THE PSYCHOLOGY OF LEARNING AND MOTIVATION

Advances in Research and Theory

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URBANA, ILLINOIS

Volume 43

ACADEMIC PRESS
An imprint of Elsevier Science
Amsterdam Boston Heidelberg London New York Oxford
Paris San Diego San Francisco Singapore Sydney Tokyo

Tarmizi, R., & Sweller, J. (1988). Guidance during mathematical problem solving. *Journal of Educational Psychology, 80*, 424–436.

Tindall-Ford, S., Chandler, P., & Sweller, J. (1997). When two sensory modes are better than one. *Journal of Experimental Psychology: Applied, 3*, 257–287.

Trafton, J. G., & Reiser, B. J. (1993). The contribution of studying examples and solving problems to skill acquisition. *Proceedings of the 15th Annual Conference of the Cognitive Science Society* (pp. 1017–1022). Hillsdale, NJ: Erlbaum.

Tuovinen, J., & Sweller, J. (1999). A comparison of cognitive load associated with discovery learning and worked examples. *Journal of Educational Psychology, 91*, 334–341.

Van Merrienboer, J. (1990). Strategies for programming instruction in high school: Program completion vs. program generation. *Journal of Educational Computing Research, 6*, 265–287.

Van Merrienboer, J., & de Croock, M. (1992). Strategies for computer-based programming instruction: Program completion vs. program generation. *Journal of Educational Computing Research, 8*, 365–394.

Van Merrienboer, J., & Krammer, H. (1987). Instructional strategies and tactics for the design of introductory computer programming courses in high school. *Instructional Science, 16*, 251–285.

Van Merrienboer, J., Schuurman, J., de Croock, M., & Paas, F. (2002). Redirecting learner's attention during training: Effects on cognitive load, transfer test performance and training efficiency. *Learning and Instruction, 12*, 11–37.

Vollmeyer, R., Burns, B., & Holyoak, K. (1996). The impact of goal specificity on strategy use and the acquisition of problem structure. *Cognitive Science, 20*, 75–100.

Ward, M., & Sweller, J. (1990). Structuring effective worked examples. *Cognition and Instruction, 7*, 1–39.

Yeung, A., Jin, P., & Sweller, J. (1998). Cognitive load and learner expertise: Split-attention and redundancy effects in reading with explanatory notes. *Contemporary Educational Psychology, 23*, 1–21.

COGNITIVE PLASTICITY AND AGING

Arthur F. Kramer and Sherry L. Willis

I. Overview

Aging is associated with a decline in a multitude of cognitive processes and brain functions. However, a growing body of literature, which is reviewed in this chapter, suggests that age-related decline in cognition can sometimes be reduced through experience, cognitive training, and other interventions, such as fitness training. Research on training and expertise has suggested that age-related cognitive sparing is often quite narrow, only being observed on tasks and skills similar to those on which individuals have been trained. Furthermore, training and expertise benefits are often only realized after extensive deliberate practice with specific training strategies. Like cognitive training, fitness training effects on the cognitive processes of older adults are relatively narrow rather than broad, with the most substantial effects being observed for executive control processes.

II. Cognition across the Adult Life Span

One of the most ubiquitous findings in research on cognition and aging is the observation of increasing decline in a wide variety of cognitive abilities across the life span. Declines in cognitive function over the adult life span have been found in both cross-sectional and longitudinal studies across a variety of tasks, abilities, and processes, including measures of perception,

THE PSYCHOLOGY OF LEARNING
AND MOTIVATION VOL. 43

0079-7421/03 $35.00

memory, abstract reasoning, and spatial orientation with the earliest and most pervasive decline occurring in speed of processing. Cross-sectional studies, which compare the performance of one age group to that of another age group (e.g., 20-to 30-year olds and 60-to 70-year olds) have, for the most part, found linear age differences in measures of a number of aspects of cognition over the adult life span (Park et al., 2001; Park, Lautenschlarger, Hedden, Davidson, Smith, & Smith, 2003).

Longitudinal studies, which range in length from a few years to over 40 years, have tended to find that abilities vary in the rate and onset of decline with accelerated decline in the late seventies and eighties (Schaie, 2000; Hultsch, Hertzog, Dixon, & Small, 1998; Zelinski & Burnight, 1997; Schaie & Hofer, 2001). The ability exhibiting the most linear pattern of decline across the entire adult life span is perceptual speed with decline beginning in young adulthood and continuing into old age. Almost two standard deviations of negative change in perceptual speed has been observed across the adult life span (Schaie, 2000). While the layperson views memory as one of the first abilities to show decline, trajectories of change vary across the types of memory. Hultsch and colleagues (1998) found significant decline in word recall, a form of episodic memory, but little decline in text recall, another form of episodic memory. Hultsch hypothesized that maintenance of text recall ability may be due to its strong association with verbal ability. The stability of verbal skills may contribute to the maintenance of text recall. Zelinski and Burnight (1997) observed decline in text recall when studied over much longer intervals. Implicit memory showed no decline as has been documented in prior research. Finally, fact recall, which is said to represent semantic memory, did show an age-related decline, whereas prior cross-sectional research had shown no age differences.

Given the discussion of executive function in later parts of the chapter, findings of age-related change in cognitive flexibility, which is closely related to selective aspects of executive control, are of interest (Schaie, 2000). Psychomotor speed flexibility exhibits a trajectory of modest increment until the early sixties and then declines approximately one standard deviation by the late eighties. In contrast, motor cognitive flexibility is relatively stable across the adult life course.

One of the most striking findings from longitudinal studies is the vast individual differences in the timing and pattern of decline (Schaie, 2000). For example, Hultsch and colleagues (1998) reported strong evidence of wide individual differences in the rate of cognitive change. Individuals were becoming less alike as they aged as a function of individual differences in change. Thus, mean or average change may present a different picture of aging than that observed when individual patterns of change are examined.

Although a number of factors may be responsible for the different performance trajectories obtained in cross-sectional and longitudinal studies (e.g., differential attrition, cohort effects in cross-sectional studies, practice effects, and study length in longitudinal studies), the important common observation is a reduction in cognitive efficiency with age beginning in young adulthood for processing speed and in late middle age and old age for more complex abilities.

Interestingly, although age-related cognitive decline is quite broad, there are some notable exceptions. It has generally been observed that knowledge-based or crystallized abilities (i.e., the extent to which a person has absorbed the content of culture), such as verbal knowledge and comprehension, continue to be maintained or improve over the life span. This is in contrast to process-based or fluid abilities (i.e., reasoning, speed, and other basic abilities not dependent on experience), which display earlier age-related declines.

A. Common Cause Explanations

An important current issue concerns the source(s) of age-related declines in process-based abilities. A large number of mostly cross-sectional studies and some longitudinal studies (Baltes & Lindenberger, 1997) have found that age-related influences on different perceptual, cognitive, and motor skills are highly related, prompting the suggestion that a common factor may be responsible for age-related declines (Salthouse, 1996). Two approaches to a common cause explanation of age-related change in cognition have been discussed in the literature. Salthouse (1996) and others have espoused a resource-based processing model suggesting that reduced processing resources explain age-related decline in cognition. Several variations of the processing model have been proposed focusing on speed of processing, working memory, inhibition, or sensory function as the key resource variable (Park, 2000). Salthouse (1996) hypothesized two important mechanisms responsible for the salience of speed as a processing resource. First, the time to perform later operations is hypothesized to be restricted greatly when a large proportion of the available time is occupied by the execution of earlier operations. Second, products of earlier processing may be lost by the time that later processing is completed. Hence, the role of speed increases in importance the more complex the task.

Working memory has been conceptualized as the amount of on-line cognitive resources available at any given moment to process information and can involve storage, retrieval, and transformation of information (Craik & Byrd, 1982). Of interest in the study of working memory as a processing resource is the finding that demands on working memory can sometimes be reduced significantly by providing environmental support in memory tasks to the elderly (Park, 2000).

A third processing resource is inhibition defined as an increase in difficulty in focusing on target information and inhibiting attention to irrelevant material (Hasher & Zacks, 1988). Inhibition effects are most pronounced when the individual has to inhibit a prepotent response and it is in these situations where older adults are most likely to show evidence for poor inhibition.

Finally, support for sensory deficits as processing resources comes from the Berlin Aging Study (Linderberger & Baltes, 1994, 1997). Most of the age-related variance in a wide variety of cognitive tests was mediated by sensory functioning as measured by simple tests of visual and auditory acuity. Sensory measures were considered to be a more fundamental index of cognitive resource than even speed of processing. Sensory measures mediated most of the variance in speed of processing, but the reverse was not true. The Berlin group has argued that sensory function is a crude measure of brain integrity.

Alternatively, Baltes and colleagues (1994) have argued that age changes in general central nervous system integrity represent a "common cause of declines in information processing capacity." Rabbitt (1993) aptly phrased the question "Does it all go together when it goes?" According to this hypothesis, processing speed and working memory share this common influence, but do not cause it.

B. Beyond a Common Cause

Contrary to the general decline proposals, a growing body of literature has pointed out a number of situations in which age-related effects remain after having been controlled statistically or methodologically for a general age-related factor (Hultsch et al., 1998; Verhaeghen, Kliegl, & Mayr, 1997). Such data suggest that a variety of different mechanisms may be responsible for age-related declines in information processing and that these mechanisms may be differentially sensitive to age. In examining longitudinal change in various memory functions, Hultsch and colleagues (1998) tested the resource and the global cognitive change models to account for age-related change in various forms of memory. Neither the resource nor the global cognitive change model consistently accounted for change in all aspects of memory. The global change model accounted for a significant amount of variance in change in the memory dimensions of fact recall, working memory, and comprehension speed. However, the global change model did not account for a variance in change associated with verbal fluency, reading comprehension, or semantic speed. Hultsch reported considerable support for working memory as a processing resource that accounted for change in memory. However, neither working memory nor speed as two of the most popular resources could account for all of the variance in changes in word recall. Indeed, a subset of the competing models of general decline may, in future research, be found to account for specific age-related cognitive deficits.

In a similar vein, Kramer, Humphrey, Larish, Logan, and Strayer (1994) examined the general inhibitory account of aging (Hasher & Zacks, 1988) and found, contrary to the predictions of the model, that age-related changes in a variety of different inhibitory processes were specific rather than general in nature. Verhaeghen et al. (1997) found age equivalence in sequential numeric operations while observing age sustantial and disproportionate age differences in coordinative operations (i.e., holding some products in mind while carrying out additional computations). Such data are inconsistent with a general slowing account of aging.

III. Changes in Brain Function and Structure across the Adult Life Span

Findings obtained in the study of cognitive aging are mirrored, in a number of ways, by research on brain aging (for an in-depth review of this literature, see Albert & Killiany, 2001; Raz, 2000; Vinters, 2001). For example, a body of research has documented nonspecific or global changes in brain volume across the adult life span. In most cases, these studies, which have employed computerized tomography (CT) or magnetic resonance imaging (MRI) scanning techniques, have been cross-sectional in nature and have found decreases in gray and white matter and increases in the size of ventricles across the adult life span (Coffey, Wilkinson, Parashos, Soady, Sullivan, Paterson, Figiel, Webb, Spritzer, & Djang, 1992; Pfefferbaum, Mathalon, Sullivan, Rawles, Zipursky, & Kim, 1994; Murphy, DeCarli, MvIntosh, Daly, Mentis, Pietrini, Szczepanik, Schapiro, Grady, Horwitz, & Rapport 1996). Similar findings have been obtained in relatively short-term longitudinal studies of morphological changes in brain structure (Davatzikos & Resnick, 2002; Resnick, Goldszal, Davatzikos, Golski, Kraut, Metter, Bryan, & Zonderman, 2000; Shear, Sullivan, Mathalon, Lim, Davis, Yesavage, Tinklenberg, & Pfefferbaum, 1995).

