

Associative and Strategic Components of Episodic Memory: A Life-Span Dissociation

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The authors investigated the strategic component (i.e., elaboration and organization of episodic features) and the associative component (i.e., binding processes) of episodic memory and their interactions in 4 age groups (10–12, 13–15, 20–25, and 70–75 years of age). On the basis of behavioral and neural evidence, the authors hypothesized that the two components are functionally related but follow different life-span gradients. In a fully crossed design, age differences in recognition memory for single words versus word pairs (associative demand manipulation) were examined under instructions that emphasized item, pair, or elaborative-pair encoding (strategy manipulation). As predicted, the results showed that the strategic and associative components follow different life-span trajectories. Relative to younger adults, children's difficulties in episodic memory primarily reflected lower levels of strategic functioning. In contrast, older adults showed impairments in both strategic and associative components. The authors conclude that the comparison of strategic and associative components of episodic memory across the life span helps to delineate the two components' unique and interactive contributions to episodic memory performance.

Keywords: episodic memory, cognitive control, child development, aging, life-span development

Episodic memory, as conceptualized by Tulving (1972), consists of processes that enable people to remember events in space and time. The integration of core content and contextual features of an event into a cohesive memory representation is crucial for the functioning of episodic memory (Tulving, 1972, 2002; Underwood, 1969). In recent years, memory researchers have been seeking a better understanding of the mechanisms by which experiences that involve rich content and contextual specificities are bound together as integrated episodes in memory (M. K. Johnson, 1992; Treisman, 1996; Zimmer, Mecklinger, & Lindenberger, 2006).

The functioning of episodic memory can be conceptualized as operated and affected by two interacting components, namely, the associative and strategic components (Moscovitch, 1992; Prull, Gabrieli, & Bunge, 2000; Werkle-Bergner, Müller, Li, & Lindenberger, 2006). The associative component of episodic memory refers to mechanisms during encoding, storage, and retrieval that bind different aspects of an event into a cohesive episode (Treisman, 1996; Zimmer et al., 2006). Binding mechanisms can operate either among different features within a given memory item (Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000), between different memory items (Gronlund & Ratcliff, 1989; Naveh-Benjamin, 2000), or between the core features of a given memory episode and its context (Spencer & Raz, 1995). In other words, binding mechanisms refer to a set of cognitive processes and their underlying neural mechanisms that associate features within a memory trace or several memory traces (Zimmer et al., 2006). Furthermore, mechanisms of association formation, consolidation, and retrieval exist at different levels of binding (Craik, 2006; Murre, Wolters, & Raffone, 2006), ranging from perceptual feature binding to the formation of higher order memory, concepts, and ideas.

We turn now to the strategic component, which refers to the organization and manipulation of the elements of a memory episode during encoding, storage, or retrieval by presumably making use of existing semantic knowledge to elaborate certain relational aspects of the memory features (Craik & Lockhart, 1972; Levin, 1988; Paivio, 1971). More specifically, elaborative strategies involve "meaning-enhancing additions, constructions, or generations that improve one's memory for what is being learned" (Levin, 1988, p. 191). Empirical research has confirmed that memory encoding can be aided by the use of mediators generated through verbal and imagery elaboration (Paivio, 1971; Richardson, 1998). It is important to note that strategic organization and elaboration can be either self-activated and occur spontaneously or elicited

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This study was carried out in the context of the Research Group "Binding: Functional Architecture, Neuronal Correlates, and Ontogeny," funded by the German Research Foundation (DFG FOR 448). The study was conducted in partial fulfillment of the doctoral dissertations of Yee Lee Shing and Markus Werkle-Bergner, who express gratitude to the support of the International Max Planck Research School, The Life Course: Evolutionary and Ontogenetic Dynamics (LIFE).

We thank the research and technical assistants at the Center for Lifespan Psychology for their help in collecting the data, and the participants for their cooperation. We give special thanks to Lars Bäckman, Yvonne Brehmer, Chris Hertzog, Axel Mecklinger, Moshe Naveh-Benjamin, Florian Schmiedek, and Hubert Zimmer for productive and valuable discussions.

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through instruction or other forms of environmental support (Kausler, 1994; Schneider & Pressley, 1997).

The functioning of episodic memory undergoes profound and continuous changes across the life span (Baltes, Lindenberger, & Staudinger, 2006; Graf & Ohta, 2002; Li et al., 2004). From childhood to young adulthood, pronounced monotonic and steep improvements in episodic memory are observed (Ceci, Lea, & Howe, 1980; Schneider & Pressley, 1997). In older adulthood, various aspects of memory, especially episodic memory, decline with age (Kausler, 1994; Light, 1991; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Zacks, Hasher, & Li, 2000). Taken together, an apparent symmetry across the life span exists: Episodic memory ability grows during childhood and adolescence and declines during old age. Despite these surface similarities in performance trajectories, life-span developmental theory postulates that the mechanisms underlying cognitive changes differ across different age periods (Baltes et al., 2006; Bialystok & Craik, 2006; Ohta, 2002). That is, episodic memory functions undergo reorganization from childhood to old age, reflecting developmental changes in the interplay among processes related to maturation, learning, and senescence. However, because of the divide between child development and aging research, little theorizing or investigation has been carried out to integrate the mechanisms of memory functioning from childhood to aging (but see Dempster, 1992; Gulya et al., 2002; Kail & Salthouse, 1994; Li et al., 2004). The present study attempts to fill this gap by empirically examining the distinction between associative and strategic components as a means to promote mechanistic explanations for life-span age differences in episodic memory. In the following sections, we gather extant empirical evidence from child and adult developmental research to provide the rationales for the experimental designs and hypotheses of the present study.

Piecing Together Life-Span Age Differences in the Associative Component

Since the 1970s, child memory research has paid little attention to age-related differences in binding mechanisms, with only a few notable recent exceptions. Sluzenski, Newcombe, and Kovacs (2006) examined age differences in recognition memory for item (i.e., pictures of animals) and item-background (animals against arbitrary backgrounds) associations in 4-year-olds, 6-year-olds, and adults. The results showed that 4-year-olds recognized the combination of item and background less well than did 6-year-olds and adults, whereas individual items were remembered equally well in both groups of children. In contrast, the 6-year-olds performed as well as the adults on remembering item-background associations. These findings suggest different developmental trajectories of single-item and associative aspects of episodic memory. In particular, the ability to bind together information in memory formation may progress significantly around 5 to 6 years of age (see also Oakes, Ross-Sheehy, & Luck, 2006), whereas memory for single items develops earlier. However, both aspects mature relatively early compared with executive/cognitive control functions that show protracted development into young adulthood (Gathercole, 1998; Luciana, Conklin, Hooper, & Yarger, 2005). In a broader perspective, young children's difficulty in binding items

with contextual information may underlie preschoolers' difficulty in source monitoring (M. K. Johnson, Hashtroudi, & Lindsay, 1993; Kovacs, Hansell, & Newcombe, 2005; Sluzenski, Newcombe, & Ottinger, 2004).

In contrast to research on memory development during childhood, adult age differences in the efficiency of binding mechanisms have attracted much recent attention among cognitive aging researchers. There is general agreement that older adults show greater difficulty relative to younger adults in remembering the context and specific details of episodic memories than in remembering the content itself (see Spencer & Raz, 1995; Zacks et al., 2000, for reviews). On the basis of this observation, the associative deficit hypothesis postulates that older adults' deficient memory performance stems in part from their difficulty in binding information into cohesive memory representations (Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). The hypothesis has been supported by the consistent finding that older adults exhibit a disproportionately lower performance on memory tasks requiring information to be bound between different aspects of memory episode in comparison with tasks requiring only single-item or feature information (Castel & Craik, 2003; Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000). Using a joint memory paradigm requiring recognition of items and associations between item pairs (cf. Humphreys, 1976), Naveh-Benjamin and colleagues (Naveh-Benjamin, 2000; Naveh-Benjamin, Brav, & Levy, 2007; Naveh-Benjamin et al., 2004; Naveh-Benjamin, Guez, & Marom, 2003; Naveh-Benjamin, Hussain, et al., 2003) consistently demonstrated that older adults showed deficits in encoding and retrieving associations among items. This decrease in the ability to remember compound information could not be attributed solely to older adults' deficit in remembering individual items, as negative age differences in item recognition memory were negligible and/or controlled for.

To integrate research findings across the life span, one can start with the observation that the associative component of episodic memory matures early during child development. At the other end of the life span, the decline in remembering bound features is especially drastic and surpasses the rate of decline for other aspects of memory functioning. A recent life-span study by Cowan, Naveh-Benjamin, Kilb, and Sauls (2006) provided empirical evidence in favor of this view. The authors investigated age differences in the ability to keep the association between a visual object (colored squares) and its spatial location in working memory. Applying a change-detection paradigm (Luck & Vogel, 1997), participants had to detect whether there was a change in a single feature (different colored squares) or a change in the feature conjunction (different color and location), which requires more binding-related processing. Older adults often failed to notice the feature-conjunction change, especially when single-feature and feature-conjunction trials were mixed. Age differences between younger and older adults followed the associative-deficit age pattern observed in studies of episodic memory (e.g., Naveh-Benjamin, 2000). The two child groups (ages 8–10 and 11–12 years) performed less well, compared with younger adults on both kinds of trials. However, they did not exhibit as disproportionately large differences on the feature-conjunction trials as the group of older adults. These findings support the notion that the associative

component of memory performance is relatively mature by middle childhood, whereas at the other end of the life span, older adults exhibit specific difficulties in retaining and/or retrieving associative information.

Piecing Together Life-Span Age Differences in the Strategic Component

For many years, age differences in episodic memory have been investigated in terms of age changes in encoding strategies (Flavell, 1970; Light, 1991). In child development, early research interest in the strategic component of episodic memory was motivated mainly by Flavell's (1970) seminal work establishing the observation that rehearsal and organization develop as memory strategies between 5 and 10 years of age. In a similar vein, Rohwer (1973) proposed that the developmental increase in the propensity of using elaborative strategies and the decreasing dependence on rote learning contribute to age-associated improvements in episodic memory performance.

