustig and Flegal, 2008), and found that these conditions facilitated the training effects. They also found that the amount of improvement was positively associated with younger age, higher levels of education and verbal ability, suggesting that the ability to learn and use deep elaborative encoding strategies partially mediate the benefit of such 'process-based' training.

Engvig et al. (2010) reported some intriguing results from a training study in which older adults learned the method of loci technique and practiced using this technique to remember lists of words in five sessions a week for eight weeks. Unsurprisingly, memory performance on a 'near transfer' source memory task was improved following training compared to a group of 'no-contact' controls. One surprising outcome was that when all participants underwent structural MRI as part of the pre- and post-assessment, it was found that those who had learned and practiced the method of loci displayed increased cortical thickness of the right fusiform and lateral orbitofrontal cortex following training. Moreover, the magnitude was correlated with the amount of improvement in source memory performance. Both of these findings support the notion of neuroplasticity in later life, and of enhanced brain reserve following memory training. Unfortunately, without comparison to an 'active' control group, it is difficult to know if the method of loci training was the underlying causal mechanism for this finding.

Recently Kirchoff et al. (2011) trained older adults to use deep, elaborative processing during encoding and collected fMRI data during an encoding task pre- and post-training. Before training, older adults reported either using no encoding strategy or using effective encoding strategies less often than younger adults, and their recognition memory performance was poorer than the young adult controls. Additionally, during an intentional encoding task before training, older adults activated areas of left frontal cortex (as well as middle and right frontal cortex) more than younger adults, somewhat surprisingly given the pattern seen in previous studies. After just two sessions of training with deep encoding strategies, older adults' recognition memory performance was brought up to the level of younger adults, and these improvements were associated with self-initiated use of semantic encoding. However, the fMRI data revealed an interesting pattern. After training, older adults had even *more* activity in bilateral prefrontal cortex during intentional encoding. Furthermore, individuals who showed the greatest training-related improvements in recognition memory also showed the greatest training-related increases in brain activity during intentional encoding. On the one hand, this pattern of age-related over-activation fits the story that such over-activation is 'compensatory,' but, on the other hand, if over-activation represents an increase in controlled processing in response to cognitive difficulty, then one might have expected a reduction in such age-related over-activation after having received instruction on ways to support encoding. Clearly this was not the case: activity increased after training and the magnitude of this increase was larger for those who attained the biggest benefit from training. This result thus supports the view that semantic processing is associated with activation of left prefrontal and temporal regions, and that the degree of such activation correlates with subsequent memory performance.

Positive effects of training and transfer suggest that neuroplasticity is preserved in later life and that even short 'doses' of memory training, particularly those that require older adults to learn and practice using deep elaborative encoding strategies, can improve older adults' memory to the level of younger adults. Such findings are exciting and have given rise to a rapidly growing billion dollar 'brain fitness' industry. However, as Reichman et al. (2010) commented, much more research is needed to determine the effectiveness of training programs for protecting against age-related declines in memory and cognition, and to assess the generality and persistence of such effects.

8. Conclusions

In this review, we have discussed various cognitive and neurocognitive age-related changes that appear to underlie age differences in memory. Age-related declines in perception, processing speed, working memory and controlled attention – the 'building blocks of encoding' as it were – negatively affect the way in which events are encoded, with the apparent result that older adults have impoverished memory representations relative to their younger counterparts. In response to such processing deficiencies, the research reviewed here has shown that older adults can clearly benefit from various compensatory strategies including the use of mnemonic devices and greater reliance on schematic and environmental support. Additionally, recent studies suggest that the aging brain attempts to compensate by recruiting additional neural circuitry in the form of bilateral recruitment and a posterior-to-anterior shift in the pattern of activation. This compensatory recruitment suggests a general shift from automatic to controlled forms of processing. Whereas young adults encode episodic events with relative ease, the aging brain must engage in more self-initiated effortful processing to achieve adequate types of encoding.