Gray matter changes were originally thought to be the result of neuron loss. However, more recent studies, which have employed unbiased stereological techniques to enumerate neurons, suggest instead that large neurons appear to shrink in normal aging. Few neurons appear to be lost in cortical regions (Morrison & Hof, 1997; Terry, DeTeresa, & Hansen, 1987).

White matter changes appear largely to be the result in changes in the myelinization of axons.

There have been a number of reports of significant statistical relationships between global age-related differences in cortical morphology and measures of cognitive function. For example, Albert, Duffy, and Naeser (1987) reported that increases in global brain atrophy resulted in decreases in performance on a battery of neuropsychological tests. More recently, MacLullich, Ferguson, Deary, Seckl, Starr, and Wardlaw (2002) reported a significant relationship between MRI-based measures of brain volume and a general cognitive factor composed of memory, attention, and decision-making tests.

A. Age-Related Changes in Brain Structure and Function Are Not Uniform

Similar to the cognitive literature, studies have also found regional differences in the time course and magnitude of age-related differences and changes in brain structure and function. Correlations between age and cortical volume have been reported to be largest for prefrontal regions, somewhat smaller for temporal and parietal areas, and small and often nonsignificant for sensory and motor cortices (Head, Raz, Gunning-Dixon, Williamson, & Acker, 2002; Raz, 2000). In general, the disproportionate changes in brain structure across the adult life span parallel findings of age-specific changes in executive control and a subset of memory processes, which are supported in large part by prefrontal and temporal regions of the brain (Robbins, James, Owen, Shaakian, Lawrence, McInnes, & Rabbitt, 1998; Schretlen, Pearlson, Anthony, Aylward, Augustine, Davis, & Barta, 2000).

Indeed, a number of theories of cognitive and brain aging are based on the specificity of age-related changes. For example, West (1996) proposed a detailed model of the relationship between the age-related decline in the structure and function of the prefrontal regions of the brain and different aspects of executive control (e.g., interference control and inhibition, working memory, multitasking, prospective memory). More recently, Braver, Barch, Keys, Carter, Cohen, Kaye, Jahowsky, Taylor, Yesavage, Mumenthaler, Jagust, and Reed (2001) suggested that a variety of aspects of executive control decline as a result of age-related deficits in the function of the dopamine system in the prefrontal cortex. Thus, these models and others have attempted to integrate research on changes in the structure and function of the aging brain with the observation of disproportionate declines in a subset of cognitive processes, namely those that subserve aspects of executive control and memory.

B. Neuroimaging Studies of Functional Brain Aging

Human neuroimaging studies, employing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), have provided a number of insights into age-related differences and changes in brain function (for in-depth reviews of this literature, see Cabeza, 2000; Park, 2003). Both of these techniques involve inferring changes in neuronal activity from changes in blood flow or metabolic activity in the brain (Reiman, Lane, Van Petten, & Bandetinni, 2000). In PET, cerebral blood flow and metabolic activity are measured on the basis of clearance of radionuclides from cortical tissues. These radionuclides, which are either inhaled or injected, decay by the emission of positrons that combine with electrons to produce gamma rays, which are detected by a series of sensors placed around the head. Each PET image, which is acquired over an interval of anywhere from 1 to 45 minutes depending on the nature of the radionuclide employed in a study, represents all of the brain activity during the integration period. These PET images are then coregistered with structural scans, often obtained from MRIs, to indicate the location of the functional activity. fMRI is similar to PET in that it provides a map of functional activity of the brain. However, fMRI activity can be obtained more quickly (within a few seconds), does not depend on the inhalation or injection of radioactive isotopes, and can be collected in the same system as the structural information. The blood oxygen level-dependent technique (BOLD) of fMRI uses the perturbation of local magnetic fields due to changes in the oxygen content of blood during increased blood flow to image functional brain activity (Belliveau, Kennedy, McKinstry, Buchbinder, Weisskoff, Cohen, Vevea, Brady, & Rosen, 1991; Ogawa & Lee, 1990).

Although a thorough review of the human aging and neuroimaging literature is beyond the scope of this chapter, a few important observations have been made in this rapidly growing literature. First, it has often been reported that older adults show lower levels of activation, in a wide variety of tasks and brain regions, than younger adults (Logan, Sanders, Snyder, Morris, & Buckner, 2002; Madden, Turkington, Coleman, Provenzale, DeGrado, & Hoffman, 1996). Two different interpretations have been offered for such data. One is that aging is associated with an irreversible loss of neural resources. Another possibility is that resources are available but are recruited inadequately. Although the reason(s) for underrecruitment remains to be determined, some evidence points toward the second possibility. Logan et al. (2002) found that underrecruitment of prefrontal regions could be reduced when old adults were instructed to use semantic association strategies during word encoding.

Another common finding is that older adults show nonselective recruitment of brain regions. That is, relative to younger adults performing the same task, older adults often show the recruitment of different brain areas in addition to those activated in younger adults. Indeed, one variety of nonselective recruitment, the bilateral activation of homologous brain regions, has been codified into a model of neurocognitive aging by Cabeza (2002). The model, referred to as hemispheric asymmetry reduction in older adults (HAROLD), suggests that, under similar circumstances, cortical activity tends to be less lateralized in older than younger adults. An important question with regard to this asymmetry is whether the additional activity observed for older adults is compensatory or a marker of cortical decline (i.e., a failure to recruit specialized neural processors). At present, this is an open question with a few memory studies reporting that older adults who perform better on a task show bilateral recruitment of homologous areas, whereas older adults who perform more poorly show unilateral activation (Cabeza, Anderson, Locantore, & McIntosh, 2003; Reuter-Lorenz, Jonides, Smith, Hartley, Miller, Marshuetz, & Koeppe, 2000). However, other studies have either failed to find a relationship between laterality and performance (Logan et al., 2002) or have reported unilateral prefrontal activation for better performing old adults and bilateral activation for poorer performing older adults (Colcombe, Kramer, Erickson, Belopolsky, Webb, Cohen, McAuley, & Wszalek, 2002). Thus far, such studies have compared the quality of performance between subjects. Clearly, it is important to examine the relationship between patterns of cortical recruitment and performance quality within subjects in the future. Ideally, examination of this relationship should take place in studies with graded cognitive challenges, as well as in intervention studies whose goal is to enhance cognition and brain function of older adults. Evaluation of the generality of asymmetry reduction across different perceptual, cognitive, and motor processes is also an important goal for the future.

Another variant of nonselectivity that has been observed is the activation of different but nonhomologous brain regions in young and old adults. For example, in a study of focused and divided attention, Madden et al. (1997) observed that older adults showed weaker activity than young adults in occipital cortex while also showing stronger activation than young adults in the prefrontal cortex. These data were interpreted as evidence for strategic differences in the processing of task-relevant stimuli.

One additional issue is important to note regarding age-related changes in brain structure and function. That is, that a substantial amount of variability has been observed in age-related changes in the brain, with some older adults showing minimal structural and functional changes and others showing dramatic changes (but less dramatic than that observed with Alzheimer's dementia). One potential implication of such data is that slowing deleterious changes in brain with aging may be achievable through training or other interventions.

Indeed, while human research has not yet addressed the question of whether changes in brain structure and function of older adults can be slowed or reversed through training or other interventions, such data are available in the animal literature. For example, while early research that examined the influence of enriched versus improvised environments with rats and mice was confined to young animals, given the belief that brain plasticity existed only for young organisms, later research discovered that morphological changes could also be obtained with older animals (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990; Kempermann, Kuhn, & Gage, 1997; Riege, 1971; Rosenzweig & Bennett, 1996). The changes, engendered by enriched environments, include increased dendritic branching, capillary development, and the development of new neurons presumably from adult stem cells, as well as a cascade of molecular and neurochemical changes. Indeed, many of these changes have also been observed when older animals are involved in fitness training (Black et al., 1990; Cottman & Berchtold, 2002; van Praag, Kempermann, & Gage, 1999). Such data, when viewed in terms of human neuroimaging data, which argue for a close coupling between cognition and brain function and structure, suggest that it is indeed conceivable that age-related cognition decline might be modifiable through experience and training. We now turn to an examination of this issue.

IV. Does Experience Reduce Age-Related Cognitive Decline?

Over the past several decades a number of researchers have examined whether previous experience, and indeed often high levels of expertise, in content areas such as driving, flying, music, medical technology, graphic art, architectural design, typing, and complex game playing (e.g., bridge, chess, go) serves to (a) reduce age-related decline on basic perceptual, cognitive, or motor abilities that underlie the complex skill and/or (b) aid in the development of domain general or specific strategies that can offset or compensate for the impact of aging on complex skills or their component processes. An early example of such research is provided by Murrell, Powesland, and Forsaith (1966), who studied the influence of skill on age-related differences in pillar drilling. The relationship between age and skill was examined in a sample of experienced and inexperienced individuals in a variety of component tasks and measures (e.g., accuracy and time required for drill aiming) related to pillar drilling. Performance differences were observed, as a function of age, only for the inexperienced individuals. Thus, these data appear to suggest that skill or expertise can indeed slow or abolish age-related psychomotor deficits. There are, however, some important caveats with respect to this study. First, very small samples (seven or fewer subjects per group) were employed in the study. Second, the subjects were not characterized beyond their performance on the drilling tasks. Thus, both of these factors may point to an alternative interpretation of the results, which might be referred to as the selective attrition hypothesis. This hypothesis states that older adults who remain in a profession and attain (and retain) the status of "expert" might represent only a very small proportion of the aging population, thereby substantially limiting the generalizability of such results.

A. EXPERTISE AS A MEANS TO REDUCE AGE-RELATED DECLINE IN PERFORMANCE AND COGNITION

Charness (1981a,b) described and implemented a research strategy that could address, at least in part, concerns about the representativeness of the older adult sample in studies of age and expertise. This proposal, referred to as the molar-equivalence molecular decomposition strategy, involves (1) selecting individuals who differ widely on both age and skill but for whom the correlation between these two factors is near zero and then (2) examining the influence of age, skill, and their interaction on a series of component processes of the task/skill of interest. An additional step in this procedure, implemented by a number of researchers (e.g., Masunaga & Horn, 2001; Morrow, Leirer, Altiere, & Fitzsimmons, 1994; Morrow, Menard, Stine Morrow, Teller, & Bryant, 2001), entails (3) the additional examination of age and skill effects on basic perceptual, memory, and motor processes not considered to be relevant to the skill of interest. Within such a research framework, expertise might be said to moderate an age-related decline in performance to the extent that older highly skilled individuals showed a smaller performance decrement than older less skilled individuals on the skill-based component tasks. In other words, older and younger highly skilled individuals should perform more similarly than less skilled old and young individuals. The extent to which such effects were also found for the nonskill related tasks would provide an assessment of the degree of generality of the expertise effects on age-related differences in cognition.

