PERGAMON

Neuroscience and Biobehavioral Reviews 26 (2002) 819–825

NEUROSCIENCE AND BIOBEHAVIORAL REVIEWS

www.elsevier.com/locate/neubiorev

Hemispheric asymmetry and aging: right hemisphere decline or asymmetry reduction

Florin Dolcos[a,b,*], Heather J. Rice[a], Roberto Cabeza[a]

[a]*Center for Cognitive Neuroscience, Duke University, P.O. Box 90999 (or LSRC Building, Room B203), Durham, NC 27708, USA*

[b]*Centre for Neuroscience of the University of Alberta, Edmonton, Canada*

Received 21 June 2002; accepted 17 August 2002

Abstract

We review evidence for two models of hemispheric asymmetry and aging: the right hemi-aging model, which proposes that the right hemisphere shows greater age-related decline than the left hemisphere, and the hemispheric asymmetry reduction in old adults (HAROLD) model, which proposes that frontal activity during cognitive performance tends to be less lateralized in older than in younger adults. The right hemi-aging model is supported by behavioral studies in the domains of cognitive, affective, and sensorimotor processing, but the evidence has been mixed. In contrast, available evidence is generally consistent with the HAROLD model, which is supported primarily by functional neuroimaging evidence in the domains of episodic memory encoding and retrieval, semantic memory retrieval, working memory, perception, and inhibitory control. Age-related asymmetry reductions may reflect functional compensation or dedifferentiation, and the evidence, although scarce, tends to support the compensation hypothesis. The right hemi-aging and the HAROLD models are not incompatible. For example, the latter may apply to prefrontal regions and the former to other brain regions.

Keywords: HAROLD model; Right hemi-aging model; Neuropsychology

It is well known that the brain hemispheres are anatomically and functionally asymmetric. Even though the molecular and genetic bases of this asymmetry are not well understood [1], its existence is supported by abundant converging evidence from in vivo and post-mortem neuroanatomy, neurochemistry, neuropsychology, neuroimaging, and behavioral research [2–4]. There is also evidence that these asymmetries are affected by conditions that alter the anatomical and functional integrity of the brain, such as brain damage and aging. In this article, we review evidence for two different models of hemispheric asymmetry and aging: the right hemi-aging model [5,6], which proposes that the right hemisphere shows greater age-related decline than the left hemisphere, and the hemispheric asymmetry reduction in old adults (HAROLD) model [7], which proposes that frontal activity during cognitive performance tends to be less lateralized in older than in younger adults.

* Corresponding author. Tel.: +1-919-668-2299; fax: +1-919-681-0815.
E-mail address: fdolcos@duke.edu (F. Dolcos).

1. Right hemi-aging model

The right hemi-aging hypothesis states that age-related cognitive declines affect functions attributed to the right hemisphere to a greater degree than those associated with the left hemisphere [5,6]. The validity of this hypothesis has been investigated in various functional domains. In this article we briefly review evidence from the areas of verbal/spatial, affective, and sensorimotor functions, which are lateralized in young adults and relevant for aging research.

1.1. Verbal/spatial

The first cognitive evidence for the right hemi-aging hypothesis comes from studies comparing the effect of aging on verbal and spatial tasks [8]. This asymmetry involving the type of information processed by the two hemispheres (verbal/spatial) is the clearest functional hemispheric asymmetry: the left hemisphere is more involved in the processing of verbal information, whereas the right hemisphere is more involved in the processing of

0149-7634/02/$ - see front matter
PII: S0149-7634(02)00068-4

pictorial/spatial information [9,10]. Using the Wechsler Adult Intelligence Scale (WAIS), Goldstein and Shelley [8] found that elderly participants were less impaired on the verbal component, which relies more heavily on the left hemisphere, than on the spatial component, which is more dependent on the right hemisphere. Consistent with these findings, Klisz [11] found that performance of elderly subjects resembled that of patients with right-hemisphere damage when tested with a neuropsychological battery intended to diagnose lateralized brain injury. Taken together, these findings suggest that functions attributed to the right hemisphere are more affected by aging. However, additional evidence has shown that, when test variables such as task complexity are controlled, elderly performance on verbal and spatial tasks does not differ significantly [12]. These findings do not support the idea that the right hemisphere processing capabilities are selectively affected by aging.