The review has dealt very largely with age-related differences in episodic memory, as opposed to changes in such other systems as sensory memory, working memory, semantic memory and procedural memory. However, our approach, and much of the evidence reviewed, leads to the conclusion that age-related difficulties in memory encoding stem principally from the declining efficiency of certain processing operations (e.g., self-initiated semantic processes) rather than to problems with specific systems. In our speculative view, the age-related difficulty with self-initiated processing most likely stems from the declining efficiency of frontal lobe functions (Raz, 2000), perhaps especially the declining efficiency of superior medial regions (Stuss et al., 2002). With regard to the point that the success of encoding must be judged relative to the retrieval task in question, episodic recollection seems to depend principally on adequate semantic encoding, and we have concentrated on such interactions. On the other hand, performance on short-term verbal tasks such as digit span seems to depend more on phonological or articulatory encoding, which older adults carry out perfectly well (e.g., Craik and Byrd, 1982). Similarly, procedural memory tasks such as word fragment completion and perceptual identification utilize shallow sensory rather than semantic codes (Jacoby, 1983), and again older adults can perform these types of encoding and therefore show comparatively slight decrements in performance on such tasks (La Voie and Light, 1994).

The better news is that more effective types of processing are clearly possible for older learners, and that the older brain retains considerable powers of plasticity. A fuller understanding of the neural mechanisms of memory acquisition, as illustrated by the accompanying articles in this special issue, will lead to remedial procedures that should help older adults. Complementary work at the cognitive level has already shown that adequate perception, sufficient time, full attention, and a focus on meaningfulness can

raise the level of memory in older adults to the level shown by younger individuals. The next phase of neurocognitive research must work to provide more insight into the neural structures and processes underlying such cognitive concepts as processing resources, self-initiated activities, and cognitive reserve.

References

- Anderson, N.D., Craik, F.I.M., Naveh-Benjamin, M., 1998. The attentional demands of encoding and retrieval in younger and older adults: evidence from divided attention costs. *Psychol. Aging* 13, 405–423.
- Anderson, N.D., Iidaka, T., Cabeza Kapur, S.R., McIntosh, A.R., Craik, F.I.M., 2000. The effects of divided attention on encoding- and retrieval-related brain activity: a PET study of younger and older adults. *J. Cogn. Neurosci.* 12, 775–792.
- Bäckman, L., Ginovart, N., Dixon, R.A., Robins, T.B., Wahlin, A., Halldin, C., Farde, L., 2000. Age-related cognitive deficits mediated by changes in the striatal dopamine system. *Am. J. Psychiatr.* 157, 635–637.
- Ball, K., Berch, D.B., Helmers, K.F., et al., 2002. Effects of cognitive training interventions with older adults: a randomized controlled trial. *JAMA* 288, 2271–2281.
- Baltes, P.B., Lindenberger, U., 1997. Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging. *Psychol. Aging* 12, 12–21.
- Benjamin, A.S., Craik, F.I.M., 2001. Parallel effects of aging and time pressure on memory for source: evidence from the spacing effect. *Mem. Cogn.* 29, 691–697.
- Bherer, L., Kramer, A.F., Peterson, M.S., Colcombe, S., Erickson, K., Bécic, E., 2005. Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychol. Aging* 20 (4), 695–709.
- Bissig, D., Lustig, C., 2007. Who benefits from psychological training? *Psychol. Sci.* 18, 720–726.
- Buckner, R.L., Kelley, W.M., Petersen, S.E., 1999. Frontal cortex contributes to human memory formation. *Nat. Neurosci.* 2, 311–314.
- Cabeza, R., 2002. Hemispheric asymmetry reduction in older adults: the HAROLD model. *Psychol. Aging* 17, 85–100.
- Cabeza, R., Anderson, N.D., Locantore, J.K., McIntosh, A.R., 2002. Aging gracefully: compensatory brain activity in high-performing older adults. *NeuroImage* 17, 1394–1402.
- Cabeza, R., Daselaar, S.M., Dolcos, F., Prince, S.E., Budde, M., Nyberg, L., 2004. Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cereb. Cortex* 14, 364–375.