To preview the discussion of the literature presented here, in general these studies have found that well-learned skills and their component processes, across a variety of different domains, can be maintained at relatively high levels of proficiency, well into the 70s. However, these same studies have found that general perceptual, cognitive, and motor processes are not preserved in these highly skilled individuals. Thus, preservation of cognitive abilities for highly skilled individuals appears to be domain specific and often compensatory in nature. Furthermore, the maintenance of proficient domain-specific skills generally requires substantial deliberate practice (i.e., practice defined as activity designed to explicitly improve performance) (Ericcson, Krampe, & Tesch-Romer, 1993).

One domain in which the question of whether skill can reduce an age-related decline on complex skills and task-relevant component processes is typing. For example, Salthouse (1984) examined the performance of young and old adult (19 to 72 years of age) typists on both domain-specific (i.e., typing tasks) and less domain-specific tasks (i.e., tapping, choice reaction time). He found a significant age-related decline in the performance of general psychomotor tasks but no age-related deficit in measures of typing proficiency. Furthermore, older typists demonstrated an interesting compensatory strategy that likely minimized the general decline in processing speed on typing speed. That is, older typists displayed a greater ability than young typists to use preview of the text to decease their interkeystroke times, thereby enhancing their typing span. Thus, older typists were able to employ their accrued knowledge of the task domain to implement a strategy that compensated for declines in processing speed.

In a series of more recent studies, Bosman (1993, 1994) replicated Salthouse's preview benefits for older typists. However, she also found evidence for other experience-based benefits for older typists. In a series of component tasks that entailed making rapid responses to multiple sequentially presented letters, Bosman found significant age × expertise interactions for the time it took to type the second of two responses to a stimulus pair. That is, while large age-related response time differences were found for the initial response, age-related differences were reduced substantially for the second response. A significant age × expertise effect was also found for a multiple finger-tapping task. Bosman interpreted these results as suggesting that expertise moderates execution but not stimulus–response translation processes. Thus, it would appear that compensatory strategies (i.e., preview effects), as well as selective sparing of task-relevant component processes (i.e., execution processes), can be obtained, at least with a well-practiced psychomotor task such as typing.

Complex game playing represents another domain in which the molar-equivalence molecular-decomposition strategy has been used to examine the influence of expertise and age on performance. Charness (1981a,b) conducted a series of studies in which he examined the influence of expertise in chess on the performance of a number of task-related components, including the recognition and recall of the spatial configuration of chess pieces and the selection of moves during simulated chess games. A number of important task components were independent of age but related to the skill level of the player. These components included the quality of the moves selected and the rapid evaluation of end game positions. Performance on recall and recognition tasks was influenced negatively by age and positively by skill. These results could be interpreted to suggest that highly skilled individuals encoded the spatial positions of the chess pieces in an elaborated representation of previously played or studied games, but that such representations could not ameliorate the influence of age. Indeed, this explanation is consistent with the observation of increases in chunk size with chess skill along with decreases in chunk size with age. An important question regarding these studies is how could it be that there are small or no age-related deficits in the game of chess and a number of its components relating to the quality of the selected move and the speed of search given the obvious memory problems exhibited by the older players? One possibility is that older adults learn to be more selective in their representation and choice of moves. Such a compensatory strategy would serve to reduce memory load while also speeding search, as was observed in the studies (Charness, 1999).

A study reported by Masunaga and Horn (2001) concerned expertise and age effects in the game of Go. Go is a game that involves two players who attempt to surround each other's stones with their own on a 19 × 19 grid board. The game, which involves complex problem solving, memory, and learning, takes at least 10 years to achieve expert status. In the Masunaga and Horn study, 263 Go players of widely varying age and expertise performed a variety of Go-related and more general memory, problem solving, and processing speed tasks. Subjects showed the typical age-related decline on non-GO related tasks. However a number of age × expertise interactions were observed on Go-related tasks involving recognition, recall, and reasoning. Thus, similar to the chess studies, the acquisition of a large and well-organized body of knowledge in Go appears to offset age-related decline in more general cognitive abilities.

The results that have been discussed so far, in the domains of typing and complex gaming, are both interesting and important in that they establish that expertise can reduce or eliminate processing declines observed during the course of normal aging both through the development of compensatory strategies as well as through the maintenance of task-related basic processes. However, an important question is whether such results can be generalized to complex skills and professions that entail the acquisition and coordination of a multitude of skills that often need to be performed under time pressure and other stressful conditions.

This question has been addressed by several different research groups in the context of piloting. For example, Tsang and Shaner (1998; see also Tsang & Voss, 1996) examined whether piloting expertise would reduce commonly observed age-related decrements in multitask processing (for a review of aging and multitask performance literature, see Kramer & Larish, 1996). Such a proposal appears plausible given the inherent multitask nature of piloting an aircraft. Ninety participants between the ages of 20 and 79, half of whom were pilots, were asked to perform a variety of different single and dual tasks. Age × expertise interactions were observed for a number of the dual-task conditions with smaller dual-task decrements [i.e., (dual-task performance–single-task performance)//single-task performance] being observed for older pilots than for older nonpilots. Age × expertise interactions were not obtained for any of the single tasks. Thus, these data suggest a specificity of expertise effects on the skills most related to piloting rather than a general effect on the performance of psychomotor and cognitive tasks. It is important, however, to point out that not all dual-task combinations produced expertise × age effects. The question of why this might be the case is discussed in the next section.

Morrow and colleagues (1992, 1994, 2001) examined whether piloting expertise reduces age-related differences in a series of laboratory tasks that were designed to be similar to routine air traffic control communications. Across a series of studies, older and younger pilots and nonpilots performed a number of tasks that entailed reading back route descriptions, answering questions about route commands, and recalling route commands. Age × expertise interactions were found on tasks that were rated to be most similar to the kinds of communication tasks performed by pilots and air traffic controllers (e.g., reading back commands concerning heading) but not for less aviation-relevant communication tasks. Interestingly, age × expertise effects were not observed for domain-relevant communication tasks that were quite complex. These results were interpreted to suggest that older pilots could compensate for declines in processing when they were able to capitalize on their knowledge of the structure of air traffic control messages, but only when working memory demands were low or moderate. Thus, while research that focused on piloting expertise as a means to reduce age-related processing deficits has clearly found expertise-related benefits, this research has also been useful in beginning to establish some boundary conditions on such effects (see also Clancy & Hoyer, 1994; Dollinger & Hoyer, 1996).

B. Expertise Does Not Always Reduce Age-Related Decline in Performance and Cognition

Research in other domains of expertise such as music has produced more limited support for the hypothesis that expertise can reduce age-related declines in cognition. Krampe and Ericcson (1996) examined the influence of expertise, with young and old amateur and expert pianists, on measures of general processing speed as well as performance on music-related tasks (i.e., single hand and bimanual finger coordination). An age-related decrement was found on general processing speed measures, regardless of the level of the individuals' music expertise. However, no such deficit was found on music-related tasks. In this case, age effects were abolished for expert but not for amateur pianists. Furthermore, high levels of deliberate practice over the past 10 years were found to be associated with decreases in age-related differences, for the expert group, in music-related performance.

The examination of expertise effects in other music-related tasks has provided less consistent and weaker support for experience-based moderation of age-related cognitive decline. Halpern, Bartlett, and Dowling (1995) examined age and expertise effects on a series of music transposition tasks that entailed deciding whether two tunes that started in a different key were otherwise identical or not. In these studies, musical expertise was broadly characterized to include either voice training or training on any instrument, with high levels of expertise being defined as at least 8 years of lessons (with no assessment of recent experience or deliberate practice). An age × experience interaction was obtained in only one of four experiments. Interestingly, this was the experiment that obtained the strongest relationship between experience and performance as well as between age and performance.

Meinz (2000; see also Meinz & Salthouse, 1998) examined age and expertise effects on musical and nonmusical perceptual speed (i.e., same/different judgments on chords) and memory tasks (i.e., comparison of short melodies) with a large group of pianists who ranged in age from 19 to 88. Although significant age × experience interactions were not obtained for either perceptual or memory tasks, age effects were larger when experience was controlled in multiple regression analyses. Such effects provide some support for the proposal that positive age–experience relations can offset the negative age–speed and memory relations. However, these results do not support the proposal that age differences will be eliminated or reduced substantially among experienced musicians.

C. SOME SPECULATIONS ON REASONS FOR DISCREPANICES BETWEEN STUDIES THAT FIND AGE-RELATED EXPERTISE BENEFITS AND STUDIES THAT DO NOT FIND SUCH BENEFITS

An interesting issue concerns the source of the discrepancy in the strength of the age × expertise effects in the Krampe and Ericcson (1996) as compared to the Meinz (2000) and Halpern et al. (1995) studies. One possibility concerns the nature of the component tasks. In Krampe and Ericcson (1996) study musicians were assessed on a series of psychomotor tasks, whereas memory-based component tasks were employed in the Meinz (2000) and Halpern et al. (1995) studies. Thus, age-related deficits in memory processes might be more difficult to overcome with expertise-accrued knowledge than psychomotor deficits. However, this explanation seems unlikely when viewed in terms of the expertise × age interactions that have been observed in gaming (i.e., chess and Go) as well as piloting. Of course, it is conceivable that the component memory tasks employed in the research with musicians were less domain relevant than those used in the other domains and were therefore less amenable to knowledge-based compensatory strategies (Morrow et al., 2001). Another possible explanation for the discrepancy in the strength of the age × expertise effects in the Krampe and Ericcson (1996) study as compared to the Meinz (2000) and Halpern et al. (1995) studies concerns the strength of the age and performance and expertise and performance effects in the different studies. These relationships were weaker in the Meinz (2000) and Halpern et al. (1995) studies than in the Krampe and Ericcson (1996) study. Given that it is more difficult to discern age × expertise interactions with weak age–performance or expertise–performance relations, it is perhaps not surprising that the influence of expertise on age-related cognitive processes was not observed in the Meinz (2000) and Halpern et al. (1995) studies. Additional studies that employ a variety of component tasks and ensure both strong age–performance and age–experience relations will be needed to examine these hypotheses further.

The studies discussed earlier establish that age-related deficits in cognition can indeed be reduced and, in some cases, even eliminated through various forms of experience and expertise. However, despite the impressive expertise effects discussed earlier, a number of cautions need to be noted. First, cognitive sparing appears to be domain specific rather than general. That is, expertise effects on the cognitive processes of older adults tend to be both more consistent and more substantial with component tasks that are similar to the complex skills on which expertise is expressed than for more general cognitive tasks. Second, in many cases the expertise × age interactions appear to be compensatory in nature rather than influencing the component processes directly. For example, well-developed and elaborate conceptual models of relevant domain knowledge appear to enable the older expert to bypass perceptual, cognitive, and motor processes that decline with age (Clancy & Hoyer, 1994; Charness, 1981; Linderberger, Kliegl, & Baltes, 1992; Morrow et al., 1994). Third, expertise benefits in the form of age × expertise interactions appear to depend on the maintenance of deliberate practice rather than just the performance of the complex skills and tasks (Ericcson et al., 1993; Krampe & Ericcson, 1996).