Evidence for the right hemi-aging hypothesis in other cognitive domains has also been inconclusive. Employing dichotic listening tasks to relate encoding, retention, and retrieval deficits in elderly to their learning performance, Clark and Knowles [13] observed age-related declines in both written and vocal recall, predominantly for material presented to the left ear. The authors attributed these results to a deficiency during encoding, probably due to an age-related decrease in left ear/right hemisphere processing capabilities. However, this effect was not replicated by later studies [14,15]. For example, a study by Schear and Nebes [15] intended to investigate the effect of aging on memory for spatial vs. verbal information, did not find any evidence of a greater decline with age in spatial compared to verbal memory. Similar results were reported in a recent study comparing visuospatial and verbal memory across the life span [16].

1.2. Affective domain

The right hemi-aging hypothesis has also been explored in the affective domain. The results of studies investigating hemispheric asymmetries in emotional processing are generally interpreted in the context of two more influential hypotheses: the right hemisphere hypothesis and the valence hypothesis. The right hemisphere hypothesis proposes that emotions are mainly processed in the right hemisphere independent of emotional valence [17], whereas the valence hypothesis proposes that pleasant emotions are mainly processed in the left hemisphere and unpleasant emotions are mainly processed in the right hemisphere [18]. To test the right hemi-aging hypothesis in the affective domain, McDowell et al. [19] compared accuracy and intensity measures of emotional and neutral facial recognition in both young and elderly participants and found that older subjects exhibited a deficit in the perception of unpleasant emotions when compared to young subjects. However, older subjects were as accurate as young subjects in identifying happy faces. Interpreting these results in the context of the right hemisphere hypothesis of emotional processing, the authors have concluded that their findings only partially support the right hemi-aging hypothesis. However, if interpreted in the context of the valence hypothesis of emotional processing, these results fully support the right hemi-aging hypothesis. Nevertheless, the results of other studies investigating emotional faces do not support this hypothesis. For instance, a study investigating the effect of aging on processing of emotional facial expressions [20] found that the patterns of left-right asymmetries were comparable for younger and older participants.

1.3. Sensorimotor processing

Finally, the right hemi-aging hypothesis has also been investigated in lower-level processing (e.g. simpler sensory/perceptual and motor tasks) and again the evidence is not conclusive. Weller & Latimer-Sayer [21] used a sensory-motor task (i.e. pegboard) to investigate changes in manipulative skill as a function of age and found evidence supporting the right hemi-aging hypothesis; abilities associated with the right hemisphere were more affected by aging when compared with those associated with the left hemisphere. Additional studies [22] reported similar results. On the other hand, studies of perceptual asymmetries using visual-field presentations have not systematically reported evidence supporting the right hemi-aging hypothesis [14,20,23].

In summary, although there are findings supporting the notion that functions attributed to the right hemisphere are more affected by aging [8,11,13–15,19–29] the overall pattern of results is not clear [12,14,15,20,23,30–34]. One possible explanation for the inconsistent results is differences in methodology. For instance, studies reporting a larger right-ear advantage with age (left-lateralized hemisphere asymmetry) involved more complex tasks than those showing no difference in the magnitude of right-ear advantage or reduced asymmetry [24]. If we assume that the cerebral hemispheres cooperate to perform complex, but not simple tasks [35], it is more likely to observe a change in hemispheric asymmetry associated with more complex tasks. Another possible explanation of the inconsistent findings is that differential age-related decline applies only to some regions within the right hemisphere [36]. If this restricted right hemi-aging hypothesis is correct, a differential effect of aging on the right hemisphere could be found in some tasks but not others depending on the particular brain regions involved. Consistent with this idea, it has been suggested that tasks relying on posterior right hemisphere are more susceptible to age-related decline [36,37]. At any rate, regardless of whether these inconsistencies are related to the complexities of the tasks or the right hemisphere regions they engage, it is clear that further research on the right hemi-aging hypothesis is required.

2. Hemispheric asymmetry reduction in older adults (HAROLD)

As mentioned earlier, the HAROLD model states that, under similar conditions, prefrontal cortex (PFC) activity tends to be less lateralized in older adults than in younger adults. This model is supported by functional neuroimaging evidence in the domains of episodic memory encoding and retrieval, semantic memory retrieval, working memory, perception, and inhibitory control (Table 1). Moreover, evidence has also been obtained using other methods, such as electrophysiological [38] and behavioral [39] measures. Here we mention only a few examples of functional neuroimaging evidence in the domains of episodic memory and working memory.