Numerous studies showed that memory strategies develop most rapidly throughout the elementary school years (for a review, see Schneider & Pressley, 1997). Effective strategies, such as elaboration and organization, are typically not observed in children younger than 6 years of age, even after instruction (termed *mediation deficiency*; Reese, 1962). At a later age, kindergarten and early-grade school children still do not spontaneously display strategic organizational behavior. However, when given instructions, their performance can be improved, indicating a *production deficiency* in strategy use (Flavell, 1970). A later identified phenomenon, termed *utilization deficiency*, refers to the behavior of children who are capable of spontaneously displaying strategic behavior (e.g., selective attention) but go through a transitional phase in which they do not benefit from strategy use (DeMarie-Dreblow & Miller, 1988). A closer look at the efficiency of strategy use reveals that it is not until the end of the elementary school years that children master the full range of memory-related strategic behaviors (see also Siegler, 1996, on the issue of strategy variability).

In the field of cognitive aging, age differences in encoding strategies have often been attributed to production deficiencies (Kausler, 1994; Verhaeghen & Marcoen, 1994) in the sense that older adults do not spontaneously engage in using strategies in the way younger adults do or do not apply the strategies efficiently. Typically, instructional paradigms were used to test this hypothesis (e.g., imagery strategy instruction/training group vs. control group), and age differences within each group before and after strategy instruction or training were compared. The general finding is that cognitively healthy older adults continue to benefit from acquiring and utilizing mnemonic techniques, which results in smaller age-group differences after instruction, training, or both. The results of these studies, however, need to be interpreted with caution because performance after relatively minor interventions (e.g., one session of instruction or training) may continue to be influenced by construct-extraneous factors, such as pre-assessment differences in practice or task-relevant knowledge (Baltes et al., 2006). To counter these problems and obtain purer estimates of individuals' performance potential, researchers have adapted testing-the-limits procedures to the study of age differences in

episodic memory (Lindenberger & Baltes, 1995). With testing-the-limits paradigms, researchers seek to approximate upper limits of performance potential by providing instruction and extensive practice, often combined with person-specific variation of task difficulty (adaptive training; see also Bissig & Lustig, 2007). Research on adult age differences in episodic memory with testing-the-limits procedures has consistently resulted in two main findings. First, in line with results from instructional and short-term intervention studies, older adults show performance improvements after initial mnemonic instruction. Second, older adults show considerably smaller performance improvements in the course of extensive practice or adaptive training than do younger adults (Kliegl, Smith, & Baltes, 1989, 1990; Singer, Lindenberger, & Baltes, 2003) and children (e.g., Brehmer, Li, Müller, von Oertzen, & Lindenberger, 2007). These results suggest that senescent changes compromise memory plasticity in old age.

Two main observations can be made from the integration of evidence from the studies of memory in childhood and old age. First, memory processes related to strategic use do not develop fully until middle or late childhood. Second, older adults show less memory plasticity than children and younger adults, as evidenced by the limited amount of improvement after extensive mnemonic strategy training (e.g., Brehmer et al., 2007). Furthermore, for reasons that are not clear thus far, older adults appear to engage in memory-relevant strategy processes in less efficient ways than do younger adults (see also Dunlosky & Hertzog, 1998; Dunlosky, Hertzog, & Powell-Moman, 2005). Converging evidence for these observations can be gathered from the literature on familiarity- and recollection-based recognition processes. According to the dual-process account (Jacoby, 1991; Yonelinas, 2002), memory for past events can be based on retrieval accompanied by specific contextual details (recollection) or on the feeling of knowing that an event is old or new without necessarily recollecting specific details (familiarity). Evidence from a range of studies suggests that the development of recollection (which relies more on strategy use such as semantic processing) extends into adolescence, whereas familiarity (which relies more on associative processes) matures during childhood (Anooshian, 1999; Brainerd, Holliday, & Reyna, 2004; Ghetti & Angelini, in press). Relatedly, older adults have been found to rely more on familiarity process during retrieval, as they face difficulties in recollecting details of memory episodes (Healy, Light, & Chung, 2005; Jacoby & Hay, 1998).

Life-Span Differences in Neural Correlates of Strategic and Associative Components of Episodic Memory

Correlates of associative and strategic components of episodic memory, and age differences therein, can also be identified at the neural level. Earlier neuronally informed models of episodic memory (e.g., Moscovitch, 1992) postulated that the strategic component depends primarily on the frontal cortex, whereas the associative component relies mostly on the medial temporal region (especially the hippocampus). This distinction has gained empirical support in recent years, as numerous studies, including case studies, involving amnesic patients and animal models have indicated that the medial temporal lobes (MTL) and the prefrontal cortex (PFC) contribute to memory in critical and separable ways (Eichenbaum, 2002; Miller & Cohen, 2001; Prull et al., 2000;

Simons & Spiers, 2003; Werkle-Bergner et al., 2006). Specifically, on the one hand, the hippocampal formation and associated structures (such as the fornix and the entorhinal cortex) contribute to the formation and maintenance of memories and particularly to the establishment of associations among features of episodes in memory (Eichenbaum, 2002; Squire, 2004). On the other hand, the PFC engages in executive control processes required for optimal memory formation (e.g., Fletcher, Shallice, & Dolan, 1998) and retrieval (e.g., Fletcher, Shallice, Frith, Frackowiak, & Dolan, 1998). Taken together, the ability to encode and retrieve episodic associations relies on a distributed functional network comprising hippocampal/MTL memory mechanisms supporting associative-binding processes as well as PFC-mediated cognitive control processes supporting strategic elaborative and organizational processes (Miller & Cohen, 2001; Simons & Spiers, 2003).

There is no doubt that the functional circuitries of episodic memory reviewed above change across the life span. However, little is known about the precise nature of these changes. Anatomical and functional studies show that PFC (particularly dorsolateral regions) and associated neural networks undergo profound maturational changes well into adolescence (Diamond, 2002; Giedd et al., 1999; M. H. Johnson, 2001; Paus, 2005), whereas MTL regions mature at relatively faster rates (Casey, Giedd, & Thomas, 2000; Gogtay et al., 2004; Ofen et al., 2007; Sowell et al., 2003; but see Gogtay et al., 2006). The differential developmental trajectories of brain regions suggest that the zone of maximum functional development progresses from MTL to neocortical PFC areas (Chugani, Phelps, & Mazziotta, 1987; for computational modeling, see Shrager & Johnson, 1996). With respect to brain aging, PFC regions are among the first to show signs of senescence-related deterioration during adulthood (Hedden & Gabrieli, 2004; Park & Gutches, 2005; Raz et al., 2005). At the same time, accelerated patterns of decline are also observed in the MTL regions, with a marked decline observed in the hippocampus and the entorhinal cortex with advanced age and aging with dementia (Buckner, 2004; Daselaar, Fleck, Dobbins, Madden, & Cabeza, 2006; Persson et al., 2006; Raz et al., 2007). Taken together, a large functional network comprising PFC and MTL areas is involved in episodic memory functioning and is affected by maturational and senescent changes.

Overview of the Present Study

Various overlapping mechanisms have been proposed to account for age-related changes in memory during childhood (Nelson, 2001; Schneider & Pressley, 1997) and aging (Light, 1991; Zacks et al., 2000), respectively. Some of the current accounts involve reduction in information-processing resources (e.g., speed, inhibitory control, working memory), or the over-reliance on familiarity, accompanied by impaired recollection (e.g., Brainerd, Holliday, & Reyna, 2004; Yonelinas, 2002). However, attempts to identify and compare mechanisms that regulate changes in memory functioning from childhood to aging are scarce (Dempster, 1992; Kail & Salthouse, 1994). When piecing together behavioral and neuronal evidence on episodic memory development in childhood and later adulthood, we noticed a life-span dissociation between the associative and strategic components of episodic memory. Specifically, the growth of the strategic component lags

behind the growth of the associative component during childhood, but both components decline concurrently in late adulthood and old age.

We postulate that the two components of episodic memory offer a process-oriented account that allows for identification and examination of mechanisms underlying life span age differences in episodic memory functioning. We do not assume that the two components refer to a unique or mutually exclusive set of component processes or that they constitute the only factors affecting episodic memory. Instead, it seems likely that a comprehensive account of life-span changes in episodic memory will involve multiple and interacting sets of mechanisms that also affect other functional domains (e.g., general slowing, decline in processing resources, decline in the efficiency of inhibitory mechanisms). However, we assume that changes in associative and strategic components are among the major driving forces, or “developables” (Flavell, 1992), of episodic memory development across the life span.

Hypotheses

The design of the present study was guided by two main hypotheses. First, given that the maturation of the hippocampus precedes the maturation of PFC areas, we expected the associative and strategic components of episodic memory to develop at different rates during childhood and adolescence. In relation to younger adults, children’s difficulties in memory are primarily due to the relatively late-developing strategic component, whereas their associative component is closer to maturation. We expected that when provided with an efficient memory strategy, children would show a boost in memory performance as a result of (a) overcoming their deficiency in strategic elaboration and (b) thereby making better use of their well-functioning associative component. On the other hand, the performance of teenagers was expected to closely approximate the performance of younger adults, as both age groups can rely on well-functioning associative and strategic components.

Second, on the basis of senescent changes in both PFC and MTL structures, we expected older adults’ deficits in memory to reflect not only lower levels of strategic functioning but also an additional impairment in the associative component that is absent in other age groups. Therefore, even when provided with an efficient strategy, older adults should show less improvement in performance in comparison with all other groups, reflecting limits on episodic memory imposed by the impaired associative component. We also expected the associative deficiencies to be exacerbated under task conditions that impose high demands on association formation and retrieval.