It is important to note that while an increasing number of studies have obtained data that suggest that age-related cognitive declines can be reduced or compensated for through experience and expertise, there have also been a substantial number of failures to observe such effects, some of which have been discussed earlier (see also Salthouse, 1991; Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990; Salthouse & Mitchell, 1990). As briefly indicated earlier, there are a number of reasons for discrepancies between studies, including (a) the manner in which expertise is characterized, including the extent of recent deliberate practice on the molar skills, (b) the strength of the relationship between age and performance and expertise and performance on component tasks, (c) the domain relevance of the component tasks, and (d) the health, age, and lifestyle choices of the subject populations. Clearly, all of these factors need to be examined in greater and more systematic detail in future studies of expertise effects on age-related changes in cognitive processes.

D. Models of Aging, Expertise, and Cognition

Before leaving the topic of expertise as a means to reduce age-related cognitive decline, it may be useful to briefly describe some attempts to model these processes. Modelers have taken two different perspectives in examining the relationship among age, expertise, and cognition. The work of Paul Baltes and colleagues (Baltes et al., 1999; Wiese, Freund, & Baltes, 2000, 2002) represents an attempt to describe the trade-offs between maximization of gains and minimization of losses in skilled performance during the adult life span. Their approach is characterized by the selection, optimization, and compensation (SOC) model. The model describes a number of processes, which, in combination, serve to maintain performance during the course of aging. Selection entails reduction in the repertoire of skills that are involved in the molar skill set that comprises a profession, sport, artistic, or leisure pursuit. For example, an older tennis player might focus on doubles rather than singles play. Optimization involves an attempt to structure the environment so as to focus attention, to a greater extent than the individual had done before, on the skill set that has been retained. For the tennis player that would entail increasing deliberate practice on strategies and skills related to doubles play. Finally, compensation involves the use of cognitive processes and skills that have been maintained or enhanced over the adult life span, such as elaborated knowledge representations, to offset costs associated with processes, such as working memory and some aspects of sensory and motor processes, which have become less efficient. The tennis player might compensate by more effectively hitting the ball to her opponent's weak side. While the SOC model has mostly been used to describe changes in cognition and skill across the adult life span, it has also been employed to prescribe environmental changes, in a number of domains to enhance older adults' performance (Wiese et al., 2002).

A second class of models is exemplified by the work of Mireles and Charness (2002; see also Hanon & Hoyer, 1994; Li, Linderberger, & Frensch, 2000). In the context of a recurrent neural network model, these researchers have examined the implications of various neuronal changes on the relationship among expertise, age, and performance. They accomplished this by training neural networks so as to develop either large or small knowledge bases of chess moves and then examining the ability of the networks, given different types and magnitudes of neural changes, to learn new moves. Several interesting results were obtained in their simulations. First, changes in the signal/noise ratio in the form of unit weight changes or the addition of random noise to the networks resulted in performance changes that favored the networks with more extensive knowledge bases. That is, the more expert networks showed less extensive performance decrements much like the age × expertise effects discussed earlier (Charness, 1981; Masunaga & Horn, 2001; Morrow et al., 1994). However, changes in neural plasticity in the form of reduced learning rates and pathological damage in the form of lesioned units produced equivalent performance decrements for the large and small knowledge bases, similar to research that has failed to observe the expertise benefits on age-related decline (Morrow et al., 2001; Salthouse, 1990; Salthouse et al., 1990). The Mireles and Charness (2002) modeling effort and others like it are interesting in that they attempt to map expertise and age effects to underlying mechanisms, many of which have been identified in cognitive and neuroscience research. Interestingly, however, the Mireles and Charness (2002) modeling did not address age differences in the learning of new skills and tasks, a topic to which we now turn.

V. Can Laboratory-Based Training Be Used to Reduce Age-Related Decline in Cognition, and If So, What are the Nature of These Training Benefits?

The previous section discussed the influence of expertise in real-world tasks, professions, and endeavors on the maintenance of cognitive skills and processing. This section discusses the results of laboratory-based practice and training studies on the development or improvement in cognitive skills, as well as the retention of these skills. We also address, as was done in the previous section, the specificity of these skills. We begin with a discussion of cross-sectional comparisons in training and practice effects and conclude this section with an examination of longitudinal studies in which specific individuals serve as their own controls for age-related practice and training benefits.

It is important to note that there are both advantages and disadvantages to the laboratory training approach as compared to the examination of expertise effects on age-related cognitive decline. A clear advantage of the laboratory-based training approach is the ability to precisely control and manipulate the nature of the training process. This might include the amount and frequency of training and practice, the type of the feedback provided to the trainee, and the environment and conditions (e.g., whether under time stress, in the presence of other tasks or demands) under which training and performance take place. None of these factors are controlled easily in professional or leisure activities in which expertise develops over the course of many years. Of course, laboratory-based studies also have the advantage of random allocation of individuals, who may differ on a multitude of factors, which may influence training benefits, to different control or training groups. Clearly, this is not possible in real-world studies of expertise effects. However, laboratory-based training is quite limited in terms of the extent to which high levels of expertise are achieved and the complexity of the tasks and skills that are examined. Such are important strengths of expertise-based research. Thus, both the expertise-based studies and the laboratory-based training approach are necessary to provide a detailed understanding of the impact of training and experience on the maintenance and enhancement of cognitive processes and skills over the course of the adult life span.

A. CROSS-SECTIONAL PRACTICE AND TRAINING STUDIES WITH YOUNG AND OLD ADULTS

In general, old and young adults have been found to learn new tasks and skills at approximately the same rate or to show the same magnitude of training gain (Hertzog, Williams, & Walsh, 1976; Peretti, Danion, Gierski, & Grange, 2002; Salthouse, 1990). This finding has been observed across a wide variety of tasks, including perceptual discrimination, visual search, recognition, recall, and spatial perception. Such data clearly suggest that older adults can learn new skills. However, given that older adults' baseline performance on most tasks is lower than that observed for younger adults, these data also suggest that age-related differences in the level of performance will be maintained at posttest.

Visual search is one domain in which age-related differences have been well documented and for which there have been a variety of practice studies that have examined the nature of improvements in underlying processes and performance across the adult life span. In general, this literature suggests that age effects are small or nonexistent in feature and conjunction search when target–distractor similarity is low (Humphrey & Kramer, 1997; Plude & Doussard-Rossevelt, 1989; Scialfa, Esau, & Joffe, 1998; Scialfa & Joffe, 1997). However, age differences can be quite large when target–distractor similarity is increased in either a feature or a conjunction search (Humphrey & Kramer, 1997; Plude & Doussard-Rossevelt, 1989; Scialfa et al., 1998).

Scialfa and colleagues (Anandam & Scialfa, 1999; Ho & Scialfa, 2002; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000) conducted a number of studies in which they examined improvements in the performance of young and old adults on a variety of consistently mapped feature and conjunction visual search tasks. In general, they found that young and older adults improved at similar rates. Interestingly, when the role of the targets and distractors was reversed, they also found large and age-equivalent disruptions of performance, particularly for targets that appeared close to fixation. This is an important observation, as disruption effects, when the role of consistently mapped targets and distractors is reversed, suggest that subjects have automatized their search processes (Shiffrin & Dumais, 1981).

Fisk, Rogers, and colleagues (Fisk, Rogers, & Giambra, 1990; Fisk, Rogers, Cooper, & Gilbert, 1997; Rogers & Fisk, 1991; Rogers, 1992; Rogers, Fisk, & Hertzog, 1994) also examined age differences in the development of automaticity in a variety of search (visual, memory, and semantic search) tasks. Given the results of the research discussed earlier, one might expect similar patterns of learning and disruption effects upon reversal of the role of targets and distractors, for young and old adults. However, instead it was observed that, in consistently mapped tasks, younger adults showed faster rates of learning and larger disruption effects with the reversal of targets and distractors than older adults. Such a pattern of results was interpreted as evidence of a failure for the older adults to automatize search performance.

An important question concerns the reason for the discrepancy in aging effects in the search tasks employed by the two different research groups. Although an unequivocal answer must await further research, one reasonable hypothesis concerns the nature of the tasks that subjects performed. Scialfa and colleagues had the subjects perform what are traditional visual search tasks (i.e., search for a single target among distractors). However, Fisk, Rogers, and colleagues often had subjects search for multiple targets (in essence a memory search task) among multiple distractors (a visual search task). Given the observation that older adults often have difficulty with large working memory loads as well as in switching between heterogeneous tasks (Bailey & Lauber, 1998; Kray & Lindenberger, 2000), it is perhaps not surprising that evidence for age-related equivalence in learning to perform the search tasks was not obtained when the tasks included both memory and attentional components. Thus, contextual constraints and additional processing requirements may limit the training benefits on visual search found for older adults.

Despite the potential age-related limits in training effects discussed earlier, Ball, Owsley, and colleagues (Ball & Owsley, 2000; Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball, Owsley, Stalvey, Roenker, Sloane, & Graves, 1998; Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Owsley, Ball, & Keaton, 1995) have reported that older adults can benefit, to the same extent as younger adults, from practice on a useful field of view (UFOV) test that entails extracting information from the visual field rapidly and accurately. Indeed, these training benefits can also be retained for up to 6 months following training. Given that a restricted attentional field has been associated with increased automobile accidents, it is important to determine whether laboratory-based training on this skill can be generalized to driving. This question has been addressed in a study that entailed on-road driving assessments prior to and following practice on a UFOV test. Older drivers who received UFOV training showed substantially larger driving performance gains than older adults who did not receive training (Ball & Owsley, 2002). Thus, it would appear that visual search and attentional skills of older adults can indeed be trained in the laboratory and transferred to complex tasks in real-world environments.

Over the past several decades, extensive research has been conducted to examine whether age-related memory loss can be reduced with mnemonic training. This body of research has been summarized in the form of a meta-analysis of 33 separate studies with 1539 participants (Verhaeghen, Marcoen, & Goossens, 1992). Several interesting results were obtained in the meta-analysis. First, training gains were found to be substantially larger for older individuals (all participants were >60 years of age) who were trained with mnemonic techniques (.73 SD) than control subjects (.38 SD). Second, no differences in training gains were found for different mnemonic training techniques (e.g., method of loci, name-face, pegword). Third, several variables were found to moderate the training effect. Training gains were larger for younger participants when pretraining was provided, when training was carried out in groups rather than individually, and when training sessions were brief. Thus, these data clearly suggest that older adults can benefit from memory training.

However, do older adults benefit to the same degree as younger adults from mnemonic training? The answer appears to be no. Kliegl and colleagues (Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989, 1990; see also Verhaeghen & Marcoen, 1996) carried out a series of studies to address this issue with a methodology that they refer to as testing the limits. The testing-the-limits method entails the design of interventions that enable an estimation of the current and future reserve capacity of individuals. Three levels of information about performance and latent potential are distinguished in the testing-the-limits paradigm. Baseline performance refers to an individual's initial performance under standardized conditions. Baseline reserve capacity is defined as an individual's maximal performance if conditions of assessment are optimized in the absence of any attempt to modify the individuals cognitive skills or motivation. Finally, developmental reserve capacity is defined as maximal performance following interventions that are aimed at maximizing motivation and cognitive processes needed for performance.

In experiments that have employed the testing-the-limits method, the general finding has been that age differences in mnemonic performance, with the method of loci, increase from pretraining assessments to assessments that follow several weeks of practice. Older adults clearly do show dramatic performance improvements in word recall with extensive training. However, younger adults show larger improvements than older adults, particularly under difficult conditions (e.g., when little time is available to encode each of the words in a list).