2.1. Episodic memory

HAROLD was first noted in the episodic memory retrieval domain, probably because in this cognitive domain there was a strong expectation concerning the lateralization of PFC activity. During episodic retrieval, PFC activity tends to be right lateralized in young adults [40,41]. This, it is not surprising to find right lateralized PFC activity during a cued-recall task in young adults. Interestingly, in older adults, bilateral PFC activations were found during the same task [42]. The finding of right-lateralized activity in young adults coupled with bilateral activity in older adults was replicated on a variety of episodic retrieval tasks, including word-stem cued recall [43], word recognition [44], and face recognition [45]. Thus, HAROLD during episodic retrieval has been demonstrated for both recall and recognition, and for both verbal and nonverbal materials. Moreover, HAROLD can be also found during episodic memory encoding [46–48]. For example, Logan and colleagues [47] found that during intentional learning of words, young adults showed more activity in left than in right PFC, whereas older adults showed similar levels of activity in both hemispheres. Furthermore, when subjects were provided with an explicit encoding strategy (concrete-abstract decision), the overall level of PFC activity in older adults increased to the level of young adults, but continued to show a bilateral pattern of activation. This finding suggests that HAROLD does not reflect the adoption of an alternative cognitive strategy, but rather reflects a change in neural architecture.

Table 1
PET/fMRI activity in left and right PFC in younger and older adults

Cognitive domain	Younger		Older	
Imaging technique: materials/task (reference)	Left	Right	Left	Right
Episodic retrieval				
PET: word pair cued-recall [42]	−	++	+	+
PET: word stem cued-recall [43]	−	+	+	+
PET: word recognition [44]	−	+	++	++
PET: face recognition [45]	−	++	+	+
Episodic encoding/semantic retrieval				
fMRI: word-incidental [46]	++	+	+	+
fMRI: word-intentional [47]	++	+	+	+
fMRI: word-incidental [47]	++	+	++	++
fMRI: word-SME [48]	++	+	++	++
Working memory				
PET: Letter DR [50]	+	−	+	+
PET: Location DR [50]	−	+	+	+
PET: Number N-back: [51]	+	+++	++	++
Perception				
PET: face matching [71, Exp. 2]	−	+	++	++
PET: Face matching [72]	+	+++	++	++
Inhibitory control				
fMRI: No-GO trials [73]	−	+	+	+

Note: Plus signs indicate significant activity in the left or right PFC, and minus signs indicate nonsignificant activity. The number of pluses is an approximate index of the relative amount of activity in left and right PFC in each study, and it cannot be compared across studies. DR, delayed response task; SME, subsequent memory effect.

2.2. Working memory

In the working memory domain, there were also expectations concerning the lateralization of PFC activity; several studies have shown that PFC activity during verbal working memory tasks tended to be left lateralized whereas PFC activity during spatial tasks tended to be right lateralized [49]. Consistent with this pattern, Reuter-Lorenz et al. [50] found that in younger adults PFC activity during a delayed response task was significant in the left hemisphere for verbal stimuli but in the right hemisphere for spatial stimuli. In contrast, PFC activity was significant bilaterally for both types of stimuli in older adults. In addition, a recent study investigating the early effects of aging on working memory found evidence for HAROLD [51]. Using an N-back task, Dixit et al. [51] found greater neural activity in right PFC than in left PFC for younger adults, whereas middle-aged subjects exhibited bilateral activity. This effect suggests that the HAROLD pattern may develop before the age of 50. As shown in Table 1, age-related asymmetry reductions can be found when PFC activity is right lateralized in young adults, as in the case of episodic retrieval, as well as when PFC activity is left lateralized in young adults, as in the case of episodic encoding/semantic retrieval. The results in the working memory domain indicate that this is also true when the task is constant and that it is the nature of the information processed that affects the lateralization of PFC. In other words, the working memory data demonstrate that age-related asymmetry reductions may be found not only for process-related hemispheric asymmetries (e.g. episodic retrieval vs. semantic retrieval) but also for stimuli-related hemispheric asymmetries (e.g. verbal vs. spatial working memory).