Experimental Paradigm and Design

To test the hypotheses above, a verbal paired-associates recognition paradigm (see Naveh-Benjamin, 2000) was administered in a fully crossed within-person repeated measures design, in which associative demand was varied by the type of word pair to be studied, whereas strategic involvement was varied by encoding instructions (see Figure 1 for illustration). Specifically, the degree of associative demands was varied by using German–German (GG) and German–Malay (GM) word pairs. For the participants,

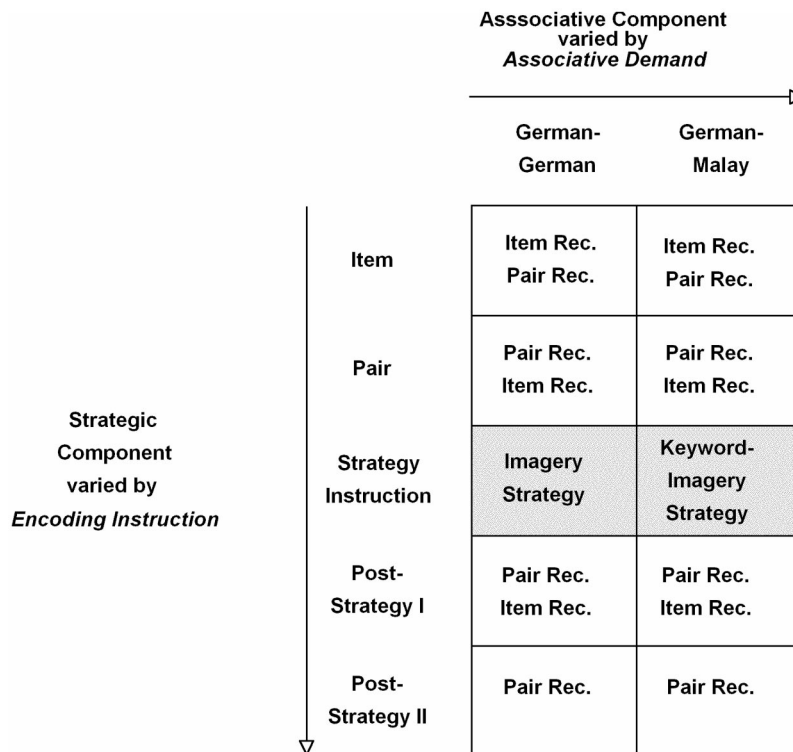


Figure 1. Graphical illustration of the memory assessment procedure of Experiment 1; Item Rec. = item-recognition test; Pair Rec. = pair-recognition test.

who were native speakers of German with no knowledge of Malay, the GM pairs demanded more associative binding than did the GG pairs, as participants had no prior knowledge of Malay words. For each GM pair, the Malay word was the direct translation of the German word.¹

The involvement of the strategic component was manipulated by encoding instructions that emphasized (a) item encoding, (b) pair encoding, and (c) elaborative-strategy encoding. First, during the baseline session (item encoding), participants were told to study the words in each pair individually in preparation for an upcoming item-recognition test. Therefore, associative information of the word pairs was learned incidentally. At the following session (pair encoding), participants were instructed to study the word pairs in preparation for an upcoming pair-recognition test. Comparisons between item and pair encoding provide information about how the age groups differ in their change in performance from incidental to self-initiated learning of the word pairs.

The pair-encoding session was followed by a strategy-instruction session, in which participants were instructed in the use of an elaborative-imagery strategy. The essence of the strategy was to elaborate on the study-word pairs with visual imagery that dynamically integrates the two words (e.g., with the use of dramatic fantasized images or with references to personal histories). The elaborative-imagery strategy was selected as the focus of the present study because of its superior effectiveness (Bower & Winzenz, 1970) relative to other associative-learning strategies and the applicability of various forms of imagery strategies in both

children and older adults (Baltes & Kliegl, 1992; Brehmer et al., 2007; Verhaeghen, Marcoen, & Goossens, 1992). For the GM condition, a variant of the imagery strategy known as the keyword strategy was taught. The keyword strategy has been shown in the literature to be highly effective for promoting foreign vocabulary acquisition (Rohwer, 1973). In the present study, participants were instructed to first find a meaningful connection (i.e., the keyword) for the unfamiliar Malay word either through the phonological or orthographical characteristics of the Malay word. Then, participants were to integrate the keyword with the familiar German word through imagery. After the strategy-instruction session, two sessions of performance measurement (post-strategy assessments) were applied. Comparisons of performance between the pair encoding and post-strategy encoding allowed the examination of age-related differences in the range of performance gain from receiving strategy elicitation externally.

¹ Instead of using within-language word pairs with varying associative strength, we used Malay as a foreign language to avoid confound between age-related difference in associative knowledge base and memory (e.g., Bjorklund & de Marchena, 1984; Kee & Guttentag, 1994). Furthermore, there is no existing German word association database in which norming is performed with life span sample data. Malay is a language written with the Latin alphabet, and the phonemes are pronounceable for German speakers. The participants were screened for previous knowledge of Malay as a foreign language. None of the participants in our sample knew this language, making the language equally unfamiliar to all age groups.

Experiment 1: Main Study

*Method**Participants*

The experiment included four age groups: 43 children (ages 10–12 years, $M = 11.2$, $SD = 0.6$), 43 teenagers (ages 13–15 years, $M = 14.4$, $SD = 0.4$), 42 younger adults (ages 20–25 years, $M = 23.3$, $SD = 1.6$), and 42 older adults (ages 70–75 years, $M = 73.2$, $SD = 1.7$). The children and teenage groups were chosen to reflect developmental differences in the maturity of the PFC. Gender was distributed almost equally across the age groups (see Table 1).

All participants were residents of Berlin, Germany. The older adults lived independently in the community. All participants reported having normal or corrected-to-normal visual and auditory acuity. Participants also filled out demographic questionnaires assessing subjective well-being and subjective health. Age differences on these measures were not reliable (see Table 1). Participants were also assessed on marker tests of crystallized intelligence (verbal knowledge; cf. Lehl, 1977) and fluid intelligence (Digit Symbol; cf. Wechsler, 1955). We found expected life-span patterns with respect to cognitive mechanics and pragmatics, namely, (a) a continuous increase in verbal knowledge across the life span and (b) an inverted U-shaped life-span function for the Digit Symbol Substitution scores, with children and older adults showing similar levels of performance but lowered performance in comparison with teenagers and younger adults.

Material

The experiment used a mixed factorial design. The two within-subject variables consisted of encoding instruction (three levels: item vs. pair vs. post-strategy) and associative demand (two levels: GG vs. GM). The between-subjects variable was age group. To minimize any possible confound of vocabulary knowledge related to age, we selected a pool of highly imaginable concrete nouns from established German norm databases (Brehmer et al., 2004; Hasselhorn, Jaspers, & Hernando, 1990; Scheithe & Bäuml, 1995). This was carried out in two steps. First, two independent raters preselected words having two to three syllables that were assumed to be well understood by most children of 11 years of age. Second, in a pilot study, 12 children ages 10 to 12 years rated these selected

words on a 3-point scale of comprehensibility; only the most comprehensible words were retained. As a result, 1,200 German concrete nouns were selected for the present study.

For the GM condition, one third of the words from the final word pool were randomly extracted, and each word was paired with its corresponding translation in Malay language. To minimize confound of foreign language knowledge, we checked the Malay words to ensure that they had two to four syllables and did not bear any obvious similarity to prominent European languages. For the GG condition, the leftover words from the word pool were randomly paired together. We validated that the word pairs were unrelated to each other in any apparent way. Across the blocks of encoding and recognition phases, no word was recycled.

Procedure

Each participant was tested in six consecutive age-homogeneous group sessions of 4 to 5 individuals spread out over 3 weeks. Before the start of the experiment, participants were randomly assigned to groups. Each individual remained in the same group throughout the entire experiment.

The first session was used to assess the covariates, including the measures of crystallized and fluid intelligence (see Table 1). Memory performance was assessed (a) after item-encoding instruction in Session 2, (b) after pair-encoding instruction in Session 3, and (c) after strategy instruction in Sessions 5 and 6. In Session 4, participants were given in-depth instructions and practice in using the elaborative-imagery strategy (see description below). At the beginning of each session, participants received the appropriate encoding instruction and were given a short practice block with eight trials. For the post-strategy sessions, participants were reminded about the elaborative-imagery strategy and were encouraged to maximize their use of the strategy during encoding and retrieval. Each session lasted between 90 and 120 min.

Memory assessment sessions. For the memory assessment sessions (Sessions 2, 3, 5, and 6), half of the participants began with the GG, followed by the GM condition (counterbalanced for the other half of the participants). The order of GG and GM conditions was preserved within each individual throughout the experiment. In each session, item as well as associative memory was assessed by the item- and pair-recognition tests, respectively. Item recognition was included in order to examine the differential age trajectories of item and associative memory and to control for pos-

Table 1
Descriptive Characteristics of Sample

Measure	Children	Teenagers	Younger adults	Older adults
	M (SD)	M (SD)	M (SD)	M (SD)
Age	11.2 (0.6)	14.4 (0.4)	23.3 (1.6)	73.2 (1.7)
Male:female (%)	47:53	51:49	48:52	50:50
Well-being	4.9 (2.3)	4.6 (2.4)	4.9 (2.7)	5.4 (2.9)
Subjective health	3.4 (0.7)	3.1 (0.6)	3.1 (0.8)	3.1 (0.7)
Digit symbol (mechanics)	45.7 (7.3)	57.3 (9.3)	62.8 (10.9)	43.4 (9.5)
Vocabulary (pragmatics)	9.4 (4.1)	13.5 (4.4)	20.6 (4.5)	27.9 (4.1)

Note. See Radloff (1977) for calculation of well-being score (highest possible score = 12, with lower numbers indicating greater well-being); questionnaire of subjective health is constructed by the authors (Scale = 1 to 5, with higher numbers indicating greater subjective health).

sible effects of item memory on associative memory. For the item-encoding session, participants were first administered the item-recognition test. This was followed by the pair-recognition test, the nature of which was explained only after the encoding phase to preserve its unexpected nature. For subsequent sessions (pair-encoding and post-strategy sessions), participants always received the pair-recognition test first, followed by the item-recognition test. The exception was Session 6 (second post-strategy session), in which participants were only tested on pair recognition, as there were not enough words to construct another block of study and test phases. Given that our primary interest was on pair-recognition performance, we opted to leave out the item recognition for Session 6.

During the encoding phase, 45 pairs of GG word pairs (or GM word pairs) were presented sequentially on the computer screen. The presentation time of each word pair was 6 s for all age groups, except for younger adults whose presentation time was set to 3 s to avoid ceiling effects. Because of the difference in presentation time, mean level differences between younger adults and the other age groups should be interpreted with caution. After the end of the encoding phase, participants counted backward by threes for 90 s as an interpolated activity.