- Cabeza, R., Kapur, S., Craik, F.I.M., McIntosh, A.R., Houle, S., Tulving, E., 1997. Functional neuroanatomy of recall and recognition: a PET study of episodic memory. *J. Cogn. Neurosci.* 9, 254–265.
- Castel, A.D., 2005. Memory for grocery prices in younger and older adults: the role of schematic support. *Psychol. Aging* 20, 718–721.
- Castel, A.D., 2007. Aging and memory for numerical information: the role of specificity and expertise in associative memory. *J. Gerontol. B: Psychol.* 62, 194–196.
- Chalfonte, B.L., Johnson, M.K., 1996. Feature memory and binding in young and older adults. *Mem. Cogn.* 24, 403–416.
- Chee, M.W., Goh, J.O., Venkatraman, V., Tan, J.C., Gutchess, A., et al., 2006. Age-related changes in object processing and contextual binding revealed using fMR adaptation. *J. Cogn. Neurosci.* 18, 495–507.
- Cowan, N., 2010. The magical mystery four: how is working memory capacity limited, and why? *Curr. Dir. Psychol. Sci.* 19, 51–57.
- Craik, F.I.M., 1983. On the transfer of information from temporary to permanent memory. *Philos. Trans. Roy. Soc. Lond., Ser. B* 302, 341–359.
- Craik, F.I.M., 1986. A functional account of age differences in memory. In: Klix, F. (Ed.), *Human Memory and Cognitive Capabilities*. North Holland, Amsterdam.
- Craik, F.I.M., 2002. Human memory and aging. In: Bäckman, L., von Hofsten, C. (Eds.), *Psychology at the Turn of the Millennium*. Psychology Press, Hove, UK, pp. 261–280.
- Craik, F.I.M., Byrd, M., 1982. Aging and cognitive deficits: the role of attentional resources. In: Craik, F.I.M., Trehub, S.E. (Eds.), *Aging and Cognitive Processes*. Plenum Press, New York.
- Craik, F.I.M., Jacoby, L.L., 1979. Elaboration and distinctiveness in episodic memory. In: Nilsson, L.G. (Ed.), *Perspectives in Memory Research*. LEA, Hillsdale, NJ.
- Craik, F.I.M., Lockhart, R.S., 1972. Levels of processing: a framework for memory research. *J. Verb. Learn. Verb. Behav.* 11, 671–684.
- Craik, F.I.M., McDowd, J.M., 1987. Age differences in recall and recognition. *J. Exp. Psychol. Learn.* 13, 474–479.
- Craik, F.I.M., Schloerscheidt, A.M., 2011. Age-related differences in recognition memory: effects of materials and context change. *Psychol. Aging* 26, 671–677.
- Craik, F.I.M., Simon, E., 1980. Age differences in memory: the roles of attention and depth of processing. In: Poon, L. (Ed.), *New Directions in Memory and Aging*. Erlbaum, Hillsdale, NJ.
- Craik, F.I.M., Tulving, E., 1975. Depth of processing and the retention of words in episodic memory. *J. Exp. Psychol. Gen.* 104, 268–294.
- Daselaar, S.M., Veltman, D.J., Rombouts, S.A., Raaijmakers, J.G., Jonker, C., 2003. Deep processing activates the medial temporal lobe in young but not in old adults. *Neurobiol. Aging* 24 (7), 1005–1011.
- Davachi, L., Wagner, A.D., 2002. Hippocampal contributions to episodic encoding: insights from relational and item-based learning. *J. Neurophysiol.* 88, 982–990.
- Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., Cabeza, R., 2007. Que PASA? The posterior anterior shift in aging. *Cereb. Cortex* 18 (5), 1201–1209.

- Dennis, N.A., Cabeza, R., 2008. Neuroimaging of healthy cognitive aging. In: Craik, F.I.M., Salthouse, T.A. (Eds.), *Handbook of Aging and Cognition*, 3rd ed. Erlbaum, Mahwah, NJ, pp. 1–54.