While growing evidence continues to support the HAROLD model, the function of the reduction in asymmetry is still under debate. One hypothesis is that bihemispheric recruitment in older adults plays a compensatory role in the aging brain [42]. This compensation account is consistent with evidence that bilateral activity in older adults is associated with enhanced cognitive performance [50] and that the particular brain regions showing age-related increases in activation are likely to enhance performance in the task being investigated. For example, there is evidence that left PFC can contribute to episodic retrieval performance. Although PFC activity during episodic retrieval is usually right lateralized, left PFC activations have also been found in many studies and seem to be associated with demanding retrieval tasks [52]. Since the same tasks tend to be more demanding for older than for younger adults, it is possible that older adults recruit left PFC in order to cope with increased retrieval demands. The compensation account is also consistent with evidence that recovery of function following unilateral brain damage is associated with the recruitment of the unaffected contralateral hemisphere [53,54].

However, there is an alternative view of age-related asymmetry reductions, the dedifferentiation account, which proposes that the reductions reflect age-related difficulty in engaging specialized neural mechanisms that were available during young adulthood [55]. It has been suggested that there is a gradual evolution from an amorphous general ability into a group of distinct cognitive processes during childhood development [56] and that during the aging process different functions once again begin to rely on similar executive or organizing resources [57,58]. In other words, a process of functional differentiation during childhood is reversed during aging by a process of functional dedifferentiation. This account is consistent with evidence that correlations among different cognitive measures, and between cognitive and sensory measures, tend to increase with age [58].

These two accounts of HAROLD were recently tested using PET [59]. Before scanning two groups of older adults were selected from a larger sample, one group that performed as well as a young group in a battery of memory tests (old-high group) and another group that performed significantly worse than the young group (old-low group). The two groups of older adults and the group of young adults were then scanned in a source memory task, which was shown to be associated with right PFC activity in young adults in a previous study [60]. The compensation hypothesis predicted bilateral PFC activity in old-high participants, whereas the dedifferentiation hypothesis predicted bilateral PFC in old-low participants. As illustrated by Fig. 1, the results supported the compensation hypothesis. Old-low participants showed no reduction in lateralization, whereas old-high participants showed a bilateral activation pattern. This finding was interpreted as suggesting that the old-low participants recruited similar PFC regions as young adults but used them inefficiently, whereas old-high participants compensated for age-related memory decline by reorganizing the episodic retrieval network. In contrast, the results in Fig. 1 are inconsistent with the dedifferentiation view, which predicts the asymmetry reduction, as other forms of age-related neurocognitive decline, should be more pronounced in low-performing than in high-performing older adults. It is important to note that