At the recognition phase, 60 memory probes were presented consecutively on the computer screen. Participants were instructed to decide whether they had seen each probe at the encoding phase (old–new judgment). In the item-recognition test, half of the probes consisted of old words drawn from the study pairs (as targets), and the other half consisted of completely new words (as lures) never seen before during the experiment. Each single word, in the case of the old words, was presented in the same left–right location as during encoding, accompanied by a string of Xs (i.e., apple – XXXXX). The new words had characteristics similar to the studied words, and these were presented with equal probability in the left or right positions, also accompanied by the string of Xs. In the pair-recognition test, half of the probes were intact pairs from the encoding phase, that is, an exact replication of the pair as seen during study. Fifteen probes were rearranged pairs, composed of words taken from different study pairs at encoding (termed *rearranged pairs*), and the remaining 15 probes were totally new pairs, composed of words that never appeared at encoding (termed *new–new pairs*). Participants were informed about the two types of lures. They were instructed to indicate “old” to intact pairs and “new” to both rearranged and new–new pairs. For both the item- and pair-recognition tests, participants had up to 5 s to respond to each probe and were encouraged to optimize accuracy instead of speed. Following each old–new judgment, participants made a confidence judgment of their decision on a 3-point scale interval: 1 (*unsure*), 2 (*in-between*), 3 (*sure*). There was no time restriction, and participants were instructed to make use of the full scale. Confidence judgment results are reported in Shing, Werkle-Bergner, Li, and Lindenberger (in press). At the end of each test block, participants received a computerized feedback about their performance in terms of accuracy percentage.

To allow for closer examination of patterns of strategy use, we asked participants to report the strategy that they had used for a subset of word pairs that they had encoded. This procedure was carried out at the end of the pair-encoding and post-strategy sessions. A subset of word pairs was again presented to the participants in the exact order as during the last encoding phase.

We informed the participants about the nature of each strategy category (cf. Dunlosky & Hertzog, 1998) and instructed them to choose the strategy that they had used to encode each word pair. There was no strategy assessment at the end of the item-encoding session to avoid priming participants to utilize strategy at the following pair-encoding session.

Strategy-instruction session. In the strategy-instruction session (Session 4), participants were first introduced to the main principles of the imagery strategy, followed by concrete examples on how to apply the strategy to GG word pairs. The participants practiced the application of the strategy on word pairs and discussed the mediators (images) that they generated with the experimenter and other participants. Following group practice, participants practiced applying the strategy intensively with three word lists (of 15 pairs) individually on a computer. Throughout the group and individual practice modules, detailed feedback was provided to improve the quality of the mediators (e.g., vividness and uniqueness of image). After completing the strategy practice for the GG word pairs, participants underwent the analogous procedure for learning to apply the keyword-imagery strategy for GM word pairs.

Results

Overview of Analyses

Trials in which a response was given within 400 ms were discarded from the analyses. Test blocks with more than 20% trials with such anticipatory responses were discarded entirely (<1% of all blocks). Rates of hits (“old” response to target probes) and false alarms (FAs; “old” response to new–new or rearranged lure probes) were computed separately for each test within each condition. To correct for guessing, we computed the main outcome measure of interest, the corrected recognition score, as hit rates minus FA rates (Pr-values; Snodgrass & Corwin, 1988). Outliers were identified when the *z* scores of Pr-values exceeded a threshold of 13.291 (Tabachnik & Fidell, 2007). Across all Pr values, less than 1% of the data was treated as missing because of either an excessive amount of anticipatory responses or outlying scores.

Main analyses in this study were conducted with the Proc Mixed procedure in SAS (SAS 9.1 for Windows). This procedure accommodates mixed-model methodology for analysis of repeated measures data. Because of maximum-likelihood estimation, and unlike analysis of variance, mixed-model methodology does not treat data as missing in a listwise fashion but considers all available data points. In addition, mixed-model methodology also relaxes two main constraints. Specifically, it (a) allows for heterogeneous variance and covariance structure across age groups and (b) flexibly estimates covariance structures in order to provide valid standard errors and statistical tests for repeated measures data instead of assuming compound symmetry structure (Littell, Stroup, & Freund, 2002). Allowing for differences in variance and covariance between age groups and sessions was not of major interest in the present investigation, but mainly served the purpose of arriving at accurate estimations of fixed effects (i.e., mean differences across age groups). Given that the experimental manipulation in the study most likely led to differences in the covariance and variance of performance within and across sessions, we decided to

fit an unstructured covariance matrix to the data.² The unstructured covariance matrix is the most general unconstrained structure, with unique variances and covariances estimated for each measurement occasion.

Planned orthogonal contrasts. We were interested in the possible interactions between age groups and encoding instructions, reflecting group differences in the level of performance and extent of memory improvement induced by strategy instructions (i.e., the strategic component). In addition, we were interested in how these patterns of age differences varied between the GG and GM conditions, reflecting the effects of the two levels of associative demand. Overall, when a significant main effect or interaction effect involving the age group variable was found, we conducted as follow-up three planned orthogonal contrasts: (a) children vs. older adults; (b) teenagers vs. younger adults; (c) extremes (children and older adults) vs. middle portion (teenagers and younger adults) of life span. Contrast 1 compared the difference in episodic memory functioning due to developmental versus senescent processes. Contrast 2 tested our assumption that both components of episodic memory are mature in teenagers and younger adults. Contrast 3 examined life-span differences of episodic memory functioning.

In the following sections, results for the item-recognition test are presented first, followed by the pair-recognition tests. Two types of outcome measures were calculated to examine the performance on pair-recognition tests, namely, Pr-values with FAs based on new–new pairs and Pr-values with FAs based on rearranged pairs. The distinction between the two types of lure probes was based on the premise that the rearranged pairs elicited a higher familiarity signal than did the new–new pairs, thereby requiring higher fidelity of the recollection process to avoid committing FA responses (Jones & Jacoby, 2001; Yonelinas, 2002). Note that the hit rate was the same in the calculation of both types of Pr-value. Results were reported at a significance level of .05, and the effect size was indicated by the intraclass correlation coefficient (p_1) or Cohen's d (Fern & Monroe, 1996). Unless otherwise specified, there was no effect of order (starting with GG or GM condition), and the data were collapsed across the two orders.

Memory Accuracy on Item-Recognition Tests

Pr-values of the item-recognition tests are presented in Figure 2. The omnibus test examined the associations among age group, encoding instruction (item vs. pair vs. strategy), and associative demand (GG vs. GM). There were significant main effects of age group, $F(3, 85) = 6.58, p < .01, p_1 = .43$; encoding instruction, $F(2, 162) = 36.95, p < .01, p_1 = .56$; and associative demand, $F(1, 165) = 289.68, p < .01, p_1 = .80$. There were also significant interactions between age and encoding instruction, $F(6, 89) = 2.70, p < .05, p_1 = .39$, and between encoding instruction and associative demand, $F(2, 157) = 45.88, p < .01, p_1 = .61$. The three-way interaction, however, was not significant, $F(6, 91) = 1.65, ns$.³

As mentioned above, orthogonal contrasts were conducted to interpret the interaction involving age group and encoding instruction. The results showed that this interaction was driven by increasing performance differences between teenagers and younger adults, as compared with children and older adults, from the item-encoding instruction, $M_{\text{middle}} = 0.47$ vs. $M_{\text{extreme}} = 0.43$,

$t(148) = -1.73, ns$, to the pair-encoding instruction, $M_{\text{middle}} = 0.52$ vs. $M_{\text{extreme}} = 0.42, t(150) = -3.94, p < .01, d = 0.64$, to the post-strategy instruction, $M_{\text{middle}} = 0.61$ vs. $M_{\text{extreme}} = 0.49, t(164) = -5.24, p < .01, d = 0.82$. In other words, with increase in the involvement of the strategic component, the differences in item-recognition memory between teenagers and younger adults versus children and older adults enlarged.

To interpret the interaction between encoding instruction and associative demand, we examined performances in the GG and GM conditions separately. In the GG condition, there was a significant main effect of encoding instruction, $F(2, 159) = 70.40, p < .01, p_1 = .69$. However, in the GM condition, there was no encoding instruction effect, $F(2, 159) = 1.83, ns$. As can be seen in Figure 2, the interaction was driven by the differences in improvement between the GG and GM conditions such that participants' item-recognition performance in the GM condition improved less as a function of encoding instructions than did item-recognition performance in the GG condition (especially from pair-encoding to post-strategy sessions).

Memory Accuracy on Pair-Recognition Tests

To reduce the complexity of the analysis, we collapsed the data across participants' performance on the two post-strategy sessions (Sessions 5 and 6). There was no specific prediction regarding differences between these two sessions, except that the participants were expected to improve their performance through more practice in using the instructed strategy. This prediction was supported by significant main effects of session (Session 5 vs. Session 6) for each type of pair recognition. However, no interaction involving age group was obtained, reflecting that the extent of improvement did not differ across age groups. Therefore, collapsing the data across the two sessions should not affect the interpretation of subsequent analyses.

Participants' pair-recognition performance is presented in Figure 3. Similar to the item-recognition test, omnibus tests were conducted to examine associations among age group, encoding instruction, and associative demand. These analyses were carried

²Another type of covariance structure that suited the data structure theoretically was the first-order ante dependence model, which permits the variance and covariance among observations to change over unequally spaced measurement points (Littell, Stroup, & Freund, 2002). All analyses were also run with this type of covariance structure and no difference was found in the results.

³As pointed out by one of the reviewers, although the three-way interaction was not significant, older adults seemed to have improved from pair-encoding to post-strategy sessions for both GG and GM, whereas the other groups did not show this improvement for GM. Indeed, when GG and GM conditions was examined separately, the interaction between age group and encoding instruction was significant in the GM condition, $F(6, 87) = 3.23, p < .01$, but not in the GG condition, $F(6, 88) = 1.66, ns$. The interaction in the GM condition was driven by difference between children and older adults from pair-encoding to post-strategy session. This result suggests that for children, but not for other age groups, the use of imagery strategy to encode pair information negatively affects item recognition (see Hockley & Cristi, 1996, on item- and pair-encoding tradeoff). However, because of the relatively small effects, this finding needs to be corroborated by further empirical evidence.