- Dennis, N.A., Hayes, S.M., Prince, S.E., Madden, D.J., Huettel, S.A., Cabeza, R., 2008. Effects of aging on the neural correlates of successful item and source memory encoding. *J. Exp. Psychol. Learn.* 34, 791–808.
- Duverne, S., Motamedinia, S., Rugg, M.D., 2009. The relationship between aging, performance, and the neural correlates of successful memory encoding. *Cereb. Cortex* 19, 733–744.
- Engvig, A., Fjell, A.M., Westlye, L.T., Moberget, T., Sundseth, Ø., Larsen, V.A., Walhovd, K.B., 2010. Effects of memory training on cortical thickness in the elderly. *NeuroImage* 52, 1667–1676.
- Erickson, K.I., Colcombe, S.J., Adhwa, R., Bherer, L., Peterson, M.S., Scaff, P.E., Kim, J.S., Alvarado, M., Kramer, A.F., 2007. Training-induced plasticity in older adults: effects of training on hemispheric asymmetry. *Neurobiol. Aging* 28, 272–283.
- Giorgio, A., Santelli, L., Tomassini, V., Bosnell, R., Smith, S., De Stefano, N., Johansen-Berg, H., 2010. Age-related changes in grey and white matter structure throughout adulthood. *NeuroImage* 51, 943–951.
- Grady, C.L., McIntosh, A.R., Horwitz, B., Maisog, J.M., Ungerleider, L.G., Mentis, M.J., Pietrini, P., Schapiro, M.B., Haxby, J.V., 1995. Age-related reductions in human recognition memory due to impaired encoding. *Science* 269, 218–221.
- Grady, C.L., McIntosh, A.R., Rajah, M.N., Beig, S., Craik, F.I.M., 1998. The effects of age on the neural correlates of episodic memory. *Cerebral Cortex* 9, 805–814.
- Gutches, A.H., Welsh, R.C., Hedden, T., Bangert, A., Minear, M., Liu, L.L., Park, D.C., 2005. Aging and the neural correlates of successful picture encoding: frontal activations compensate for decreased medialtemporal activity. *J. Cogn. Neurosci.* 17, 84–96.
- Hale, S., Rose, N.S., Myerson, J., Strube, M.J., Sommers, M., Tye-Murray, N., Spehar, B., 2011. The structure of working memory abilities across the adult lifespan. *Psychol. Aging* 26 (1), 92–110.
- Hasher, L., Zacks, R.T., 1988. Working memory, comprehension, and aging: a review and a new view. In: Bower, G.H. (Ed.), *The Psychology of Learning and Motivation*, vol. 22. Academic Press, New York, NY, pp. 193–225.
- Hasher, L., Zacks, R.T., May, C.P., 1999. Inhibitory control, circadian arousal, and age. In: Gopher, D., Koriat, A. (Eds.), *Attention & Performance, XVII, Cognitive Regulation of Performance: Interaction of Theory and Application*. MIT Press, Cambridge, MA, pp. 653–675.
- Healey, M.K., Campbell, K.L., Hasher, L., 2008. Cognitive aging and increased distractibility: costs and potential benefits. In: Sossin, W.S., Lacaille, J.C., Castellucci, V.F., Bellevill, S. (Eds.), *Progress in Brain Research*, vol. 169. Elsevier, Amsterdam, pp. 353–363.
- Iidaka, T., Anderson, N.D., Kapur, S., Cabeza, R., Craik, F.I.M., 2000. The effect of divided attention on encoding and retrieval in episodic memory revealed by positron emission tomography. *J. Cogn. Neurosci.* 12, 267–280.
- Jacoby, L.L., 1983. Remembering the data: analyzing interactive processes in reading. *J. Verb. Learn. Verb. Behav.* 22, 485–508.
- Jacoby, L.L., 1991. A process dissociation framework: separating automatic from intentional uses of memory. *J. Mem. Lang.* 30, 513–541.
- Jacoby, L.L., Shimizu, Y., Velanova, K., Rhodes, M.G., 2005. Age differences in depth of retrieval: memory for foils. *J. Mem. Lang.* 52, 493–504.