Results obtained using the testing-the-limits method with mnemonic practice may indeed set some boundaries on the cognitive plasticity of older adults. However, thus far there are a number of unanswered questions with respect to these findings. For example, would an amplification of age-related performance differences still be observed with additional practice (comparable to the amounts of practice/training received in most professions or leisure activities)? Will age-related amplification effects hold up with within subject designs or when other tasks and processes are trained? To what extent do lifestyle factors (e.g., fitness, nutrition, education) influence the course of training effects? Clearly, additional research will be required to answer these questions.

There have, in recent years, been some interesting exceptions to the general observations of age-equivalent and age-deficient training outcomes. For example, Baron and Mittila (1989) examined the influence of training on the speed and accuracy with which young and older adults performed a memory search task (i.e., a task in which they compared probe items to items stored in memory). Subjects were trained for 44 hours with a deadline procedure in which they were required to constantly increase the speed with which they performed the task. Prior to training, young and older adults performed the memory search task with comparable accuracy but the older adults were substantially slower than the younger adults. During training with the deadline procedure, both young and older adults performed more quickly but with a substantially elevated error rate. Most interestingly, when the deadline procedure was relaxed, both young and old adults performed with equivalent accuracies and the response time differences between the groups were reduced substantially. Thus, these data suggest a more substantial improvement in performance related to speed of responding for the old than for the younger adults (for an age-related decrease in the effects of complexity on performance with practice, see Falduto & Baron, 1986).

A similar pattern of results was obtained in the study of training effects on the dual-task performance of young and old adults (Kramer, Larish, Weber, & Bardell, 1999; see also Kramer, Larish, & Strayer, 1995). Young and old adults were trained to concurrently perform two tasks, a pattern-learning task and a tracking task, with either of two training strategies. In the fixed priority training strategy, subjects were asked to treat each of the tasks as equal in importance. In the variable priority training procedure, subjects were required to constantly vary their priorities between the two tasks. On-line performance feedback was presented in both training conditions.

Several interesting results were obtained. First, consistent with previous studies, young and old adults improved their dual-task performance at the same rate with the fixed priority training strategy. Second, variable priority training led to faster acquisition and a higher level of mastery in performing the tasks together than fixed priority training. Furthermore, individuals trained in the variable priority condition also displayed a superior transfer to untrained tasks and better retention of time-sharing skills over a 2-month period than those individuals trained in the fixed priority condition. Finally, and most importantly, age-related differences in the efficiency of dual-task performance were reduced substantially for individuals trained in the variable priority condition (for another example of diminished age effects with practice in task switching, see Kramer, Hahn, & Gopher, 1999).

Finally, Jennings, Webster, Kleykamp, and Dagenbach (2002) presented some intriguing data with respect to memory training of older adults. Their study involved recollection training with unrelated word lists of a small (12) group of older adults. A key component of this strategy was the use of Jacoby's (Jacoby, 1998; Kelly & Jacoby, 2000) process dissociation paradigm, which enables the dissociation of two different types of memory processes: recollection and familiarity. Recollection processes entail conscious and effortful memory processes, just those processes with which older adults have great difficulty. Familiarity processes involve more automatic and some would say unconscious memory processes. Older adults show small to negligible deficits in familiarity-based processes (Hay & Jacoby, 1999).

Jennings et al. (2002) emphasized recollection processes by requiring subjects to respond differently to words that they had remembered from previous lists from words that were repeated from a recently presented study list. They used an adaptive algorithm, based on subjects recollection performance, to gradually increase the number of intervening items between previously presented words. The older adults recollection performance improved from 1 to over 25 intervening items in less than 30 sessions of practice. Furthermore, the training improvements transferred to several other memory tasks, including working memory (n-back), self-ordered pointing, and digit–symbol substitution. A second study replicated these effects and included a control group who did not show memory improvements. These results are quite remarkable given previous studies that report (a) large and persistent age deficits in recollection and (b) little transfer of training between different memory tasks. Clearly, additional research is needed to examine potential age differences in the efficacy of this training procedure and to explicate the boundary conditions for transfer. However, these results do suggest a substantial amount of plasticity in recollection for healthy older adults.

An obvious question concerning the Baron and Mittila (1989) and Kramer et al. (1999) studies (and the Jennings study in terms of the magnitude of the training benefits) is why these projects and several others have observed decreased age-related performance differences with training while many other studies have observed age-equivalent training effects. Although there is quite likely not a single answer to this question, one possibility centers on the nature of the training procedures. Both the Baron and Mattila (1989) and the Kramer et al. (1999) training strategies (i.e., the variable priority strategy) focused explicitly on aspects of performance on which young and older adults showed large differences. For example, one may conceptualize the Baron and Mattila (1989) deadline strategy as encouraging individuals to shift their response criterion from emphasizing accurate to emphasizing speeded performance. Given that older adults typically emphasize accuracy rather than speed, the deadline strategy may be well suited to older adults. Similarly, older adults have been observed to have difficulty in flexibly setting and modifying processing priorities. The variable priority training strategy targets this skill explicitly. Indeed, while Sit and Fisk (1999) found a decrease of age-related dual-task performance decrements with training, they also observed an increase in age-related performance differences when task emphasis instructions were changed. Interestingly, they did not formally train their subjects to shift priorities among multiple tasks. Thus, although additional research is clearly needed to further examine the techniques and situations in which the age gap in performance can be reduced, one potentially fruitful area of inquiry concerns targeting training strategies to specific difficulties encountered by older adults.

B. Longitudinal Studies of Practice and Training

While a main focus in cross-sectional training studies has been on comparing the training improvement of young and older age cohorts and on examining the efficacy of strategies targeted at deficits in elders, a central focus in training research conducted within longitudinal studies has been to examine the extent to which training remediates or improves cognition in elders in tasks for which there is long-term data. Given the wide individual differences in timing of age-related ability decline, some adults in their sixties and seventies have experienced reliable decline on a given cognitive ability and others have not. Two questions arise: Would training be effective in remediating decline for elders who had shown loss in a specific ability? Second, for elders showing no decline in a specific ability, would training enhance their performance to a level beyond that shown previously? Elders in the Seattle longitudinal study were classified as to whether they had shown reliable decline over the prior 14-year interval on two fluid abilities known to show early age-related decline: inductive reasoning and spatial orientation (Schaie & Willis, 1986; Willis & Schaie, 1994). Elders who exhibited decline on only one of the two abilities were trained on that ability. Elders who had declined on both abilities or showed no decline on either ability were assigned randomly to training on one of the abilities. Over two thirds of trained elders showed reliable improvement on the ability trained immediately after training. Of elders who had declined on the ability trained, 40% showed remediation of performance, such that after training their performance was at the same level or above their performance 14 years prior to training. Elders who had not declined also showed reliable improvement. There was maintenance of training effects for those trained on inductive reasoning up to 7 years after training (Saczynski & Willis, submitted for publication). That is, elders trained on reasoning were performing at a higher level 7 years after training compared to those trained on another ability.

To summarize, cross-sectional training research suggests that both young and old adults profit from training, but that strategies targeted at skills known to decline with age are particularly effective in training of elders, such that performances of young and old are more comparable at posttest. Training research conducted within longitudinal studies allows the investigator to identify the abilities that have declined for a given individual and to examine whether training targeted at individual-level deficits is effective. The longitudinal approach permits examination of the range of plasticity over time within the same individual rather than comparing the magnitude of training effects for different age cohorts. Both types of training research support the position that considerable plasticity in cognitive functioning is present even at advanced ages. The training findings also support the descriptive experiential studies of sparing in that effects are specific to the particular domain that was practiced or trained.

VI. Can Other Interventions Reduce Age-Related Decline in Cognition: Healthy Body, Healthy Mind?

The study of the relationship between fitness and mental function has been a topic of interest to psychologists, exercise physiologists, physicians, and other scientists and practitioners for the past several decades (Dustman, Ruhling, Emmerson, Shearer, 1994; Spirduso, 1975). The logic behind these studies has been predicated on the assumption that improvements in aerobic fitness would translate into increased brain blood flow, which in turn would support more efficient brain function, particularly in older adults for whom such function is often compromised. Indeed, these assumptions are supported, in part, by findings of compromised mental functions with pulmonary disease and exposure to low oxygen environments such as that experienced during high-altitude mountaineering. Furthermore, animal research has found that aerobic fitness, like psychomotor skills training, promotes the development of new capillary networks in the brains of old rats, the enhancement of cortical high-affinity choline uptake and increased dopamine receptor density in the brains of old rats, and increases in brain-derived neurotrophin factor (BDNF) gene expression in rats (Black et al., 1990; Churchill, Galvez, Colcombe, Swain, Kramer, & Greenough, 2003; Cotman & Berchtold, 2002; van Praag et al., 1999). Thus, the logic that underlies examination of the relationship between fitness and mental function in humans appears well supported by the relevant scientific literatures.

Unfortunately, however, results from intervention studies that have examined the influence of aerobic fitness training on cognition have been mixed. Some studies have reported fitness-related improvements for older adults (Dustman et al., 1984; Hawkins, Kramer, & Capaldi, 1992; Kramer et al., 1999; Rikli & Edwards, 1991), whereas others have failed to observe such improvements (Blumenthal, Emery, Madden, Schniebolk, Walsh-Riddle, George, McKee, Higginbotham, Cobb, & Coleman, 1991; Hill, Storandt, & Malley, 1993; Madden, Blumenthal, Allen, & Emery, 1989). Clearly, there are a number of potential theoretical and methodological reasons for this ambiguity. For example, studies have differed in terms of the length and the nature of the fitness interventions, the manner in which fitness changes have been assessed, the health and age of the study populations, and the aspects of cognition that have been examined.

Colcombe and Kramer (2003) conducted a meta-analysis to ask whether (a) fitness effects on cognition could be discerned when aggregating data across longitudinal studies and (b) whether this effect, if observed, is moderated by other variables such as age, length, and intensity of fitness training and the nature of the tasks used to assess cognition. Fitness intervention studies conducted from 1966 through 2001 were included in the analysis. Several interesting and potentially important results were obtained in the meta-analysis. First, a clear and significant effect of aerobic fitness training was found. Thus, when aggregating across studies, fitness training does indeed have positive effects on the cognitive function of older humans. Second, fitness training had selective effects on cognitive function. Although fitness effects were observed across a wide variety of tasks and cognitive processes, the effects were largest for those tasks that entailed executive control (i.e., planning, scheduling, working memory, interference control, task coordination) processes. As discussed previously, executive control processes have been found to decline substantially as a function of aging (Kramer et al., 1994; West, 1996), as have the brain regions that support them (Raz, 2000). Therefore, results of the meta-analysis suggest that even processes that are quite susceptible to age-related changes appear to be amenable to intervention, as consistent with the research on expertise and cognitive training discussed earlier.

The meta-analysis also revealed that a number of other moderator variables influenced the relationship between fitness training and cognition. For example, fitness training programs that were combined with strength and flexibility training regimens had a greater positive effect on cognition than fitness training programs that included only aerobic components. This effect may be the result of increases in the production of insulin-like growth factor 1 (IGF-1), which has been shown to accompany improvements in strength. IGF-1 is a neuroprotective factor involved in neuronal growth and differentiation (Carro, Nunez, Busiguina, & Torres-Aleman, 2001; Cottman & Berchtold, 2002). Fitness training programs also had a larger impact on cognition if the study samples included more than 50% female participants. Although highly speculative, this effect may be due, in part, to the positive influence of estrogen (in the present case, estrogen replacement therapy) on both brain-derived neurotrophin factor (BDNF) and increased exercise participation (Cotman & Berchtold, 2002). Estrogen has been found to upregulate BDNF, a neuroprotective molecule that is also increased by exercise. Finally, exercise effects on cognition were found to be largest for exercise training interventions that exceeded 30 minutes per session.