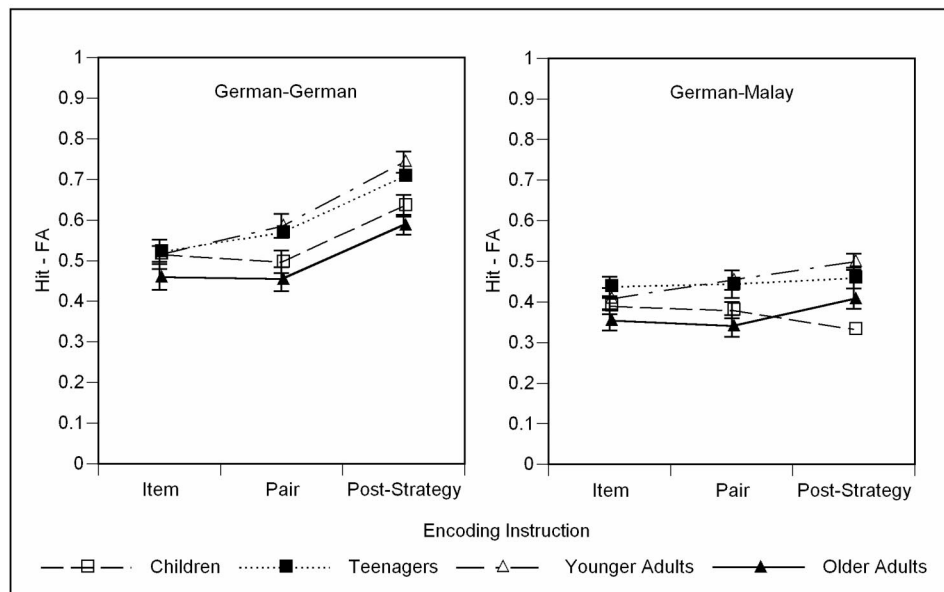


Figure 2. Mean corrected recognition (hit rate minus false alarm [FA] rate) performance for item-recognition tests as a function of age group and encoding instruction across the German–German and German–Malay conditions (Experiment 1).

out separately for Pr-values with rearranged pairs (Figure 3, top panel) and Pr-values with new–new pairs (bottom panel).

Pr-value with rearranged pairs. The omnibus test revealed significant main effects of age, $F(3, 76) = 11.38, p < .02, p_1 = .56$; encoding instruction, $F(2, 157) = 325.64, p < .01, p_1 = .90$; and associative demand, $F(1, 159) = 443.72, p < .01, p_1 = .86$. There were also significant interactions between age and encoding instruction, $F(6, 86) = 2.79, p < .05, p_1 = .40$, and between encoding instruction and associative demand, $F(2, 163) = 16.36, p < .01, p_1 = .41$, and a significant three-way interaction among the three variables, $F(6, 79) = 2.50, p < .05, p_1 = .40$. To further examine the highest order interaction, performance within GG and GM conditions was examined separately.

In the GG condition, in addition to the age and encoding instruction main effects, a significant interaction between the two variables was found, $F(6, 95) = 2.84, p < .05, p_1 = .39$,⁴ reflecting the difference among the age groups in the amount of change across the three encoding instructions. As a follow-up, we conducted the planned orthogonal contrasts. First, from item- to pair-encoding instruction, there was no significant difference in the amount of change between children and older adults, $t(81) = -0.93, ns$, or between teenagers and younger adults, $t(79) = 0.08, ns$. However, teenagers and younger adults improved more than children and older adults, $t(157) = -2.74, p < .05, d = 0.44$. Evidently, teenagers and younger adults improved their performance from item- to pair-encoding instruction to a greater extent than did children and older adults. Second, from pair-encoding to post-strategy instruction, children differed from older adults in the amount of change, $t(74) = 2.98, p < .01, d = 0.69$, reflecting that children profited more from strategy instruction. There was no other significant contrast.

In the GM condition, the pattern of results differed from that in the GG condition. There were significant main effects of age, $F(3,$

$80) = 7.45, p < .01, p_1 = .47$, and encoding instruction, $F(2, 160) = 123.46, p < .01, p_1 = .78$. However, contrary to our hypothesis, there was no significant interaction between age and encoding instruction, $F(6, 80) = 1.77, p = .12$. The age effect was driven by higher performance of teenagers and younger adults, as compared with children and older adults at all time points, $t(160) = 4.37, p < .01, d = 0.69$. The remaining planned comparisons were not significant. The effect of the encoding instruction was driven by the improvement of performance from item- to pair-encoding instruction, $t(155) = 5.41, p < .01, d = 0.87$, and from pair-encoding to post-strategy instruction, $t(162) = 9.63, p < .01, d = 1.51$. The corresponding effect sizes suggest a higher performance gain induced by strategy instruction than by pair-encoding instruction.

Pr-value with new–new pairs. We conducted the same three-way omnibus test for the Pr-value for new–new pairs. There were significant main effects of age, $F(3, 76) = 9.18, p < .01, p_1 = .52$; encoding instruction, $F(2, 164) = 123.14, p < .01, p_1 = .77$; and

⁴ For Pr values with rearranged pairs in the GG condition, there was also a significant interaction effect between encoding instruction and order, $F(2, 153) = 9.79, p < .01, p_1 = .34$. This interaction was driven by the higher performance among participants who started with GM ($M_{\text{startGM}} = 0.42$) at item-encoding instruction than among participants who started with the GG condition ($M_{\text{startGG}} = 0.25$). On the basis of informal inquiry, we speculated that the former group, who had already received the surprise pair-recognition test in the GM condition, might have anticipated the subsequent pair-recognition test in the GG condition. Therefore, these participants might have intentionally induced strategy use for the GG condition, leading to higher performance. This pattern did not differ across age groups, $F(6, 90) = 0.28, ns$. In addition, the difference between the two start orders no longer existed in the subsequent pair-encoding and post-strategy sessions.

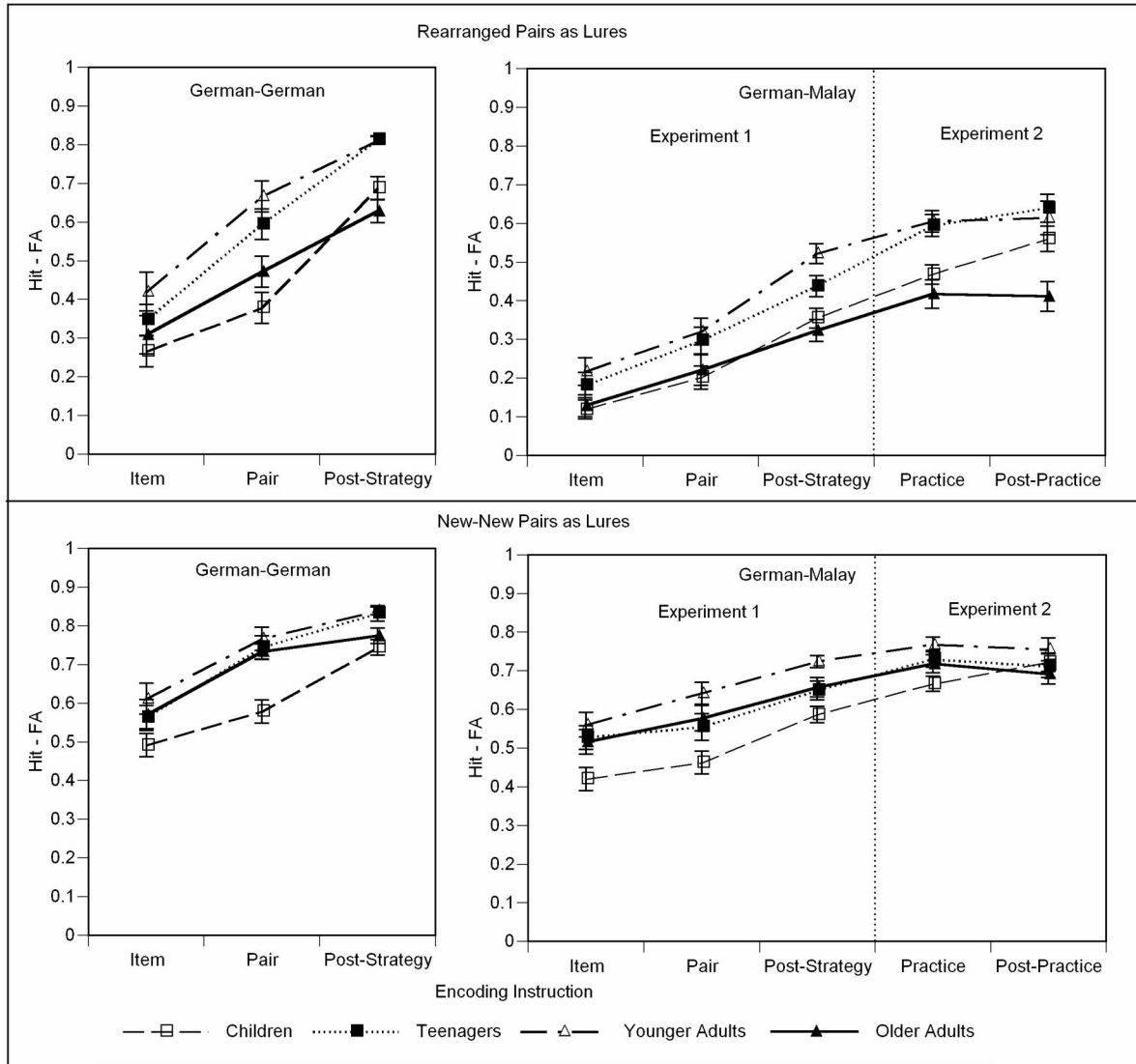


Figure 3. Mean corrected recognition (hit rate minus false alarm [FA] rate) performance for pair-recognition tests (segregated by rearranged and new–new pairs as lures) as a function of age group and encoding instruction across the German–German and German–Malay conditions (Experiments 1 and 2). Performance during practice sessions was not included in the analysis.

associative demand, $F(1, 164) = 168.86, p < .01, p_1 = .71$. There was also a significant interaction between encoding instruction and associative demand, $F(2, 154) = 13.97, p < .01, p_1 = .39$. No other interaction effect was significant.