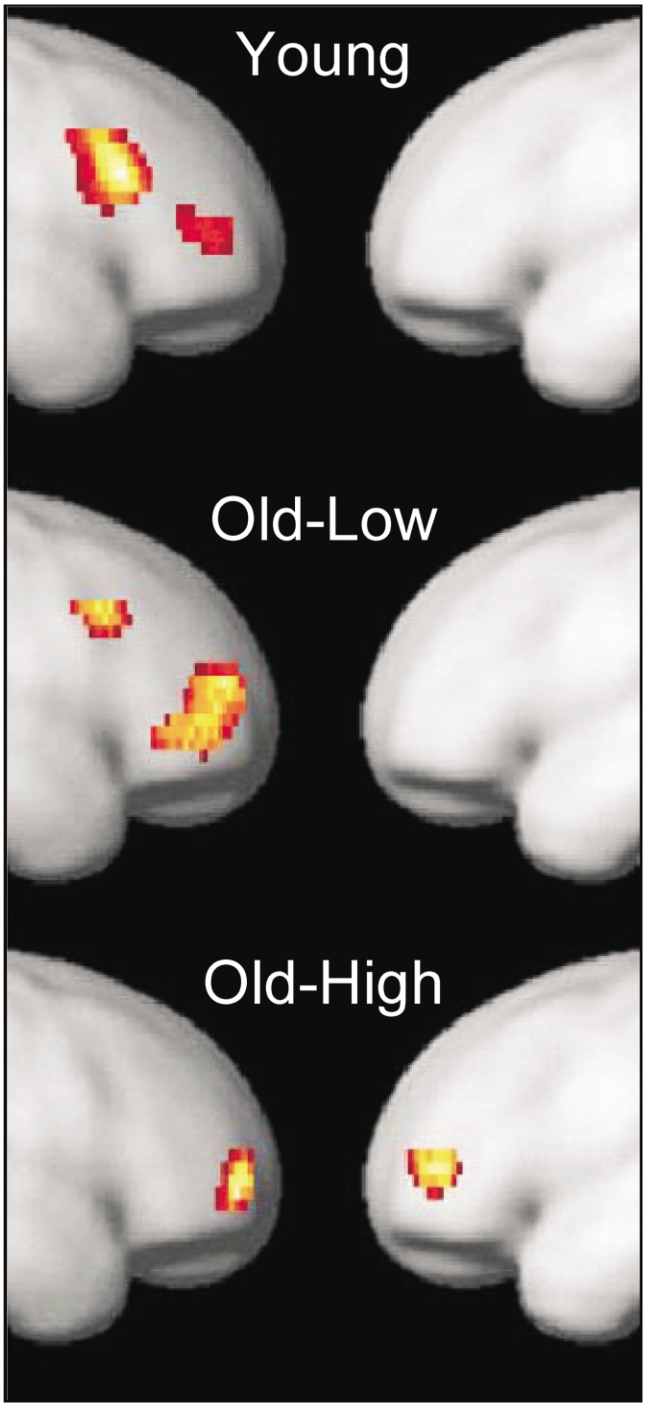

Fig. 1. PFC activity supporting the compensation account of HAROLD. In a source memory task, low performing participants (old-low) showed no reduction in lateralization, whereas high-performing participants (old-high) showed a bilateral activation pattern.

the term 'dedifferentiation' may also be used in a more neutral sense, as a description of more widespread activation pattern [61]. In that sense, the term dedifferentiation is not incompatible with the concept of dedifferentiation [7], and one may even talk about compensatory forms of dedifferentiation [61]. However, since the term dedifferentiation implies a deficit (i.e. de-differentiation denotes a lack or loss of differentiation) using it to merely mean 'widespread activation pattern' can be confusing.

Recently, Randy Buckner suggested an alternative explanation based upon previous research revealing age-related decreases in callosal volume [62,63]. If one assumes there is competition between the two hemispheres in young adults, an age-related decrease in lateralization could reflect an age-related reduction of interhemispheric inhibition due to callosal deterioration [64]. Yet, the notion that the two hemispheres compete with each other in young adults has not received strong empirical support [65]. On the contrary, there are strong suggestions that the two hemispheres collaborate during the performance of cognitive tasks, particularly when the tasks are more complex or difficult [35,66–68]. The issue of task difficulty is particularly important when comparing young and elderly groups, because what is difficult for elderly subjects may not be that difficult for young subjects. Consistent with the compensation view, an experiment investigating the effect of aging on performance of a task with three difficulty levels [39] suggests that older adults may indeed benefit from bi-hemispheric processing at levels of task complexity for which unilateral processing seems to be enough for young adults.

In summary, evidence for HAROLD continues to mount within the functional neuroimaging literature, across such domains as perception, episodic, semantic, and working memory. However, it is necessary to address a caveat of the HAROLD model. Evidence for HAROLD comes predominantly from neuroimaging studies. The functional imaging studies reviewed here do not take into account structural changes that have been shown to occur during the aging process [69]. Consequently, it is unclear whether differences in activation patterns reflect structural changes within the neural architecture, rather than alterations in recruitment patterns. Although the neuroimaging evidence of age-related structural changes is not clear with regard to the issue of hemispheric asymmetry, given that different brain areas show preferential patterns of age-related decline [70], it would be interesting to simultaneously investigate functional and structural aspects to see how changes in activation patterns relate to structural changes during aging.

3. Conclusion

The two models reviewed here provide different views of age-related changes in hemispheric asymmetry. The right hemi-aging model proposes that the right hemisphere shows greater age-related decline than the left hemisphere [5,6], whereas the HAROLD model [7] proposes that frontal activity during cognitive performance tends to be less lateralized in older than in younger adults. Whereas empirical evidence relevant to the right hemi-aging model has been mixed, empirical evidence relevant to the HAROLD model has been largely consistent. Although no study has explicitly compared the two models, several of the functional neuroimaging studies reviewed earlier have investigated conditions in which the two models make opposite predictions. These conditions involve tasks in which PFC activity in young adults is left lateralized. Tasks in which PFC in young adults is right lateralized are not very useful for testing the models because in such conditions both models predict a more symmetric activation pattern in older adults (either due to an age-related reduction in right hemisphere function or to a reduction in hemispheric asymmetry). In contrast, when PFC activity is left lateralized in young adults, the two models make opposite predictions: the right hemi-aging model predicts an increased in hemispheric asymmetry, whereas HAROLD predicts reduced hemispheric asymmetry. The results of three functional neuroimaging studies of episodic encoding/semantic retrieval [46–48] support the latter prediction. At any rate, the two models are not necessarily mutually exclusive. Whereas the right hemi-aging hypothesis attempts to account for changes throughout the entire brain, HAROLD primarily accounts for changes in PFC. It may be that aging results in differing patterns of hemispheric asymmetry throughout the brain, with regions such as the occipital and temporal lobes exhibiting a pattern more indicative of the right hemi-aging hypothesis, while PFC shows a reduction in asymmetry. Therefore, it would be important to compare the effects of aging on the lateralization of brain activity both inside and outside PFC.