The link between brain and cognition has also been examined with regard to fitness differences and fitness training of older adults. Colcombe, Erickson, Raz, Webb, Cohen, McAuley, & Kramer (2003) explored the implied relationship between cardiovascular fitness and brain health in aging humans using a voxel-based morhpometric (VBM) approach. In VBM analyses, high-resolution brain scans are segmented into gray and white matter maps, spatially warped into a common coordinate system, and examined for systematic changes in tissue density as a function of some other variable (e.g., age, cardiovascular fitness). This technique allows examination of the entire brain in a point-by-point fashion, revealing spatially precise estimates of systematic variation in brain tissues. This technique provides a substantial advantage over other techniques, such as global estimates of gray and white matter volume in that it allows researchers to localize the effects of a given variable to a specific region of the brain.

In a cross-sectional examination of 55 older adults, Colcombe and Kramer (2003) found that, consistent with previous findings, age-related losses in gray and white matter tended to be greatest in the frontal, prefrontal, and temporal regions (e.g., Raz, 2000; O'Sullivan, Jones, Summers, Morris, Williams, & Markus, 2001). Moreover, consistent with predictions derived from the human and animal literatures, there was a significant reduction of declines in these areas as a function of cardiovascular fitness. That is, older adults who had better cardiovascular fitness also tended to lose much less tissue in the frontal, parietal, and temporal cortices as a function of age. Subsequent analyses, factoring out other potential moderating factors such as hypertension, caffeine, tobacco, and alcohol consumption, confirmed that none of these other variables significantly moderated the effect of cardiovascular fitness.

A preliminary cross-sectional analysis of the relationship between cardiovascular fitness and brain function in older adults has shown promising results and is consistent with the notion that cardiovascular fitness tends to spare the brain from the aging process (Kramer, Colcombe, McAuley, Eriksen, Scalf, Jerome, Marquez, Elavsky, & Webb, 2003). Participants in this study performed a modified version of the Ericksen flanker task in which they were asked to identify the orientation of a central arrow presented among an array of distracting stimuli while brain function was recorded using fMRI. On 50% of the trials, the orientation of the distracting stimuli was consistent with the central cue (e.g., '<<<<<'), whereas on the other 50% the distracting stimuli were oriented inconsistently with the central cue (e.g., '>><>>'). On inconsistent trials, participants were required to suppress the information provided by the flanking stimuli in order to make a correct response. On these trials, highly fit older adults, much like young adults, tended to show less activity in the left prefrontal regions of the cortex than their low-fit older counterparts.

These results, although preliminary, suggest that cardiovascular fitness may provide a prophylactic effect to the functional integrity of the older adult brain.

VII. Conclusions and Future Directions

The research reviewed in this chapter clearly suggests that the cognitive vitality of older adults can be enhanced through cognitive training, whether in the form of domain-relevant expertise or laboratory training, and improved fitness. However, it is important to note that these benefits are often quite specific and not universally observed. Therefore, one important goal of future research is to explicate the boundary conditions for the beneficial effects of cognitive and fitness training on the cognitive efficiency of older adults. Clearly, there are some obvious candidate factors that should be examined in more detail. These include age, health conditions, medication use, gender, education, lifestyle choices, genetic profile, and family and social support.

The nature and length of training, whether in terms of cognitive or fitness training, bear further study. It is important to note that many of the previous studies of "training" have entailed unsupervised practice rather than an examination of specific training procedures that might be well suited to the capabilities of older adults. The development of new methods, such as the testing-the-limits approach (Kliegl et al., 1989), will clearly also be important in future studies of training and other interventions.

At present, we have little understanding of the mechanisms and processes that subserve age-related enhancements in cognitive efficiency. Possibilities include improvements in basic cognitive abilities, the development of compensatory strategies, and automatization of selective aspects of a skill or task (Baltes, Staudinger, & Lindenberger, 1999). Thus, the nature of cognitive and brain (Churchill et al., 2003; Cotman & Berchtold, 2002) processes that support improvements in cognitive efficiency is an important topic for future research.

A related question concerns the extent to which cognitive improvements, engendered by intellectual training, fitness training, social networks and interactions (Fillit, Albert, Birren, Butter, Carey, Cotman, Grecnough, Gold, Kramer, Kuller, O'Connell, Perls, Reynolds-Foley, Sahagan, & Tully, 2002; Ybarra et al., 2001), and nutritional interventions (Bickford, Gould, Briederick, Chadman, Pollock, Young, Shukitt-Hale, & Joseph, 2000; Galli, Shukitt-Hale, Youdim, & Joseph, 2002), have similar effects on neural structure and processes or whether these interventions improve aspects of cognition through different neuronal routes. Previous animal studies that have examined a myriad of interventions, including psychomotor skills training, fitness training, and social manipulations, suggest at least some overlap in the effects of these influences on brain and performance (Rosenzweig & Bennett, 1996). However, clearly more research will be needed to explore these potential interactions in animals and humans.

Finally, the development of models, preferably quantitative in nature (e.g., Braver et al., 2001; Hanon & Hoyer, 1994; Li et al., 2000; Mireles & Charness, 2002) that describe the mechanisms that relate changes in cognition and brain function across the adult life span, will be necessary to further enhance our understanding of cognitive plasticity and aging.

ACKNOWLEDGMENTS

Preparation of this chapter was supported in part by grants from the National Institute on Aging, the Institute for the Study of Aging, and the General Motors Corporation.

REFERENCES

Albert, M., Duffy, F. H., & Naeser, M. (1987). Nonlinear changes in cognition with age and their neurophysiological correlates. *Canadian Journal of Psychology, 41*, 141–157.

Albert, M., & Killiany, R. J. (2001). Age-related cognitive changes and brain-behavior relationships. In J. Birren & W. K. Schaie (Eds.), *Handbook of the psychology of aging* (5th ed., pp. 161–185). San Diego, CA: Academic Press.

Anandam, B. T., & Scialfa, C. T. (1999). Aging and the development of automaticity in feature search. *Aging, Neuropsychology, and Cognition, 6*, 117–140.

Bailey, A., & Lauber, E. J. (1998). *Learning to task switch and aging*. Paper presented at the meeting of the 1998 Cognitive Aging Conference in Atlanta, GA.

Ball, K., Beard, B., Roenker, D., Miller, R., & Griggs, D. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America, 5*, 2210–2219.

Ball, K., & Owsley, C. (2000). Increasing mobility and reducing accidents of older drivers. In W. Schaie & M. Pietrucho (Eds.), *Mobility and transportation in the elderly* (pp. 213–249). New York: Springer.

Ball, K., Owsley, C., Stalvey, B., Roenker, D., Sloane, M., & Graves, M. (1998). Driving avoidance and functional impairment in older drivers. *Accident Analysis and Prevention, 30*, 313–322.

Baltes, P. B., & Kliegl, R. (1992). Further testing of limits of cognitive plasticity: Negative age differences in a mnemonic skill are robust. *Developmental Psychology, 28*, 121–125.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the life span: A new window to the study of cognitive aging? *Psychology and Aging, 12*, 12–21.

Baltes, P. B., Mayr, K. V., Helmchen, H., & Steinhagenthiessen, E. (1994). The Berlin Aging Study: Reply to and reflections on commentaries. *Ageing and Society, 14*, 604–617.

Baltes, P. B., Staudinger, U. M., & Lindenberger, U. (1999). Lifespan psychology: Theory and application to intellectual functioning. *Annual Review of Psychology, 50*, 471–507.

Baron, A., & Mattila, W. R. (1989). Response slowing of older adults: Effects of time-contingencies on single and dual-task performances. *Psychology and Aging, 4*, 66–72.

Belliveau, J. W., Kennedy, D. N., Mckinstry, R. C., Buchbinder, B. R., Weisskoff, R. M., Cohen, M. S., Vevea, J. M., Brady, T. J., & Rosen, B. R. (1991). Functional mapping of the human visual cortex by magnetic resonance imaging. *Science, 254*, 716–719.

Bickford, P. C., Gould, T., Briederick, L., Chadman, K., Pollock, A., Young, D., Shukitt-Hale, B., & Joseph, J. (2000). Antioxidant rich diets improve cerebellar physiology and motor learning in aged rats. *Brain Research, 866*, 211–217.

Black, J. E., Isaacs, K. R., Anderson, B. J., Alcantara, A. A., & Greenough, W. T. (1990). Learning causes synaptogenesis, whereas motor activity causes angiogenesis, in cerebellar cortex of adult rats. *Proceedings of the National Academy of Science, 87*, 5568–5572.

Blumenthal, J. A., Emery, C. F., Madden, D. J., Schniebolk, S., Walsh-Riddle, M., George, L. K., McKee, D. C., Higginbotham, M. B., Cobb, F. R., & Coleman, R. E. (1991). Long-term effects of exercise on psychological functioning in older men and women. *Journal of Gerontology: Psychological Sciences, 46*, 352–361.

Bosman, A. A. (1993). Age-related differences in the motoric aspects of transcription typing skills. *Psychology and Aging, 8*, 87–102.

Bosman, A. A. (1994). Age and skill differences in typing related and unrelated reaction time tasks. *Aging and Cognition, 1*, 310–322.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., Janowsky, J. S., Taylor, S. F., Yesavage, J. A., Mumenthaler, M. S., Jagust, W. J., & Reed, B. R. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General, 130*, 746–763.

Cabeza, R. (2000). Functional neuroimaging of cognitive aging. In R. Cabeza & A. Kingstone (Eds.), *Handbook of functional neuroimaging of cognition*. Cambridge, MA: MIT Press.

Cabeza, R. (2002). Hemispheric asymmetry reduction in old adults: The HAROLD model. *Psychology and Aging, 17*, 85–100.

Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. (2002). Aging gracefully: Compensatory brain activity in high performing older adults. *Neuroimage, 17*, 1394–1402.

Carro, E., Nunez, A., Busiguina, S., & Torres-Aleman, I. (2001). Circulating insulin-like growth factor 1 mediates the protective effects of physical exercise against brain insults of different etiology and anatomy. *Journal of Neuroscience, 20*, 2926–2933.

Charness, N. (1981a). Aging and skilled problem solving. *Journal of Experimental Psychology: General, 110*, 21–38.

Charness, N. (1981b). Search in chess: Age and skill differences. *Journal of Experimental Psychology: Human Perception and performance, 7*, 467–476.

Charness, N. (1999). Can acquired knowledge compensate for age-related declines in cognitive efficiency? In S. H. Qualls & N. Ables (Eds.), *Psychology and the aging revolution: How we adapt to longer life* (pp. 99–117). Washington, DC: American Psychological Association.

Churchill, J. D., Galvez, R., Colcombe, S., Swain, R. A., Kramer, A. F., & Greenough, W. T. (2003). Exercise, experience and the aging brain. *Neurobiology of Aging, 23*, 941–955.

Clancy, S. M., & Hoyer, W. J. (1994). Age and skill in visual search. *Developmental Psychology, 30*, 545–552.