The main effect of age was driven by older adults’ higher performance in comparison with children, $t(82) = -2.99, p < .01, d = 0.66$, and the higher performance of teenagers and younger adults in comparison with children and older adults, $t(163) = -3.65, p < .01, d = 0.80$. The interaction between encoding instruction and associative demand was mainly driven by the larger improvement of performance from item- to pair-encoding instruction in the GG than in the GM condition, $t(150) = 5.06, p < .01, d = 0.83$. In contrast, there was no difference in the GG and GM conditions for change between pair-encoding and post-

strategy instruction. Taken together, other than pre-existing mean-level differences in performance, participants of different age groups showed much greater similarity in the pattern of performance change for the Pr-values with new–new pairs than with the rearranged pairs.

Discussion

Several conclusions can be derived from Experiment 1. First, focusing on the pair-recognition performance, we observe that age-related patterns were different for the high (GM) and the low (GG) associative-demand conditions. In the GG condition, teenagers and younger adults showed highest performance levels throughout all encoding instructions and, particularly, for the Pr-

scores with rearranged pairs. Most of the improvement in performance occurred between item- and pair-encoding instruction and less so between pair-encoding and post-strategy instruction. This result suggests that participants in both groups made use of self-initiated elaborations (Craik, 1983), demonstrating the well-functioning memory systems of teenagers and younger adults.

Both children and older adults improved their performance from item-encoding to pair-encoding instruction, but to a lesser extent than did the teenagers and younger adults. In addition, at baseline, children showed the lowest performance. However, from pair-encoding to post-strategy instruction, children benefited significantly more from the strategy instruction than did the older adults, and their performance at post-strategy instruction showed trends toward reaching higher (Pr-value with rearranged pairs) or similar (Pr-value with new–new pairs) levels of performance as the older adults. Apparently, environmental support in strategy use (cf. Craik, 1983) uncovers children's latent potential in associative binding. It is also important to note that when the analyses of pair recognition reported above were conducted with item recognition as a covariate, the outcome of the statistical comparisons remained the same. Thus, the age differences found for pair recognition cannot be reduced to age differences in item recognition.

For the GM condition, we hypothesized that, as a result of the higher demand on the associative component, age-related differences (particularly between older adults and the other age groups) would be even more apparent across encoding instructions. This hypothesis was not supported, given the nonsignificant interaction between age and encoding instruction. In this context, inspection of Figure 3 (see Experiment 1) leads to several observations. First, participants' overall performance was much lower in the GM than in the GG condition. Participants' performance in the GM condition after strategy instruction was only in the range of their own performance in the item-encoding instruction of the GG condition, reflecting the difficulty of the GM condition. Second, younger adults seemed to improve their performance after strategy instruction to a greater degree than did participants in the other age groups. This is in contrast to the pattern found in the GG condition, in which younger adults' improvement in performance was self-initiated. Taken together, it appears that younger adults were able to use the instructed strategy with GM word pairs but that participants with less functional memory system (i.e., teenagers, children, and older adults) did not use the strategy or were not using it effectively. It follows that such individuals may need more practice to make good use of the strategy with GM word pairs. Hence, we conducted a follow-up study to provide individuals with further practice.

Experiment 2: Follow-Up Study

In Experiment 2, we further trained our participants on the high associative-demand GM condition. We invited all of the participants from Experiment 1 to participate in the follow-up study, which took place around 4.5 months after the completion of Experiment 1. As associative memory was the main interest of our study, participants were only tested on pair-recognition memory in the GM condition. We provided participants with five practice sessions in using the keyword-imagery strategy. In the sixth session, participants were tested on their pair-recognition memory. The performance in this session (termed *post-practice*) was com-

pared with participants' performance in the post-strategy session of Experiment 1.

Method

Participants

We successfully recruited 85.29 % of the 170 participants of Experiment 1 to participate in the follow-up experiment. The number of participants in each age group was as follows: 35 children (out of 43; 49% female; $M_{\text{age}} = 11.5$ years, $SD_{\text{age}} = 0.6$), 42 teenagers (out of 43; 47% female; $M_{\text{age}} = 14.8$ years, $SD_{\text{age}} = 0.4$), 30 younger adults (out of 42; 50% female; $M_{\text{age}} = 23.5$ years, $SD_{\text{age}} = 1.6$), and 38 older adults (out of 42; 50% female; $M_{\text{age}} = 73.5$ years, $SD_{\text{age}} = 1.7$). Many of the dropouts were younger adults, and the main reason was relocation. On average, the time gap between Experiments 1 and 2 was 18 weeks ($SD = 4.05$), with no differences in the gap among the age groups.

Material

For the five sessions of practice, encoding and test word lists were compiled from randomly drawn word pairs used in Experiment 1. Across sessions, no word pairs were recycled. For the post-practice assessment at Session 6, novel words were used to compile both the study and test lists.⁵ The characteristics of the words (e.g., length of words, number of pairs in list) remained the same as in Experiment 1.

Procedure

In the first practice session, participants received a brief instruction with practice to remind them of the keyword imagery strategy. After that, participants performed the encoding and test blocks of pair recognition as in Experiment 1. This procedure was continued in the subsequent practice sessions, but without the strategy instruction. Throughout the practice sessions, participants were encouraged to make use of the keyword imagery strategy in order to improve their performance. At the end of test blocks, participants were also prompted to discuss all aspects of their usage of the strategy, including heuristics for keyword and image generation, particular difficulties in using the strategy, and the quality of generated mediators.

In the sixth session, participants were tested with the same procedures as in Experiment 1. In addition, they were informed that performance in this session would be used as the main comparison with the post-strategy performance in Experiment 1. Participants were encouraged to perform as well as they could and were told that a small prize would be awarded to the highest performer within each age group.

Results

Selectivity Effect and Overview of Analysis

Given that there was about a 15% dropout rate between the two experiments, we examined the extent of selectivity in the final

⁵ Because of limitation in the number of word stimuli available, we could only have one assessment of performance after the practice phase.

sample of Experiment 2. Selectivity was expressed in terms of effect size estimates that were computed as the standardized difference between the final sample and the initial sample of Experiment 1 (i.e., selectivity = $[M_{\text{final}} - M_{\text{initial}}]/SD_{\text{initial}}$). Details of this procedure can be obtained in Lindenberger, Singer, and Baltes (2002). We found that the extent of selectivity was close to zero in Experiment 2, based on performance in either the item-encoding instruction (between $-.02$ and $.03$) or the post-strategy instruction ($-.03$ to $.03$) of Experiment 1. Therefore, dropouts in Experiment 2 appeared random and were unlikely to bias the results reported below.

Similar to Experiment 1, the main outcome measure of interest was the corrected recognition score (Pr-values), computed as hit rates minus FA rates, again calculated separately with rearranged and new–new pairs. Pr-values from practice (aggregated across the five practice sessions) and post-practice are illustrated in Figure 3. Practice data were not considered in the analysis because participants were exposed to the study words from Experiment 1, and their practice performance might be affected by proactive interference. To examine the extent of improvement in performance, we examined the associations between age groups and study phase (post-strategy vs. post-practice) separately for rearranged pairs and new–new pairs. The methodological details and planned contrasts remained the same as in Experiment 1.

Pr-Value With Rearranged Pairs

Omnibus tests revealed significant main effects of age, $F(3, 78) = 9.91, p < .01, p_1 = .53$, and study phase, $F(1, 120) = 71.91, p < .01, p_1 = .61$, and a significant interaction between the two variables, $F(3, 80) = 5.79, p < .01, p_1 = .42$. The interaction was followed up by the three planned contrasts. When comparing performance change from post-strategy to post-practice, we found that children improved their performance significantly more than older adults, $t(63) = 2.88, p < .05, d = 0.73$, and that teenagers improved their performance significantly more than younger adults, $t(58) = 2.46, p < .01, d = 0.66$. In terms of mean-level performance, we found that children significantly outperformed older adults at post-practice, $t(73) = 3.36, p < .01, d = 0.79$. A

post hoc contrast between children and the two middle age groups (i.e., teenager and younger adults) yielded no significant difference in performance between these age groups, $t(78) = -1.44, ns$.

Pr-Value With New–New Pairs

Omnibus tests showed significant main effects of age, $F(3, 77) = 3.28, p < .05, p_1 = .34$, and study phase, $F(1, 135) = 31.05, p < .01, p_1 = .43$, and a significant interaction between the two variables, $F(3, 77) = 3.82, p < .05, p_1 = .36$. Planned contrasts revealed that the interaction effect was driven by a significantly higher performance gain of children as compared with older adults from post-strategy to post-practice, $t(70) = 2.83, p < .05, d = 0.68$. There was no other significant contrast.

Taken together, participants' performance in recognizing GM word pairs was greatly improved after extensive practice in using the imagery strategy. This improvement was accompanied by a reorganization of age differences in the hypothesized direction. In particular, children significantly improved their performance as a function of strategy practice, whereas older adults did not, leading to a magnification of age differences in the high associative-demand condition.