References

[1] Geschwind DH, Miller BL. Molecular approaches to cerebral laterality: development and neurodegeneration. Am J Med Genet 2001;101:370–81.

[2] Davidson RJ, Hugdahl K, editors. Brain asymmetry. Cambridge, MA: MIT Press; 1995.

[3] Geshwind DH, Iacobini M. Structural and functional asymmetries of the frontal lobes. In: Miller B, Cummings J, editors. The frontal lobes. New York: Guilford Publications; 1999. p. 45–70.

[4] Hellige JB. Hemispheric asymmetry: what's right and what's left. Cambridge, MA: Harvard University Press; 1993.

[5] Albert MS, Moss MB. Geriatric neuropsycholgy. New York: Guilford Press; 1988.

[6] Brown JW, Jaffe J. Hypothesis on cerebral dominance. Neuropsychologia 1975;13:107–10.

[7] Cabeza R. Hemispheric asymmetry reduction in old adults: the HAROLD Model. Psychol Aging 2002;17:85–100.

[8] Goldstein G, Shelly C. Does the right hemisphere age more rapidly than the left? J Clin Neuropsychol 1981;3:65–78.

[9] Nebes RD. Hemispheric specialization in commissurotomized man. Psychol Bull 1974;81:1–14.

[10] Sergent J, Ohta S, MacDonald B. Functional neuroanatomy of face and object processing. Brain 1992;115:15–36.
[11] Klisz D. Neuropsychological evaluation in older persons. In: Storandt M, Siegler IC, Elias MF, editors. The clinical psychology of aging. New York: Plenum Publishing; 1978. p. 71–95.
[12] Elias MF, Kinsbourne M. Age and sex differences in the processing of verbal and non-verbal stimuli. J Gerontol 1974;29:162–71.
[13] Clark LE, Knowles JB. Age differences in dichotic listening performance. J Gerontol 1973;28:173–8.
[14] Nebes RD, Madden DJ, Berg WD. The effect of age on hemispheric asymmetry in visual and auditory identification. Exp Aging Res 1983; 9:87–91.
[15] Schear JM, Nebes RD. Memory for verbal and spatial information as a function of age. Exp Aging Res 1980;6:271–81.
[16] Park DC, Lautenschlager G, Hedden T, et al. Models of visuospatial and verbal memory across the adult life span. Psychol Aging 2002;17: 299–320.
[17] Borod JC, Koff E, Caron H. Right hemisphere specialization for the expression and appreciation of emotion: a focus on the face. In: Perecman E, editor. Cognitive processing in the right hemisphere. New York: Academic Press; 1983. p. 83–110.
[18] Davidson RJ. Cerebral asymmetry, emotion and affective style. In: Davidson RJ, Hugdahl K, editors. Brain asymmetry. Cambridge, MA: MIT Press; 1995. p. 361–87.
[19] McDowell CL, Harrison DW, Demaree HA. Is right hemisphere decline in the perception of emotion a function of aging? Int J Neurosci 1994;79:1–11.
[20] Cherry BJ, Hellige JB, McDowd JM. Age differences and similarities in patterns of cerebral hemispheric asymmetry. Psychol Aging 1995; 10:191–203.
[21] Weller MP, Latimer-Sayer DT. Increasing right hand dominance with age on a motor skill task. Psychol Med 1985;15:867–72.
[22] Riege WH, Metter EJ, Williams MV. Age and hemispheric asymmetry in nonverbal tactual memory. Neuropsychologia 1980; 18:707–10.
[23] Nebes RD. Hemispheric specialization in the aged brain. In: Trevarthen C, editor. Brain circuits and functions of the mind: essays in honor of Roger W. Sperry. Cambridge, England: Cambridge University Press; 1990. p. 364–70.
[24] Rastatter MP, Lawson-Brill C. Reaction times of aging subjects to monaural verbal stimuli: some evidence for a reduction in right-hemisphere linguistic processing capacity. J Speech Hear Res 1987; 30:261–7.
[25] Billings LS, Harrison DW, Alden JD. Age differences among women in the functional asymmetry for bias in facial affect perception. Bull Psychodyn Soc (Bull Psychon Soc) 1993;31:317–20.
[26] Lima SD, Hale S, Myerson J. How general is general slowing? Evidence from the lexical domain. Psychol Aging 1991;6:416–25.
[27] Meudell PR, Greenhalgh M. Age-related differences in left and right hand skill and in visuospatial performance: their possible relationships to the hypothesis that the right hemisphere ages more rapidly than the left. Cortex 1987;23:431–45.
[28] Polster MR, Rapcsak SZ. Hierarchical stimuli and hemispheric specialization: two case studies. Cortex 1994;30:487–97.
[29] Rastatter MP, McGuire RA. Some effects of advanced aging on the visual-language processing capacity of the left and right hemispheres: evidence from unilateral tachistoscopic viewing. J Speech Hear Res 1990;33:134–40.