Coffey, C. E., Wilkinson, W. F., Parashos, I. A., Soady, A. A. R., Sullivan, R. J., Paterson, L. J., Figiel, G. S., Webb, M. C., Spritzer, C. E., & Djang, W. T. (1992). Quantitative cerebral anatomy of the aging human brain: A cross-sectional study using magnetic resonance imaging. *Neurology, 42*, 527–536.

Colcombe, S., & Kramer, A. F. (2003). Fitness effects on the cognitive function of older adults: A meta-analytic study. *Psychological Science*. (In press).

Colcombe, S. J., Erickson, K. I., Raz, N., Webb, A. G., Cohen, N. J., McAuley, E., & Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans.. *Journal of Gerontology: Medical Sciences, 58*, 176–180.

Colcombe, S., Kramer, A. F., Erickson, K., Belopolsky, A., Webb, A., Cohen, N., McAuley, E., & Wszalek, T. (2002). An fMRI examination of models of age-related decline in cognitive functioning. Paper presented at the 2002 Cognitive Aging Conference, Atlanta, GA.

Cottman, C. W., & Berchtold, N. C. (2002). Exercise: A behavioral intervention to enhance brain health and plasticity. *Trends in Neuroscience, 25*, 295–301.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits: The role of attentional resources. In F. I. M. Craik & S. Trehub (Eds.), *Aging and cognitive processes* (pp. 191–211). New York: Plenum.

Davatzikos, C., & Resnick, S. M. (2002). Degenerative age changes in white matter connectivity visualized in vivo using magnetic resonance imaging. *Cerebral Cortex, 12*, 767–771.

Dollinger, S. M., & Hoyer, W. J. (1996). Age and skill differences in the processing demands of visual inspection. *Applied Cognitive Psychology, 10*, 225–239.

Dustman, R., Emmerson, R., & Shearer, D. E. (1994). Physical activity, age, and cognitive neuropsychological function. *Journal of Aging and Physical Activity, 2*, 143–181.

Dustman, R. E., Ruhling, R. O., Russell, E. M., Shearer, D. E., Bonekat, W., Shigeoka, J. W., Wood, J. S., & Bradford, D. C. (1984). Aerobic exercise training and improved neurophysiological function of older adults. *Neurobiology of Aging, 5*, 35–42.

Ericcson, K. A., Krampe, R. T., & Tesch-Romer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100*, 363–406.

Falduto, L. L., & Baron, A. (1986). Age-related effects of practice and task complexity on card sorting. *Journal of Gerontology, 41*, 659–661.

Fillit, H. M., Albert, M. S., Birren, J. E., Butler, R. N., Carey, L. A., Cotman, K. W., Greenough, W. T., Gold, P. E., Kramer, A. F., Kuller, L. H., O'Connell, A. W., Perls, T. T., Reynolds-Foley, S., Sahagan, B. G., & Tully, T. (2002). Achieving and maintaining cognitive vitality with aging. *Mayo Clinic Proceedings, 77*(7), 681–696.

Fisk, A. D., Rogers, W. A., Cooper, B. P., & Gilbert, D. K. (1997). Automatic category search and its transfer: Aging, type of search, and level of learning. *Journals of Gerontology Series B Psychological Sciences and Social Sciences, 52B*, 91–102.

Fisk, A. D., Rogers, W. A., & Giambra, L. M. (1990). Consistent and varied memory/visual search: Is there an interaction between age and response-set effects? *Journal of Gerontology: Psychological Sciences, 45*, P81–P87.

Galli, R. L., Shukitt-Hale, B., Youdim, K. A., & Joseph, J. A. (2002). Fruit polphenolics and brain aging: Nutritional interventions targeting age-related neuronal and behavioral deficits. In H. Denham (Ed.), *Increasing healthy lifespan: Conventional measures and slowing the inate aging process* (Vol. 959, pp. 128–132). New York: New York Academy of Sciences.

Halpern, A. R., Bartlett, J. C., & Dowling, J. C. (1995). Aging and experience in the recognition of musical transpositions. *Psychology and Aging, 10*, 325–342.

Hanon, D. J., & Hoyer, W. J. (1994). Mechanisms of visual-cognitive aging: A neural network account. *Aging and Cognition, 1*, 105–119.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Hay, J., & Jacoby, L. (1999). Separating habit and recollection in young and older adults: Effects of elaborative processing and distinctiveness. *Psychology and Aging, 14*, 122–134.

Hawkins, H. L., Kramer, A. F., & Capaldi, D. (1992). Aging, exercise, and attention. *Psychology and Aging, 7*, 643–653.

Head, D., Raz, N., Gunning-Dixon, F., Williamson, A., & Acker, J. D. (2002). Age-related differences in the course of cognitive skill acquisition: The role of regional cortical shrinkage and cognitive resources. *Psychology and Aging, 17*, 72–84.

Hertzog, C. K., Williams, M. V., & Walsh, D. A. (1976). The effect of practice on age differences in central perceptual processing. *Journal of Gerontology, 31*, 428–433.

Hill, R. D., Storandt, M., & Malley, M. (1993). The impact of long-term exercise training on psychological function in older adults. *Journal of Gerontology, 48*, 12–17.

Ho, G., & Scialfa, C. T. (2002). Age, skill transfer, and conjunction search. *Journal of Gerontology: Psychological Sciences, 57B*, 277–287.

Hultsch, D. F., Hertzog, C., Dixon, R. A., & Small, B. J. (1998). *Memory change in the aged.* New York: Cambridge.

Humphrey, D. G., & Kramer, A. F. (1997). Age differences in visual search for feature, conjunction, and triple-conjunction targets. *Psychology and Aging, 12*, 704–717.

Jacoby, L. L. (1998). Invariance in automatic influences of memory: Toward a user's guide for the process-dissociation procedure. *Journal of Experimental Psychology: Learning, Memory and Cognition, 24*, 3–26.

Jennings, J. M., Webster, L. M., Kleykamp, B. A., & Dagenbach, D. (2002). *Executive function training and generalization of a recollection training procedure*. Presented at the Cognitive Aging Conference, Atlanta, GA.

Kelly, C., & Jacoby, L. L. (2000). Recollection and familiarity: Process dissociation. In E. Tulving & F. I. M. Craik (Eds.), *The Oxford handbook of memory* (pp. 215–228). New York: Oxford University Press.

Kempermann, G., Kuhn, H. G., & Gage, F. H. (1997). More hippocampal neurons in adult mice living in an enriched environment. *Nature, 386*, 493–495.

Kliegl, R., Smith, J., & Baltes, P. B. (1989). Testing-the-limits and the study of adult age difference in cognitive plasticity of a mnemonic skill. *Developmental Psychology, 2*, 247–256.

Kliegl, R., Smith, J., & Baltes, P. B. (1990). On the locus and process of magnification of age differences during mnemonic training. *Developmental Psychology, 26*, 894–904.

Kramer, A. F., Colcombe, S. J., McAuley, E., Eriksen, K. I., Scalf, P., Jerome, G. J., Marquez, D. X., Elavsky, S., & Webb, A. (2003). Enhancing brain and cognitive function of older adults through fitness training. *Journal of Molecular Neuroscience.* (In press).

Kramer, A., Humphrey, D., Larish, J., Logan, G., & Strayer, D. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*, 491–512.

Kramer, A. F., Hahn, S., Cohen, N. J., Banich, M. T., McAuley, E., Harrison, C. R., Chason, J., Vakil, E., Bardell, L., Boileau, R. A., & Colcombe, A. (1999). Ageing, fitness and neurocognitive function. *Nature, 400*, 418–419.

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica, 101*, 339–378.

Kramer, A. F., & Larish, J. (1996). Training for attentional control in dual-task settings. In W. Rogers, A. Fisk, & N. Walker (Eds.), *Aging and skilled performance: Advances in theory and applications.* Hillsdale, NJ: Erlbaum.

Kramer, A. F., Larish, J., & Strayer, D. L. (1995). Training for attentional control in dual-task settings: A comparison of young and old adults. *Journal of Experimental Psychology: Applied, 1*, 50–76.

Kramer, A. F., Larish, J., Weber, T., & Bardell, L. (1999). Training for executive control: Task coordination strategies and aging. In D. Gopher & A. Koriat (Eds.), *Attention and Performance XVII.* Cambridge, MA: MIT Press.

Krampe, R. T., & Ericsson, K. A. (1996). Maintaining excellence: Deliberate practice and elite performance in young and older pianists. *Journal of Experimental Psychology: General, 125*, 331–359.

Kray, J., & Lindenberger, U. (2000). Adult age differences in task switching. *Psychology and Aging, 15*, 126–147.

Li, S. C., Linderberger, U., & Frensch, P. (2000). Unifying cognitive aging: From neuromodulation to representation to cognition. *Neurocomputing: An International Journal, 33*, 879–890.

Linderberger, U., & Baltes, P. B. (1997). Intellectual functioning in old and very old age. Cross-Sectional results from the Berlin Aging Study. *Psychology and Aging, 12*, 410–432.

Linderberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age. A strong connection. *Psychology and Aging, 9*, 339–355.

Linderberger, U., Kliegl, R., & Baltes, P. B. (1992). Professional expertise does not eliminate age differences in imagery-based memory performance during adulthood. *Psychology and Aging, 4*, 585–593.

Logan, J. M., Sanders, A. L., Snyder, A. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and non-selective recruitment: Dissociable neural mechanisms associated with cognitive decline in older adults. *Neuron, 33*, 827–840.

MacLullich, A. M. J., Ferguson, K. J., Deary, I. J., Seckl, J. R., Starr, J. M., & Wardlaw, J. M. (2002). Intracranial capacity and brain volumes are associated with cognition in healthy elderly men. *Neurology, 59*, 169–174.

Madden, D. J., Blumenthal, J. A., Allen, P. A., & Emery, C. F. (1989). Improving aerobic capacity in healthy older adults does not necessarily lead to improved cognitive performance. *Psychology and Aging, 4*, 307–320.

Madden, D. J., Turkington, T. G., Coleman, R. E., Provenzale, J. M., DeGrado, T. R., & Hoffman, J. M. (1996). Adult age differences in regional cerebral blood flow during visual word identification: Evidence from PET. *Neuroimage, 3*, 127–142.

Madden, D. J., Turkington, T. G., Provenzale, J. M., Hawk, T. C., & Hoffman, J. M. (1997). Selective and divided visual attention: Age-related changes in regional cerebral blood flow measured by (H_2O)-O-15 PET. *Human Brain Mapping, 5*, 389–409.

Masunaga, H., & Horn, J. (2001). Expertise and age-related changes in components of intelligence. *Psychology and Aging, 16*, 293–311.

Meinz, E. J. (2000). Experience-based attenuation of age-related differences in music cognition. *Psychology and Aging, 15*, 297–312.

Meinz, E. J., & Salthouse, T. A. (1998). The effects of age and experience on memory for visually presented music. *Journals of Gerontology: Psychological Science, 53B*, P60–P69.

Mireles, D. E., & Charness, N. (2002). Computational explorations of the influence of structured knowledge on age-related decline. *Psychology and Aging, 17*, 245–259.

Morrison, J. H., & Hof, P. R. (1997). Life and death of neurons in the aging brain. *Science, 278*, 412–419.

Morrow, D. G., Leirer, V., & Altiere, P. (1992). Aging, expertise and narrative processing. *Psychology and Aging, 7*, 376–388.