- Jennings, J.M., Jacoby, L.L., 1993. Automatic versus intentional uses of memory: aging, attention, and control. *Psychol. Aging* 8, 283–293.
- Jennings, J.M., Jacoby, L.L., 1997. An opposition procedure for detecting age-related deficits in recollection: telling effects of repetition. *Psychol. Aging* 12, 352–361.
- Jennings, J.M., Jacoby, L.L., 2003. Improving memory in older adults: training recollection. *Neuropsychol. Rehabil.* 13, 417–440.
- Jennings, J.M., Webster, L.M., Kleykamp, B.A., Dagenbach, D., 2005. Recollection training and transfer effects in older adults: successful use of a repetition-lag procedure. *Aging Neuropsychol.* 12, 278–298.
- Kane, M.J., Hambrick, D.Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., Engle, R.W., 2004. The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *J. Exp. Psychol. Gen.* 133, 189–217.
- Kapur, S., Craik, F.I.M., Tulving, E., Wilson, A.A., Houle, S., Brown, G.M., 1994. Neuroanatomical correlates of encoding in episodic memory: levels of processing effect. *Proc. Natl. Acad. Sci. U.S.A.* 91, 2008–2011.
- Kensinger, E.A., Clarke, R.J., Corkin, S., 2003. What neural correlates underlie successful encoding and retrieval? A functional magnetic resonance imaging study using a divided attention paradigm. *J. Neurosci.* 23, 2407–2415.
- Kirchhoff, B.A., Anderson, B.A., Barch, D.M., Jacoby, L.L., 2011. Cognitive and neural effects of semantic encoding strategy training in older adults. *Cereb. Cortex*, in press.
- Köhler, S., McIntosh, A.R., Moscovitch, M., Winocur, G., 1998. Functional interactions between the medial temporal lobes and posterior neocortex related to episodic memory retrieval. *Cereb. Cortex* 8 (5), 451–461.
- Kolers, P.A., 1973. Remembering operations. *Mem. Cogn.* 1, 347–355.
- La Voie, D.J., Light, L.L., 1994. Adult age differences in repetition priming: a meta-analysis. *Psychol. Aging* 9, 539–553.
- Li, S.C., Lindenberger, U., Sikstrom, S., 2001. Aging cognition: from neuromodulation to representation to cognition. *Trends Cognit. Sci.* 5, 479–486.
- Lindenberger, U., Marsiske, M., Baltes, K.B., 2000. Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychol. Aging* 15, 417–436.
- Logan, J.M., Sanders, A.L., Snyder, A.Z., Morris, J.C., Buckner, R.L., 2002. Under-recruitment and nonselective recruitment: dissociable neural mechanisms associated with aging. *Neuron* 33, 827–840.
- Luk, G., Bialystok, E., Craik, F.I.M., Grady, C.L., 2011. Lifelong bilingualism maintains white matter integrity in older adults. *J. Neurosci.* 31, 16808–16813.
- Luo, L., Hendriks, T., Craik, F.I.M., 2007. Age differences in recollection: three patterns of enhanced encoding. *Psychol. Aging* 22, 269–280.
- Lustig, C., Flegel, K., 2008. Targeting latent function: encouraging effective encoding for successful memory training and transfer. *Psychol. Aging* 23 (4), 754–764.
- Mandler, G., 1980. Recognizing: the judgment of previous occurrence. *Psychol. Rev.* 87, 252–271.
- McCoy, S.L., Tun, P.A., Cox, L.C., Colangelo, M., Stewart, R.A., Wingfield, A., 2005. Hearing loss and perceptual effort: downstream effects on older adults' memory for speech. *Q. J. Exp. Psychol.* 58A, 22–33.
- McDaniel, M., Einstein, G., Jacoby, L., 2008. New considerations in aging and memory: the glass may be half full. In: Craik, F.I.M., Salthouse, T.A. (Eds.), *The Handbook of Aging and Cognition*, 3rd ed. Erlbaum, Mahwah, NJ, pp. 251–310.