[30] Benton AL, Eslinger PJ, Damasio AR. Normative observations on neuropsychological test performances in old age. J Clin Neuropsychol 1981;3:33–42.
[31] Byrd M, Moscovitch M. Lateralization of peripherally and centrally masked words in young and elderly people. J Gerontol 1984;39: 699–703.
[32] Mittenberg W, Seidenberg M, O'Leary DS, DiGiulio DV. Changes in cerebral functioning associated with normal aging. J Clin Exp Neuropsychol 1989;11:918–32.
[33] Moreno CR, Borod JC, Welkowitz J, Alpert M. Lateralization for the expression and perception of facial emotion as a function of age. Neuropsychologia 1990;28:199–209.
[34] Obler LK, Woodward S, Albert ML. Changes in cerebral lateralization in aging. Neuropsychologia 1984;22:235–40.
[35] Weissman DH, Banich MT. The cerebral hemispheres cooperate to perform complex but not simple tasks. Neuropsychology 2000;14: 41–59.
[36] Gerhardstein P, Peterson MA, Rapcsak SZ. Age-related hemispheric asymmetry in object discrimination. J Clin Exp Neuropsychol 1998; 20:174–85.
[37] Lamb LC, Robertson MR. The processing of hierarchical stimuli: effects of retinal loci, locational uncertainty, and stimulus identity. Percept Psychophys 1988;44:172–81.
[38] Bellis TJ, Nicol T, Kraus N. Aging affects hemispheric asymmetry in the neural representation of speech sounds. J Neurosci 2000;20: 791–7.
[39] Reuter-Lorenz PA, Stanczak L, Miller AC. Neural recruitment and cognitive aging: two hemispheres are better than one, especially as you age. Psychol Sci 1999;10:494–500.
[40] Tulving E, Kapur S, Craik FIM, et al. Hemispheric encoding/retrieval asymmetry in episodic memory: positron emission tomography findings. Proc Natl Acad Sci USA 1994;91:2016–20.
[41] Nyberg L, Cabeza R, Tulving E. PET studies of encoding and retrieval: the HERA model. Psychon Bull Rev 1996;3:135–48.
[42] Cabeza R, Grady CL, Nyberg L, et al. Age-related differences in neural activity during memory encoding and retrieval: a positron emission tomography study. J Neurosci 1997;17:391–400.
[43] Bäckman L, Almkvist O, Andersson J, et al. Brain activation in young and older adults during implicit and explicit retrieval. J Cogn Neurosci 1997;9:378–91.
[44] Madden DJ, Turkington TG, Provenzale JM, et al. Adult age differences in functional neuroanatomy of verbal recognition memory. Hum Brain Mapp 1999;7:115–35.
[45] Grady CL, Bernstein LJ, Beig S, Siegenthaler AL. The effects of encoding strategy on age-related changes in the functional neuroanatomy of face memory. Psychol Aging 2002;17:7–23.
[46] Stebbins GT, Carrillo MC, Dorman J, et al. Aging effects on memory encoding in the frontal lobes. Psychol Aging 2002;17:44–55.
[47] Logan JM, Sanders AL, Snyder AZ, et al. Under-recruitment and nonselective recruitment: dissociable neural mechanisms associated with aging. Neuron 2002;33:827–40.
[48] Morcom AM, Good CD, Frackowiak RS, Rugg MD. Age effects on the neural correlates of successful encoding. In press, Brain.
[49] Smith EE, Jonides J. Storage and executive processes in the frontal lobes. Science 1999;283:1657–61.
[50] Reuter-Lorenz P, Jonides J, Smith ES, et al. Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. J Cogn Neurosci 2000;12:174–87.
[51] Dixit NK, Gerton BK, Dohn P, et al. Age-related changes in rCBF activation during an n-back working memory paradigm occur prior to age 50. Neuroimage 2000;5(Part 2):S94.
[52] Nolde SF, Johnson MK, Raye CL. The role of prefrontal cortex during tests of episodic memory. Trends Cogn Sci 1998;2:399–406.
[53] Silvestrini M, Cupini LM, Placidi F, et al. Bilateral hemispheric activation in the early recovery of motor function after stroke. Stroke 1998;29:1305–10.
[54] Cao Y, Vikingstad EM, Paige George K, et al. Cortical language activation in stroke patients recovering from aphasia with functional MRI. Stroke 1999;30:2331–40.
[55] Li S-C, Lindenberger U. Cross-level unification: a computational exploration of the link between deterioration of neurotransmitter systems dedifferentiation of cognitive abilities in old age. In: Nilsson L-G, Markowitsch HJ, editors. Cognitive neuroscience of memory. Seattle, WA, US: Hogrefe and Huber Publishers; 1999. p. 103–46.
[56] Garret HL. A developmental theory of intelligence. Am Psychol 1946; 1:372–8.

