FM sweep direction was assessed by comparing responses to upward- and downward-directed sweeps at the preferred speed. An index of direction selectivity (DS) is calculated using the following equation: $DS = (RU - RD)/(RU + RD)$, where DS is the index of direction selectivity and RU and RD are the responses (PFR in spikes/s) to upward- and downward-directed FM sweeps, respectively. A DS index equal to or greater than $+0.33$, corresponded to a preference for upward-directed FM sweeps, while an index value equal to or greater than -0.33 corresponded to a downward-directed FM preference.

Results. The average CF for the cortical cells was 14.2 kHz for the young rats and 11.0 kHz for the old rats. In terms of direction selectivity, there was no significant difference between young and old animals. For the young animals, just over half (56%) of the units exhibited no preference for the direction of FM sweeps. Of the cells that were direction selective, most (75%) preferred upward-directed sweeps. For the old animals, the majority of units (54%) were direction-selective. Of these direction-selective units, 62% preferred upward-directed FM sweeps. For preferred speed, there was a significant difference in temporal processing speed between young and old animals ($\xi^2 = 7.82$; $p < 0.05$). The largest percentage of cells (67%) recorded from young animals responded most vigorously to the fast and medium speed, with relatively few units preferring the slower speeds. In the old rats, the majority of units (67%) responded best to the slow speeds with relatively few units preferring the medium and fast speeds (33%). These results suggest a neurophysiological basis for the difference in preferred speed of FM stimuli between the cortical cells from young and old rats.

In conclusion, our results provide the first evidence of a neural locus for temporal processing speed changes between the young and senescent auditory system. This or some closely allied alteration in cortical processing with age may underlie some of the difficulties experienced by many older individuals in discriminating speech.

8. Age-Related Changes in Regional Cerebral Blood Flow Associated with Item and Temporal-Order Memory Retrieval

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Young and older adults studied a word list and were then PET scanned while retrieving information about what words were in the list (item retrieval) or when words occurred within the list (temporal-order retrieval). There were three main findings. First, younger but not older adults engaged right prefrontal regions more during temporal-order retrieval than during item retrieval. This result is consistent with the hypothesis that context memory deficits in older adults are due to frontal dysfunction. Second, ventromedial activity during item retrieval was relatively unaffected by aging. This result concurs with the hypothesis that automatic retrieval operations mediated by the medial temporal lobes are spared by aging. Third, older adults showed weaker activations than young adults in the right prefrontal cortex, but showed stronger activations in the left prefrontal cortex. This last result may be interpreted as evidence for functional compensation in older adults.

Rationale

The present study was motivated by three well-supported findings. First, structural and functional changes in the frontal lobes contribute to older adults' memory problems (for a review, see West, 1996). Second, context memory depends more on frontal function than does content memory (for a review, see Schacter, 1987). For example, we recently showed using PET that prefrontal regions were more activated during temporal-order retrieval than during item retrieval (Cabeza, Mangels, Nyberg, Habib, Houle, McIntosh, & Tulving, 1997c). Third, age-related impairments generally are greater in context memory than in content memory (for a review, see Spencer & Raz, 1995).

Taken together, these findings suggest that context memory is particularly sensitive to aging because it depends on a brain region that is especially affected by aging: the frontal lobes. However, the evidence linking context memory deficits in old adults to frontal dysfunction is indirect (e.g., correlations with ''frontal lobe'' tests, Craik, Morris, Morris, & Loewen, 1990; Parkin, Walter, & Hunkin, 1995). In order to establish a direct link between older adults' context memory deficits and altered frontal functions, we used PET to compare brain activity in young and old adults during item and temporal-order memory retrieval. We had three expectations. First, on the basis of the aforementioned findings, we predicted less frontal activity during temporal-order retrieval in old adults than in young adults. Second, we predicted small age-related differences in ventromedial temporal activity during item retrieval. This expectation was based on the fact that item memory performance is only modestly affected by aging (Spencer & Raz, 1995) and that ventromedial regions, which are engaged by young adults during item memory (Cabeza et al., 1997c), are resistant to effects of aging on brain structure (Raz, Gunning, Head, Dupuis, McQuain, Briggs, Loken, Thornton, & Acker, 1997) and function (Schacter, Savage, Alpert, Rauch, & Albert, 1996). Finally, we expected to replicate a finding from our previous study (Cabeza et al., 1997a), where old adults showed weaker activations than young adults in the right prefrontal cortex but stronger activations in the left prefrontal cortex.

Methodology

Participants. Twelve young (mean: 24.7 years) and ten old (mean: 68.6 years) adults were included in our study. All participants were right-handed and none were taking medication or had conditions that could affect cerebral blood flow. The two groups were matched in education and word fluency. Old participants had a better vocabulary, but performed significantly worse than young adults in word recall, self-ordered pointing, and the WCST.

Materials and procedure. The critical materials were 8 lists of words, which were assigned to the 8 scans. Before each scan, participants studied a list of words, and during the scan, they tried to retrieve them. Two words were presented in each trial, and participants had to select one of the words by pressing either the left or right button of the mouse. Each pair of the item retrieval test (recognition) consisted of one word from the study list and one new word, and participants had to choose the studied word. In each pair of the temporal-order retrieval test (recency discrimination), both words were from the study list (e.g., word 5 and word 15), and participants had to choose the one that appeared later in the study list. Each task had two levels of difficulty, easy and hard. PET scans were obtained by using a bolus injection of $H_2{}^{15}O$. Common regions were identified by masked contrasts ($p < .01$; combined probability $= .01 \times .01 = .0001$), and regions differentially activated in the two groups were identified by a 2 (young vs. old) × 2 (item vs. temporal-order retrieval) × 2 (easy vs. hard) factorial analysis ($p < .001$ uncorrected).