Exploratory Analysis: Inspecting Hits and FA Rates Separately

We conducted a set of exploratory analyses examining the hit and FA rates of pair recognition separately as an attempt to more precisely locate age differences in memory functioning. The hit and FA rates of Experiments 1 and 2 are presented in Tables 2 and 3, respectively. The motivation for this set of analyses was based on previous research suggesting that age-related declines in memory arise from reduced efficiency in recollection, with relative preservation of familiarity-based processes (Daselaar et al., 2006; Healy et al., 2005; Jacoby & Hay, 1998; Light, Prull, La Voie, & Healy, 2000; Yonelinas, 2002). Given that the rearranged word pairs required a higher recollection effort to be correctly rejected, we expected that, in comparison with the other age groups, older adults would show especially high FA rates on the rearranged pairs

Table 2
Means and Standard Deviations of Hit Rates for Target Pairs and False-Alarm Rates for New–New and Rearranged Lure Presented in the Pair-Recognition Test of Experiment 1

Encoding instruction / group	False alarm rate								
	Hit rate			New–new pairs			Rearranged pairs		
	Item <i>M (SD)</i>	Pair <i>M (SD)</i>	Post-strategy <i>M (SD)</i>	Item <i>M (SD)</i>	Pair <i>M (SD)</i>	Post-strategy <i>M (SD)</i>	Item <i>M (SD)</i>	Pair <i>M (SD)</i>	Post-strategy <i>M (SD)</i>
German–German									
Children	.61 (.16)	.69 (.13)	.81 (.11)	.11 (.11)	.11 (.10)	.06 (.06)	.34 (.15)	.31 (.18)	.12 (.08)
Teenagers	.67 (.18)	.81 (.15)	.87 (.09)	.11 (.11)	.06 (.06)	.05 (.04)	.32 (.19)	.21 (.16)	.07 (.05)
Younger adults	.73 (.19)	.82 (.20)	.88 (.06)	.12 (.12)	.06 (.06)	.04 (.01)	.31 (.18)	.16 (.17)	.06 (.04)
Older adults	.71 (.19)	.81 (.14)	.84 (.11)	.14 (.13)	.08 (.08)	.06 (.08)	.40 (.24)	.34 (.23)	.21 (.16)
German–Malay									
Children	.59 (.15)	.60 (.16)	.68 (.12)	.17 (.14)	.14 (.11)	.09 (.07)	.47 (.17)	.40 (.16)	.32 (.13)
Teenagers	.67 (.14)	.68 (.17)	.73 (.12)	.14 (.11)	.12 (.12)	.08 (.08)	.48 (.15)	.38 (.15)	.29 (.12)
Younger adults	.71 (.14)	.77 (.14)	.79 (.08)	.15 (.12)	.13 (.10)	.07 (.04)	.49 (.18)	.45 (.18)	.27 (.12)
Older adults	.73 (.18)	.76 (.16)	.80 (.10)	.22 (.18)	.19 (.16)	.14 (.13)	.61 (.17)	.55 (.22)	.48 (.17)

Table 3
Means and Standard Deviations of Hit Rates for Target Pairs and False-Alarm Rates For New–New and Rearranged Lure Pairs of Experiment 2 (Post-Practice Session Only)

Group	Hit rate <i>M</i> (<i>SD</i>)	False-alarm rates	
		New–new pairs <i>M</i> (<i>SD</i>)	Rearranged pairs <i>M</i> (<i>SD</i>)
Children	.77 (.14)	.07 (.06)	.24 (.13)
Teenagers	.80 (.14)	.08 (.09)	.17 (.16)
Younger adults	.82 (.10)	.07 (.10)	.21 (.18)
Older adults	.82 (.09)	.13 (.12)	.41 (.20)

but not on the new–new pairs (Castel & Craik, 2003). At the same time, the development of familiarity is found to be earlier than recollection across childhood (e.g., Ghetti & Angelini, in press; Ghetti, Qin, & Goodman, 2002). Given that a direct comparison between children and older adults is lacking, it was of interest to explore how children's hit and FA rates would compare with those of the other three age groups, especially the older adults.

As can be seen in Table 2, older adults exhibited the highest level of FA rates on the rearranged pairs in both the GG and GM conditions. This pattern remained even after strategy instruction. For illustration, we focused on performance at the post-strategy session (GG and GM conditions) and the post-practice session (GM condition only). We examined the effects of age group and response type (hits, FAs on new–new pairs, and FAs on rearranged pairs) separately for the GG and GM conditions. Significant effects ($p < .01$ as more stringent criteria) were followed up by pairwise comparisons corrected by Bonferroni adjustments ($p_{\text{critical}} = .002$).

GG condition. There were significant main effects of age, $F(3, 60) = 5.75, p < .01, p_1 = .47$, and response type, $F(2, 102) = 3,541.24, p < .01, p_1 = .99$, and a significant interaction between the two variables, $F(6, 77) = 9.12, p < .01, p_1 = .64$. Each response type was followed up by pairwise comparisons. For hit responses, we found a significant difference between children and younger adults such that children showed lower hit rates than did younger adults, $t(66) = -3.55, p < .002, d = 0.87$. The other pairwise comparisons for hit responses were not statistically significant. For FAs on new–new pairs, there was no significant pairwise difference. For FAs on rearranged pairs, pairwise comparisons revealed that older adults showed significantly higher FA rates than children, $t(61) = -3.27, p < .002, d = 0.84$; teenagers, $t(49) = -5.34, p < .002, d = 1.53$; and younger adults, $t(45) = -5.69, p < .002, d = 1.70$. Children also showed significantly higher FA rates than teenagers, $t(69) = 3.28, p < .002, d = 0.79$, and younger adults, $t(57) = 3.96, p < .002, d = 1.05$. As expected, older adults showed more FAs than the other age groups, especially for rearranged pairs. Children's FA rates on rearranged pairs were higher than the rates of teenagers and younger adults but lower than the rates of older adults.

GM condition. There were significant main effects of age, $F(3, 70) = 13.74, p < .01, p_1 = .61$, and response type, $F(2, 156) = 1,934.40, p < .01, p_1 = .98$, and a significant interaction between the two variables, $F(6, 84) = 9.29, p < .01, p_1 = .63$. Similar to the GG condition, each response type was followed up by pairwise

comparisons. In terms of hit responses, children were found to be significantly lower than younger adults, $t(75) = -5.07, p < .002, d = 1.17$, and older adults, $t(80) = -5.13, p < .002, d = 1.15$. No other comparison was significant. For FAs on new–new pairs, the only significant comparison was that older adults showed significantly higher FA rates than younger adults, $t(48) = -3.71, p < .002, d = 1.07$. In terms of FAs on rearranged pairs, older adults showed significantly higher FA rates than children, $t(77) = -4.66, p < .002, d = 1.06$; teenagers, $t(72) = -5.70, p < .002, d = 1.34$; and younger adults, $t(75) = -6.34, p < .002, d = 1.47$. Comparison among children, teenagers, and younger adults did not yield any reliable differences.

To examine whether the pattern of high FA rates in older adults could be reduced through extensive practice, we also examined the hit and FA rates at the post-practice session of Experiment 2 (see Table 3). There were again significant main effects of age, $F(3, 60) = 11.56, p < .01, p_1 = .61$, and response type, $F(2, 134) = 1,712.17, p < .01, p_1 = .98$, as well as a significant interaction between the two variables, $F(6, 64) = 6.48, p < .01, p_1 = .61$. Follow-up pairwise comparisons showed no age differences in hits and FAs for new–new pairs. However, older adults persistently showed significantly higher FA rates for rearranged pairs than children, $t(65) = -4.41, p < .002, d = 1.10$; teenagers, $t(73) = -5.76, p < .002, d = 1.35$; and younger adults, $t(65) = -4.36, p < .002, d = 1.09$.

Discussion

Experiment 2 was conducted as a direct follow-up of Experiment 1 to examine whether it was possible to induce further improvements in participants' performance as a function of extensive practice and, more importantly, whether the pattern of age differences for GM pairs would emerge according to the prediction. Generally, these expectations were borne out. First, comparing performance from post-strategy (Experiment 1) to post-practice (Experiment 2), we found that children and teenagers benefited significantly more from practicing the use of the strategy than did younger and older adults. It is also noteworthy that the performance of children and teenagers converged to similar levels at post-practice. By contrast, older adults' performance did not improve much from further practice in the strategy. These findings support the general prediction that children and teenagers possess a readily functional associative component that can be put to work after being provided with an effective strategic tool, whereas older adults could not improve further in performance, because of declines in associative binding abilities.

Second, and again in line with our general expectations, inspecting the hits and FAs from both experiments revealed older adults' excessive difficulties in rejecting rearranged pairs, which presumably elicited a strong familiarity response (see also Castel & Craik, 2003). Given that older adults did not show similarly high FA rates for new–new pairs, this finding cannot be attributed to a generally more liberal decision criterion among older adults. A comparison of effect sizes suggests that age differences on the FA rates of rearranged pairs were especially pronounced in the GM condition, further supporting our hypothesis that older adults showed a disproportionately large associative deficit in the GM condition (i.e., under high associative demands). It is striking to note that high FA rates in older adults neither disappeared nor diminished after

extensive practice. On the basis of the neurocomputational theory by Li and colleagues (Li, Lindenberger, & Sikström, 2001; Li, Naveh-Benjamin, & Lindenberger, 2005) and the aging hippocampus model by Wilson, Gallagher, Eichenbaum, and Tanila (2006), we suggest that the excessively high FA rates in older adults are a behavioral manifestation of memory representations that lack distinctiveness as a result of senescent declines in neuromodulation and in functional connectivity between the entorhinal cortex, hippocampus, and PFC. We elaborate on this interpretation below.

General Discussion

The present study investigated age-related differences in episodic memory performance in a life-span sample. On the basis of available behavioral and recent neurocognitive evidence, the main hypotheses of the study encompassed dissociations between the life-span age gradients of the associative and strategic components of episodic memory. Specifically, we expected the development of the associative component to precede the development of the strategic component in children and teenagers. Thus, children's episodic memory would be supported by a functioning associative component, even though the strategic component may not yet be fully developed. In contrast, we hypothesized that both components undergo decline in late adulthood. Taken together, the results from Experiments 1 and 2 support these hypotheses.