- McIntyre, J.S., Craik, F.I.M., 1987. Age differences in memory for item and source information. *Can. J. Psychol.* 41, 175–192.
- Morcom, A.M., Good, C.D., Frackowiak, R.S., Rugg, M.D., 2003. Age effects on the neural correlates of successful memory encoding. *Brain* 126 (1), 213–229.
- Morris, C., Bransford, J., Franks, J., 1977. Levels of processing versus transfer appropriate processing. *J. Verb. Learn. Verb. Behav.* 16 (5), 519–533.
- Murphy, D.R., Craik, F.I.M., Li, K.Z.H., Schneider, B.A., 2000. Comparing the effects of aging and background noise on short-term memory performance. *Psychol. Aging* 15, 323–334.
- Naveh-Benjamin, M., 2000. Adult age differences in memory performance: tests of an associative deficit hypothesis. *J. Exp. Psychol. Learn.* 26, 1170–1187.
- Naveh-Benjamin, M., Guez, J., Kilb, A., Reedy, S., 2004. The associative deficit of older adults: further support using face-name associations. *Psychol. Aging* 19, 541–546.
- Nyberg, L., et al., 2000. Reactivation of encoding-related brain activity during memory retrieval. *Proc. Natl. Acad. Sci. U.S.A.* 97, 11120–11124.
- Park, D.C., Lautenschlager, G., Hedden, T., Davidson, N.S., Smith, A.D., Smith, P.K., 2002. Models of visuospatial and verbal memory across the adult life span. *Psychol. Aging* 17, 299–320.
- Park, D.C., Polk, T.A., Park, R., Minear, M., Savage, A., Smith, M.R., 2004. Aging reduces neural specialization in ventral visual cortex. *Proc. Natl. Acad. Sci. U.S.A.* 101 (35), 13091–13095.
- Park, D., Reuter-Lorenz, P.A., 2009. The adaptive brain: aging and neurocognitive scaffolding. *Annu. Rev. Psychol.* 60, 173–196.
- Park, D.C., Smith, A.D., Lautenschlager, G., Earles, J., Frieske, D., Zwahr, M., Gaines, C., 1996. Mediators of long-term memory performance across the life span. *Psychol. Aging* 11, 621–637.
- Rabbitt, P.M.A., 1968. Channel capacity, intelligibility and immediate memory. *Q. J. Exp. Psychol.* 20, 241–248.
- Raz, N., 2000. Aging of the brain and its impact on cognitive performance: integration of structural and functional findings. In: Craik, F.I.M., Salthouse, T.A. (Eds.), *Handbook of Aging and Cognition II*. Erlbaum, Mahwah, NJ, pp. 1–90.
- Raz, N., Lindenberger, U., Rodrigue, K.M., Kennedy, K.M., Head, D., et al., 2005. Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cereb. Cortex* 15 (11), 1676–1689.
- Reichman, W., Fiocco, A., Rose, N.S., 2010. Exercising the brain to avoid cognitive decline: examining the evidence. *Aging Health* 6 (5), 565–584.
- Reuter-Lorenz, P.A., Cappell, K., 2008. Neurocognitive aging and the compensation hypothesis. *Curr. Dir. Psychol. Sci.* 17 (3), 177–182.
- Rönnlund, M., Nyberg, L., Bäckman, L., Nilsson, L.-G., 2003. Recall of subject-performed tasks verbal tasks, and cognitive activities across the adult life span: parallel age-related deficits. *Aging Neuropsychol.* 10 (3), 182–201.
- Rose, N.S., Myerson, J., Sommers, M., Hale, S., 2009. Are there age differences in the executive component of working memory? Evidence from domain-general interference effects. *Aging Neuropsychol.* 16 (6), 633–653.
- Rossi, S., Miniussi, C., Pasqualetti, P., Babiloni, C., Rossini, P.M., Cappa, S.F., 2004. Age-related functional changes of prefrontal cortex in long-term memory: a repetitive transcranial magnetic stimulation study. *J. Neurosci.* 24 (36), 7939–7944.