Results

Regions engaged by both groups during item retrieval included bilateral ventromedial temporal areas and the caudate nucleus. Areas associated with temporal-order retrieval in both groups included bilateral posterior/inferior parietal regions and the left prefrontal cortex. Several regions showed significant interactions between age group and task type. In particular, there were regions more activated during temporal-order than during item retrieval in young adults but not in old adults, such as right prefrontal and medial parieto-occipital areas. Also, some regions were more activated during item retrieval than during temporal-order retrieval in older adults but not in young adults, including the left prefrontal cortex and the cerebellar vermis.

Discussion

The results confirmed our three expectations.

1. *Whereas the young adults engaged right prefrontal regions more during temporal-order retrieval than during item retrieval, the old adults did not.* This result provides the first direct evidence that context memory deficits in old adults are related to compromised frontal functions. In contrast to young adults, the old adults did not show an increase in right frontal activa-

tion during temporal-order retrieval relative to item retrieval, suggesting impaired temporal-order retrieval mechanisms in old age. One possibility is that context memory is particularly dependent on a general cognitive function mediated by prefrontal regions, such as attention, working memory, or inhibition (Mangels, 1997). In this sense, the age-related reduction of frontal activity during temporal-order retrieval would be consistent with evidence that attention, working memory, and inhibition are disrupted by aging (for reviews see, Hartley, 1990; Salthouse, 1991; Zacks & Hasher, 1997). Another alternative is that the frontal lobes play a specific role in context memory.

2. *Ventromedial temporal activity during item memory was relatively unaffected by aging.* This result is consistent with evidence that medial temporal regions are relatively resistant to effects of aging on brain structure (Raz et al., 1997) and function (Schacter et al., 1996). The pattern of compromised right frontal activity paired with a relatively preserved ventromedial-temporal activity is consistent with a theory concerning the role of these regions in episodic memory proposed by Moscovitch and Umiltà (1990; 1991). According to this view, medial temporal regions are involved in automatic associative retrieval processes such as item recognition, whereas frontal regions are involved in controlled strategic retrieval processes such as temporal-order retrieval.

3. *The effect of aging on frontal activity was asymmetric.* Unlike their younger counterparts, the old adults did not differentially activate right prefrontal cortex during the temporal order task, but they did show stronger activation of left prefrontal cortex during item retrieval than during temporal-order retrieval. The differential involvement of left prefrontal cortex during item retrieval among the older adults replicates a finding of our previous PET study of memory and aging (Cabeza, Grady, Nyberg, McIntosh, Kapur, Jennings, Houle, & Craik, 1997a). We previously suggested that this pattern of activity may reflect compensation on the part of the old adults for deficits in episodic memory retrieval (mediated by right prefrontal cortex—see Nyberg, Cabeza, & Tulving, 1996; Tulving, Kapur, Craik, Moscovitch, & Houle, 1994) through the superior use of semantic processing (mediated by left prefrontal cortex—see Cabeza & Nyberg, 1997). The fact that in the present study the age-related increase in left prefrontal activation occurred in item memory rather than in temporal-order memory is suggestive because item memory tends to be relatively preserved in old age.

Other findings included an age-related rCBF decrease in the medial parieto-occipital cortex and an age-related rCBF increase in the cerebellar vermis. In functional neuroimaging studies, both regions are typically activated during episodic memory retrieval (for a review, see Cabeza & Nyberg, 1997). Age-related decreases in medial parieto-occipital regions included the region of the precuneus, whose role in episodic memory retrieval has been related to the use of imagery (Fletcher, Frith, Baker, Shallice, Frackowiak, & Dolan, 1995a; Fletcher, Frith, Grasby, Shallice, Frackowiak, & Dolan, 1995b).

Given that imagery operations tend to decline with age (e.g., Craik & Dirkx, 1992) it is possible that the age-related reduction in precuneus activation found in this study is related to impoverished imagery processes in older adults.

In contrast, the age-related increase in cerebellar activation—like the one in the left prefrontal cortex—could reflect a compensatory mechanism. This idea is consistent with evidence that the cerebellum is involved in episodic memory retrieval (for a review, see Cabeza, Kapur, Craik, McIntosh, Houle, & Tulving, 1997b) and that its structure (Luft, Skalej, Welte, Voigt, & Klockgether, 1997) and metabolism (Loessner, Alavi, Lewandrowski, Mozley, Souder, & Gur, 1995) are relatively preserved in old adults. Moreover, there is evidence that while frontal regions show hypometabolism in old adults, metabolic activity in the cerebellum may even increase with aging (Moeller, Ishikawa, Dhawan, Spetsieris, Mandel, Alexander, Grady, Pietrini, & Edelberg, 1996). Volumetric analyses of MRI data have revealed age-related atrophy in the cerebellar hemispheres but not in the anterior vermis (Raz, Dupuis, Briggs, McGavran, & Acker, 1998). Consistent with this pattern, a previous PET study showed an age-related decrease in activation in the left cerebellar hemisphere (Bäckman, Almkvist, Andersson, Nordberg, Windblad, Rineck, & Lågström, 1997), whereas the present study showed an age-related increase in the vermis.

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