Morrow, D. G., Leirer, V., Altiere, P., & Fitzsimmons, C. (1994). When expertise reduces age differences in performance. *Psychology and Aging, 9*, 134–148.

Morrow, D. G., Menard, W. E., Stine-Morrow, E. A. L., Teller, T., & Bryant, D. (2001). The influence of expertise and task factors on age differences in pilot communication. *Psychology and Aging, 16*, 31–46.

Murphy, D. G. M., DeCarli, C., MvIntosh, A. R., Daly, E., Mentis, M. J., Pietrini, P., Szczepanik, J., Schapiro, M. B., Grady, C. L., Horwitz, B., & Rapport, S. I. (1996). Sex differences in human brain morphometry and metabolism: An in vivo quantitative magnetic resonance imaging and positron emission tomography study on the effect of aging. *Archives of General Psychiatry, 53*, 585–594.

Murrell, K. F. H., Powesland, P. F., & Forsaith, B. (1966). A study of pillar-drilling in relation to age. *Occupational Psychology, 36*, 45–52.

Ogawa, S., & Lee, T. M. (1990). Magnetic resonance imaging of blood vessels at high fields: In vivo and in vitro measurements and image simulation. *Magnetic Resonance Medicine, 16*, 9–18.

O'Sullivan, M., Jones, D. K., Summers, P. E., Morris, R. G., Williams, S. C. R., & Markus, H. S. (2001). Evidence for cortical "disconnection" as a mechanism of age-related cognitive decline. *Neurology, 57*, 632–638.

Owsley, C., Ball, K., & Keaton, D. (1995). Relationship between visual sensitivity and target localization in older adults. *Vision Research, 35*, 579–587.

Owsley, C., Ball, K., Sloane, N., Roenker, D., & Bruni, J. (1991). Visual perceptual/cognitive correlates of vehicle crashes in older drivers. *Psychology and Aging, 6*, 403–415.

Park, D. C. (2000). The basic mechanisms accounting for age-related decline in cognitive function. In D. C. Park & N. Schwartz (Eds.), *Cognitive aging: A primer*. Philadelphia, PA: Psychology Press.

Park, D. C., Lautenschlarger, G., Hedden, T., Davidson, N., Smith, A. D., & Smith, P. K. (2003). Models of visuospatial and verbal memory across the lifespan. *Psychology and Aging*. (In press).

Park, D. C., Polk, T. A., Mikels, J. A., Taylor, S. F., & Marshuetz, C. (2001). Cerebral aging: Integration of brain and behavioral models of cognitive function. *Dialogues in Clinical Neuroscience: Cerebral Aging, 3*, 151–165.

Peretti, C.-S., Danion, J. M., Gierski, F., & Grange, D. (2002). Cognitive skill learning and aging: A component process analysis. *Archives of Clinical Neuropsychology, 445–459.*

Pfefferbaum, A., Mathalon, D. H., Sullivan, E. V., Rawles, J. M., Zipursky, R. B., & Kim, K. O. (1994). A quantitative magnetic resonance imaging study of changes in brain morphology from infancy to late adulthood. *Archives of Neurology, 51*, 874–887.

Plude, D., & Doussard-Rossevelt, J. (1989). Aging, selective attention, and feature integration. *Psychology and Aging, 4*, 98–105.

Rabbitt, P. M. A. (1993). Does it all go together when it goes? The Nineteenth Barlett Memorial Lecture *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 46*, 385–434.

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp 1–90). Mahwah, NJ: Lawrence Erlbaum.

Reiman, E. M., Lane, D., Van Petten, C., & Bandetinni, P. A. (2000). Positron emission tomography and functional magnetic resonance imaging. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *Handbook of psychophysiology*. (2nd ed. pp. 85–118). New York: Cambridge University Press.

Resnick, S. M., Goldszal, A. F., Davatzikos, C., Golski, S., Kraut, M. A., Metter, J. E., Bryan, N., & Zonderman, A. B. (2000). One-year age changes in MRI brain volumes in older adults. *Cerebral Cortex, 10*, 464–472.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. S., Hartley, A., Miller, A., Marshuetz, C., & Koeppe, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience, 12*, 174–187.

Riege, W. H. (1971). Environmental influences on brain and behavior of old rats. *Developmental Psychobiology, 4*, 157–167.

Rikli, R., & Edwards, D. (1991). Effects of a three year exercise program on motor function and cognitive processing speed in older women. *Research Quarterly for Exercise and Sport, 62*, 61–67.

Robbins, T. W., James, M., Owen, A. M., Shaakian, B. J., Lawrence, A. D., McInnes, L., & Rabbitt, P. M. A. (1998). A study of performance from tests from the CANTAB battery sensitive to frontal lobe dysfunction in a large sample of normal volunteers: Implications for theories of executive functioning and cognitive aging. *Journal of the International Neuropsychological Society, 4*, 474–490.

Rogers, W. A. (1992). Age differences in visual search: Target and distractor learning. *Psychology and Aging, 7*, 526–535.

Rogers, W. A., & Fisk, A. D. (1991). Are age differences in consistent-mapping visual search due to feature learning or attention training? *Psychology and Aging, 6*, 542–550.

Rogers, W. A., Fisk, A. D., & Hertzog, C. (1994). Do ability-performance relationships differentiate age and practice effects in visual search? *Journal of Experimental Psychology: Learning, Memory and Cognition, 20*, 710–738.

Rosenzweig, M. R., & Bennett, E. L. (1996). Psychobiology of plasticity: Effects of training and experience on brain and behavior. *Behavioral Brain Research, 78*, 57–65.

Salthouse, T. A. (1984). Effects of age and skill in typing. *Journal of Experimental Psychology: General, 113*, 345–371.

Salthouse, T. A. (1990). Influence of experience on age difference in cognitive functioning. *Human Factors, 32*, 551–569.

Salthouse, T. A. (1991). Age and experience effects on the interpretation of orthographic drawings of three-dimensional objects. *Psychology and Aging, 6*, 426–433.

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

Salthouse, T. A., Babcock, R. L., Skovronek, E., Mitchell, D. R. D., & Palmon, R. (1990). Age and experience effects in spatial visualization. *Developmental Psychology, 26*, 128–136.

Salthouse, T. A., & Mitchell, D. R. D. (1990). Effects of age and naturally occurring experience on spatial visualization performance. *Developmental Psychology, 26*, 845–854.

Saczynski, J., & Willis, S. L. (2003). Cognitive training and maintenance of intervention effects in the elderly. Submitted for publication.

Schaie, K. W. (2000). The impact of longitudinal studies on understanding development from young adulthood to old age. *International Journal of Behavioral Development, 24*, 257–266.

Schaie, K. W., & Hofer, S. M. (2001). Longitudinal studies in aging research. In J. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging*(5th ed., pp 53–77). San Diego, CA: Academic Press.

Schaie, K. W., & Willis, S. L. (1986). Can decline in adult intellectual functioning be reversed? *Developmental Psychology, 22*, 223–232.

Schretlen, D., Pearlson, G. D., Anthony, J. C., Aylward, E. H., Augustine, A. M., Davis, A., & Barta, P. (2000). Elucidating the contributions of processing speed, executive ability, and frontal lobe volume to normal age-related differences in fluid intelligence. *Journal of the International Neuropsychological Society, 6*, 52–61.

Scialfa, C. T., Esau, S. P., & Joffe, K. M. (1998). Age, target-distractor similarity, and visual search. *Experimental Aging Research, 24*, 337–358.

Scialfa, C. T., Jenkins, L., Hamaluk, E., & Skaloud, P. (2000). Aging and the development of automaticity in conjunction search. *Journal of Gerontology: Psychological Sciences, 55B*, 27–46.

Scialfa, C. T., & Joffe, K. M. (1997). Age differences in feature and conjunction search: Implications for theories of visual search and generalized slowing. *Aging, Neuropsychology, and Cognition, 4*, 1–21.

Scialfa, C. T., Thomas, D. M., & Joffe, K. M. (1994). Age differences in the useful field of view: An eye movement analysis. *Optometry and Vision Science, 71*, 1–7.

Shear, P. K., Sullivan, E. V., Mathalon, D. H., Lim, K. O., Davis, L. F., Yesavage, J. A., Tinklenberg, J. R., & Pfefferbaum, A. (1995). Longitudinal volumetric computed tomographic analysis of regional brain changes in normal aging and Alzheimer's disease. *Archives of Neurology, 52*, 392–402.

Shiffrin, R. M., & Dumais, S. T. (1981). The development of automatism. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 111–140). Hillsdale, NJ: Erlbaum.

Sit, R. A., & Fisk, A. D. (1999). Age-related performance in a multi-task environment. *Human Factors, 41*, 26–34.

Spirduso, W. W. (1975). Reaction and movement time as a function of age and physical activity level. *Journal of Gerontology, 30*, 18–23.

Terry, R. D., DeTeresa, R., & Hansen, L. A. (1987). Neocortical cell counts in normal human adult aging. *Annals of Neurology, 21*, 530–539.

Tsang, P. S., & Shaner, T. L. (1998). Age, attention, expertise, and time sharing performance. *Psychology and Aging, 13*, 323–347.

Tsang, P. S., & Voss, D. T. (1996). Boundaries of cognitive performance as a function of age and flight experience. *International Journal of Aviation Psychology, 6*, 359–377.

van Praag, H., Kempermann, G., & Gage, F. H. (1999). Running increases cell proliferation and neurogenesis in the adult mouse dentate gyrus. *Nature Neuroscience, 2*, 266–270.

Verhaegehen, P., Kliegl, R., & Mayr, U. (1997). Sequential and coordinative complexity in time-accuracy functions for mental arithmetic. *Psychology and Aging, 12*, 555–564.

Verhaegehen, P., & Marcoen, A. (1996). On the mechanisms of plasticity in young and older adults after instruction in the method of loci: Evidence for an amplification model. *Psychology and Aging, 11*, 164–178.

Verhaegehen, P., Marcoen, A., & Goossens, L. (1992). Improving memory performance in the aged through mnemonic training: A meta-analytic study. *Psychology and Aging, 7*, 242–251.

Vinters, H. V. (2001). Aging and the human nervous system. In J. Birren (Ed.), *Handbook of the psychology of aging* (5th ed., pp 135–159). San Diego, CA: Academic Press.

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*, 272–290.

Wiese, B. S., Freund, A. M., & Baltes, P. B. (2000). Selection, optimization, and compensation: An action-related approach to work and partnership. *Journal of Vocational Behavior, 57*, 273–300.

Wiese, B. S., Freund, A. M., & Baltes, P. B. (2002). Subjective career success and emotional well being: Longitudinal predictive power of selection, optimization and compensation. *Journal of Vocational Behavior, 60*, 321–335.

Willis, S. L., & Schaie, K. W. (1994). Cognitive training in the normal elderly. In F. Forette, Y. Christen, & F. Boller (Eds.), *Plasticité cérébrale et stimulation cognitive* (pp. 91–113). Paris: Foundation National de Gérontologie.

Ybarra, O., Chan, E., & Park, D. (2001). Young and old adult concerns about mortality and competences. *Motivation and Emotion, 25*, 85–100.

Zelinski, E., & Burnight, K. P. (1997). Sixteen-year longitudinal and time lag changes in memory and cognition in older adults. *Psychology and Aging, 12*, 503–513.

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