- Salthouse, T.A., 1990. Working memory as a processing resource in cognitive aging. *Dev. Rev.* 10, 101–124.
- Salthouse, T.A., 1991. *Theoretical Perspectives on Cognitive Aging*. Lawrence Erlbaum Associates, Hillsdale, NJ.
- Salthouse, T.A., 1996. The processing speed theory of adult age differences in cognition. *Psychol. Rev.* 103, 403–428.
- Schacter, D.L., Harbluk, J.L., McLachlan, 1984. Retrieval without recollection: an experimental analysis of source amnesia. *J. Verb. Learn. Verb. Behav.* 23 (5), 593–611.
- Schneider, B.A., Pichora-Fuller, S.K., 2000. Implications of perceptual deterioration for cognitive aging research. In: Craik, F.I.M., Salthouse, T.A. (Eds.), *The Handbook of Aging and Cognition*, 2nd ed. Erlbaum, Mahwah, NJ, pp. 155–219.
- Shallice, T., Fletcher, P., Frith, C.D., Grasby, P., Frackowiak, R.S.J., Dolan, R.J., 1994. Brain regions associated with acquisition and retrieval of verbal episodic memory. *Nature* 368, 633–635.
- Shing, Y.L., Werkle-Bergner, M., Brehmer, Y., Müller, V., Li, S.C., Lindenberger, U., 2010. Episodic memory across the lifespan: the contributions of associative and strategic components. *Neurosci. Biobehav. Rev.* 34, 1080–1091.
- Stebbins, G.T., Carrillo, M.C., Dorfman, J., Dirksen, C., Desmond, J.E., Turner, D.A., et al., 2002. Aging effects on memory encoding in the frontal lobes. *Psychol. Aging* 17, 44–55.
- Stern, Y., 2002. What is cognitive reserve? Theory and research application of the reserve concept. *J. Int. Neuropsychol. Soc.* 8 (3), 448–460.

- Stuss, D.T., Alexander, M.P., Floden, D., Binns, M.A., Levine, B., McIntosh, A.R., et al., 2002. Fractionation and localization of distinct frontal lobe processes: evidence from focal lesions in humans. In: Stuss, D.T., Knight, R.T. (Eds.), *Principles of Frontal Lobe Function*. New York, NY, Oxford University Press, pp. 392–407.
- Troyer, A.K., Häfliger, A., Cadieux, M.J., Craik, F.I.M., 2006. Name and face learning in older adults: the effects of level of processing, self-generation, and intention to learn. *J. Gerontol. B: Psychol.* 61B, P67–P74.
- Tulving, E., 1983. *Elements of Episodic Memory*. Clarendon Press, Oxford.
- Tulving, E., Kapur, S., Craik, F.I.M., Moscovitch, M., Houle, S., 1994. *Proc. Natl. Acad. Sci. U.S.A.* 91, 2016–2020.
- Tulving, E., Thomson, D., 1973. Encoding specificity and retrieval processes in episodic memory. *Psychol. Rev.* 80 (5), 352–373.
- Uncapher, M.R., Rugg, M.D., 2005. Effects of divided attention on fMRI correlates of memory encoding. *J. Cogn. Neurosci.* 17 (12), 1923–1935.
- Vaidya, C.J., Zhao, M., Desmond, J.E., Gabrieli, J.D., 2002. Evidence for cortical encoding specificity in episodic memory: memory-induced re-activation of picture processing areas. *Neuropsychologia* 40, 2136–2143.
- Verhaeghen, P., Marcoen, A., Goossens, L., 1992. Improving memory performance in the aged through mnemonic training: a meta-analytic study. *Psychol. Aging* 7, 242–251.
- Yonelinas, A.P., 2002. The nature of recollection and familiarity: a review of 30 years of research. *J. Mem. Lang.* 46, 441–517.
- Zacks, R.T., Hasher, L., Li, K.Z.H., 2000. Human memory. In: Salthouse, T.A., Craik, F.I.M. (Eds.), *Handbook of Aging and Cognition*, 2nd ed. Mahwah, NJ, Lawrence Erlbaum, pp. 293–357.