[57] Balinsky B. An analysis of the mental factors of various groups from nine to sixty. Genet Psychol Monogr 1941;23:191–234.
[58] Baltes PB, Lindenberger U. Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? Psychol Aging 1997;12: 12–21.
[59] Cabeza R, Anderson ND, Kester J, McIntosh AR. Aging gracefully: compensatory brain activity in high-performing older adults. Neuroimage 2002; in press.
[60] Cabeza R, Anderson ND, Kester J, et al. Involvement of prefrontal regions on episodic retrieval: evidence for a generate-recognize asymmetry model. Brain Cogn 2001;47:62–6.
[61] Park DC, Polk T, Mikels JA, et al. Cerebral aging: integration of brain and behavioral models of cognitive function. Dialog Clin Neurosci 2001;3:151–64.
[62] Driesen NR, Raz N. The influence of sex, age, and handedness on corpus callosum morphology: a meta-analysis. Psychobiology 1995; 23:240–7.
[63] Jeeves MA, Moes P. Interhemispheric transfer time differences related to aging and gender. Neuropsychologia 1996;34:627–36.
[64] Buckner RL. Age-related changes in neural activity during episodic memory. Symposium on neuroscience. Aging & Cognition; 2002.
[65] Chiarello C, Maxfield L. Varieties of interhemispheric inhibition, or how to keep a good hemisphere down. Brain Cogn 1996;36:81–108.
[66] Banich MT, Belger A. Interhemispheric interaction: how do the hemispheres divide and conquer a task? Cortex 1990;26:77–94.
[67] Berryman ML, Kennelly KJ. Letter memory loads change more than visual-field advantage: interhemispheric coupling effects. Brain Cogn 1992;18:152–68.
[68] Brown WS, Jeeves MA. Bilateral visual field processing and evoked potential interhemispheric transmission time. Neuropsychologia 1993;31:1267–81.
[69] Raz N. Aging of the brain and its impact on cognitive performance: integration of structural and functional findings. In: Craik FIM, Salthouse TA, editors. Handbook of aging and cognition—II. Mahwah, NJ: Erlbaum; 2000. p. 1–90.
[70] Raz N, Gunning FM, Head D, et al. Selective aging of the human cerebral cortex observed in vivo: differential vulnerability of the prefrontal gray matter. Cereb Cortex 1997;7:268–82.
[71] Grady CL, Maisog JM, Horwitz B, et al. Age-related changes in cortical blood flow activation during visual processing of faces and location. J Neurosci 1994;14:1450–62.
[72] Grady CL, McIntosh AR, Horwitz B, Rapoport SI. Age-related changes in the neural correlates of degraded and nondegraded face processing. Cogn Neuropsychol 2000;217:165–86.
[73] Nielson KA, Langenecker SA, Garavan HP. Differences in the functional neuroanatomy of inhibitory control across the adult lifespan. Psychol Aging 2002;17:56–71.