Summary of Main Findings

Differential patterns of performance gains shed light on differences in mechanisms operating among the four age groups. On the one hand, in comparison with children, older adults showed slightly higher initial performance in item- and pair-instruction sessions. This may have reflected older adults' larger repertoire of semantic knowledge acquired through life experience. On the other hand, children showed their highest performance gains from strategy instruction for the GG condition and also from practice for the GM condition. We conclude that children improve more than older adults in forming associations between memory items when provided with a combination of an experimenter-provided strategy tool and task-relevant practice, demonstrating their formerly latent potential for associative binding. This interpretation is in line with the hypothesis that the associative component of episodic memory matures earlier than the strategic component in childhood, both at the behavioral level (e.g., Cowan et al., 2006; Sluzenski et al., 2006) and at the neural level (Gogtay et al., 2004; Ofen et al., 2007; Sowell et al., 2003). Older adults, in contrast, did not benefit as much from instruction and practice in the mnemonic strategy as the children. Their performance gain was especially small in the associatively demanding GM condition, supporting the hypothesis that older adults' episodic memory is impaired by an additional deficit in associative binding. Taken together, older adults' deficiency in episodic memory is brought about by decreased efficiency of the associative component in addition to reduced support through elaborative and control processes linked to the strategic component. In agreement with this interpretation, the associative deficit of older adults has been found to be less pronounced under conditions that require less effortful binding and self-initiated strategic processing, such as in cases in which features of the memory episodes are relatively easy to associate during encoding

(e.g., semantically related word pairs; Castel & Craik, 2003; Naveh-Benjamin, Hussain, et al., 2003).

Teenagers and younger adults required less environmental support to improve their memory performance than did children and older adults. In the GG condition, teenagers and younger adults improved their performance substantially simply by being instructed to encode the words together as pairs. Differential patterns of change between teenagers and younger adults were observed in the GM condition: Younger adults showed performance improvements mainly after strategy instruction, whereas teenagers showed improvements only after extensive practice. This might have been due to the high difficulty of the GM condition such that even younger adults were unable to come up with an efficient strategy on their own. However, when provided with a strategy, younger adults seemed able to immediately apply it as an aid for memory encoding. Teenagers, on the other hand, needed more extensive practice in putting the strategy to use. The close similarity in performance change between teenagers and younger adults in the GG condition partly supported the hypothesis that the strategic component is relatively mature in adolescence, corresponding to the burst in PFC development after puberty (Gogtay et al., 2004). At the same time, the difference between teenagers and younger adults under the more challenging GM condition support the claim that the strategic component continues to undergo protracted development until adulthood.

Contribution to the Literature

The present study makes a novel contribution by advancing the distinction between associative and strategic components as mechanistic explanations for life-span differences in episodic memory (see also Brehmer et al., 2007; Moscovitch, 1992; Werkle-Bergner et al., 2006). Our findings of divergent life-span age gradients for these two episodic memory components at the behavioral level lend further support to cognitive neuroscience findings, suggesting separate but interactive functional circuitries for these two components. Specifically, the late emergence of the strategic component in children parallels the late maturation of PFC in similar ways as older adults' disproportionate deficits in strategic aspects of episodic memory functioning parallel the relatively early deterioration of certain areas of PFC during adulthood. (Werkle-Bergner et al., 2006). However, the associative component of episodic memory supported by MTL brain circuitry may be relatively functional in middle childhood but impaired in older adults, with the latter paralleling senescent changes in hippocampus and entorhinal cortex (Raz et al., 2007; Wilson et al., 2006). The life-span dissociation between the two components offers a plausible explanatory framework that can guide future work attempting to identify specific mechanisms of life-span changes in episodic memory at behavioral and neural levels of analysis.

A noteworthy finding from this study is the excessively high rates of FA errors committed by older adults in response to rearranged lure pairs. Although older adults showed overall improved level of performance after strategy instruction and practice, this characteristic pattern of high FA rates did not disappear throughout both experiments. Apparently, older adults' deficit in associative binding is not easily overcome by strategy instruction and extensive practice focusing only on encoding (see also Naveh-Benjamin et al., 2007). Older adults' robust difficulties in rejecting

rearranged pairs as lure are consistent with the proposition that older adults rely more on familiarity signals in memory retrieval and show a reduced ability to recollect specific features about past events (Daselaar et al., 2006; Healy et al., 2005; Jacoby & Hay, 1998). According to the neurocomputational theory proposed by Li and colleagues (Li & Lindenberger, 1999; Li et al., 2001, 2005; Li, von Oertzen, & Lindenberger, 2006), decrements in the distinctiveness of representations due to deficient neuromodulation contribute to older adults' difficulties at all stages of learning and memory, such as initial learning, consolidation, and retrieval from memory (cf. Craik, 1983, 2006). In line with ample empirical evidence, the theory postulates that deficient neuromodulation leads to noisier neural activity. Consequently, the task of accurately binding together experienced memory events during encoding becomes harder and results in less distinctive associative representations. At retrieval, this leads to difficulties in discriminating between actually encoded associations and lures, as also postulated by the aging hippocampal model (Wilson et al., 2006). Furthermore, simulation results indicate that suboptimal neuromodulation lead not only to less distinctive, but also to more highly activated, patterns of neural activity (e.g., Li et al., 2005). If more highly active memory representations, erroneously triggered by presented lures, result in a greater sense of assuredness, then deficient neuromodulation may also help explain older adults' tendency to commit commission errors with high confidence, as emerging evidence suggests (e.g., Dodson, Bawa & Krueger, 2007; Shing et al., in press).

In addition, aging may affect the strategic component of episodic memory by senescent changes in the structure and connectivity of the PFC (see reviews in Buckner, 2004; Hedden & Gabrieli, 2004). Prefrontally mediated strategic processes during memory encoding storage and retrieval are thought to enhance the signal-to-noise ratio and to bias memory search in task-relevant ways (Miller & Cohen, 2001; Rugg & Wilding, 2000; Simons & Spiers, 2003). It is likely that the rejection of rearranged pairs places particularly high demands on controlled processing during retrieval to overcome familiarity triggered response tendencies.

In sum, we suggest that older adults' excessively high FA rates are the most salient symptoms of a general decline in associative learning and memory that reflects the combined outcome of less distinct memory representations and less efficient prefrontally triggered biasing signals. Future work needs to address the relative contributions of, and interactions among, various neurochemical and neuroanatomical changes in different brain areas as they affect this decline. Additionally, research should assess the malleability of this decline through cognitive intervention.

Limitations of the Study and Future Directions

Despite the distinction between associative and strategic components of episodic memory, the two components are functionally related during memory encoding, storage, and retrieval. This intrinsic functional interdependence poses conceptual and methodological challenges. Conceptually, levels of processing may differ between the GG and GM conditions, assuming that greater associative demand may elicit or require deeper processing (Craik & Lockhart, 1972). However, in this case, the levels-of-processing approach and the current framework lead to identical predictions because older adults tend to encode incoming stimuli in more

shallow and general ways, which can be considered a failure of binding processes (see Craik, 2006). In terms of neural correlates, it is probably overly simplistic to assume that age-related structural changes in PFC and MTL map onto functional changes in strategic and associative components in a mutually exclusive fashion. In particular, the connectivity between hippocampus and PFC undergoes substantial changes during child development (e.g., Menon, Boyett-Anderson, & Reiss, 2005) and aging (e.g., Grady, McIntosh, & Craik, 2003; Mitchell, Johnson, Raye, & D'Esposito, 2000). These age-dependent alterations in functional connectivity between hippocampus and PFC may have important implications for the development of the associative and strategic components, which remain to be uncovered.

Methodologically, we must acknowledge that the application of the memory strategy may have been more difficult in the GM condition. Older adults may have difficulties in applying imagery strategies, and these difficulties may have been more pronounced in the GM condition, providing an alternative explanation for the persisting difficulties of older adults in the GM conditions. We offer two counterarguments against this explanation. First, a large number of age-comparative training studies have shown that older adults can be trained to utilize imagery strategies (Baltes & Lindenberger, 1988; Verhaeghen et al., 1992). Likewise, Dunlosky and Hertzog (1998) found that older and younger adults reported using effective mediators, imagery included, to a similar degree. Second, on the basis of the self-report measure of strategy use, we found that after strategy instruction, participants in all age groups reported a high percentage use of transformation and imagery generation in the GG condition, with means ranging from 91% to 94%. For the GM condition, all age groups reported reduced use of effective strategies, with older adults actually reporting the highest percentage of use (71%) in comparison with the other age groups (ranging from 63% to 68%).

During the practice phase in Experiment 2, participants of all age groups increased their use of transformation and imagery strategy, with increases ranging from 73% to 79%. Thus, participants in all age groups were equally likely to produce imagery mediators. Also, the performance of children and older adults showed improvements across the practice sessions. Their performance diverged at the post-practice session, in which older adults reported using imagery strategy similar to their usual level (72%), but children reported increased use (82%). We are not certain whether this difference purely reflected a sudden burst in the use of the strategy in children or whether motivational components induced by the final session of the experiment might have played a role in boosting children's performance.

Although the present study mainly focused on manipulations on the encoding side, it is important to note that there are age-related differences in retrieval operations (Anderson, Craik, & Naveh-Benjamin, 1998; Brainerd & Reyna, 2004; Ghetti & Angelini, in press; Yonelinas, 2002). For example, a recent study by Naveh-Benjamin et al. (2007) showed that instructions to use appropriate associative strategies during both encoding and retrieval results in a decrease of the associative deficit among older adults to a greater extent than during encoding alone (see also training that focuses on retrieval; Bissig & Lustig, 2007; Dodson & Schacter, 2002; Jennings & Jacoby, 2003). Given that aging has greater effects on recollection than on familiarity (e.g., Healy et al., 2005; Jacoby & Hay, 1998), future studies should further examine the interaction

between encoding and retrieval operations in affecting memory outcomes and the age differences therein.

Conclusion

In this article, we introduced a two-component model for the study of episodic memory across the life span. We distinguished between the *strategic* component, which refers to the elaboration and organization of episodic features, and the *associative* component, which refers to mechanisms of binding. In two experiments, we found that associative and strategic components evolve differently from childhood to old age (see also Brehmer et al., 2007, in press; Werkle-Bergner et al., 2006). Children's difficulties in episodic memory were primarily due to lower levels of strategic functioning. In contrast, older adults' deficits in episodic memory not only reflected lower levels of strategic functioning but also an additional deficit in the associative component. Furthermore, older adults, but not children, were especially likely to erroneously recognize rearranged lure pairs, presumably reflecting difficulties in rejecting familiarity signals as a result of less efficient cognitive control processes. Future investigations of life-span changes in episodic memory are recommended to test the generality of the model and to identify relevant mechanisms at behavioral and neural levels of analysis.

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Received October 2, 2007

Revision received March 12, 2008

Accepted March 14, 2008 ■

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