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Neurobiology of Aging 21 (2000) 577–584

NEUROBIOLOGY OF AGING

www.elsevier.com/locate/neuaging

Age-related differences in visual perception: a PET study☆

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Received 17 February 2000; received in revised form 31 January 2000; accepted 4 February 2000

Abstract

To assess age-related differences in cortical activation during form perception, two classes of visual textures were shown to young and older subjects undergoing positron emission tomography (PET). Subjects viewed even textures that were rich in rectangular blocks and extended contours and random textures that lacked these organized form elements. Within-group significant increases in regional cerebral blood flow (rCBF) during even stimulation relative to random stimulation in young subjects were seen in occipital, inferior and medial temporal regions, and cerebellum, and in older subjects, in posterior occipital and frontal regions. Group by texture type interactions revealed significantly smaller rCBF increases in older subjects relative to young in occipital and medial temporal regions. These results indicate that young subjects activate the occipitotemporal pathway during form perception, whereas older subjects activate occipital and frontal regions. The between-group differences suggest that age-related reorganization of cortical activation occur during early visual processes in humans.

Keywords: Positron emission tomography; Aging; Vision; Form; Imaging; Brain; Human

1. Introduction

Evidence from recent neuroimaging studies has shown age-related differences in the brain regions and networks activated during visual stimulation. Age-related differences in cortical activation during visual word identification [29], visual processing of faces and location [18], and working memory for faces [19] have been found using positron emission tomography (PET). In addition, age-related differences using PET have been shown during memory encoding and retrieval of word pairs [6] and during a card-sorting task [32]. Grady et al. [20] has also shown that older subjects demonstrated a markedly different activation pattern during a face recognition task relative to young subjects, especially in the ventral occipital cortical regions. Although these studies provide insight into age-related differences in visual perception that may result from differences in high level visual processes such as complex feature integration required for the perception of complex objects, the present study was designed to address a more basic aspect of visual function. That is, do perceptual differences associated with normal aging begin earlier in visual processing with changes in feature extraction?

The present study investigates the hypothesis that the activation pattern generated by viewing salient form elements differs for young and older healthy subjects. Based on prior functional neuroimaging studies that have shown age-related differences in visual processing, we predict that the two groups will differ in a specific manner, with either decreased occipitotemporal activation and/or additional activation outside of the occipitotemporal pathway with aging.

Experiments in nonhuman primates [44], and lesion [11, 45] and functional neuroimaging studies in humans [17,22, 30] have shown that there are two distinct visual processing pathways in extrastriate cortex. Anatomical studies have shown projections from striate cortex into occipital extrastriate regions. From these extrastriate regions the projections diverge either into inferior temporal cortex or into the

☆ This work is supported by the NIA Intramural Research Program. Keith Purpura is supported by NIH NS36699.

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0197-4580/00/$ – see front matter
PII: S0197-4580(00)00144-5

inferior parietal cortex, thus the anatomical basis for the two pathways [46]. The ventral occipitotemporal pathway is used primarily for perception of objects whereas the dorsal occipitoparietal pathway is important for organization of spatial relationships among objects. Many age-related changes are reported to occur in regions along these visual pathways based on structural neuroimaging studies of the aging human brain [10], determinations of neocortical cell counts in normal aging human brain [43], and studies of pyramidal neuronal loss with aging in the hippocampus, the anterior most extent of the ventral visual pathway [2,49].

Many aspects of visual function deteriorate slightly with age such as acuity [12] and contrast sensitivity [40,51]. Higher level functions such as those needed for visual search [28,33], visual attention [13,26], visual word identification [25,27], and visuomotor tracking [31,50] are also impaired in healthy aging. Additionally, visuospatial functions change with age such as processes required for spatial integration [37], localization [39], and mental rotation of visual stimuli [34]. Age-related changes have also been observed in tasks involving perception [1] as well as encoding and recognition of visual stimuli [9,41]. This age-related slowing of visual function has been interpreted as reduced processing efficiency or effectiveness [37] and may be related to the neuropathological changes associated with aging.

In this study, the ability to perceive structural organization within visual images was assessed using a passive visual stimulation paradigm [5]. To define cortical regions involved in this type of form perception, two classes of achromatic textures were presented to both young and older subjects undergoing PET. The baseline condition involved viewing random textures, which exhibit a random arrangement of black and white pixels. The stimulation condition involved viewing even textures, which exhibit pixels organized into elongated contours and rectangular blocks of a single color. The random and even textures share the same average luminance and spatial frequency content but differ in the organization of the pixels that make up the image. Previous studies of texture perception [24] have shown that humans can readily discriminate between random and even textures based on the differences in these local features. Furthermore, previous imaging studies have shown that the perception of this type of visual form involves the occipitotemporal pathway in young subjects [3–5]. Assessment of brain activation in the elderly in the present study will provide additional information regarding age-related cortical function along this visual pathway.

2. Methods

2.1. Subjects

Twelve healthy young adults (five women, seven men; ages 20–37; mean ± SD = 27.3 ± 6.0 years; 10 right handed, two left handed) and 14 healthy older adults (six women, eight men; ages 51–73; mean ± SD = 62.1 ± 8.5 years; 11 right handed, three left handed) participated in this study. The NIA Institutional Review Board approved all procedures. After full explanation of purpose, procedures and risks of the study, informed consent was obtained from each subject upon enrollment. During screening, subjects underwent a rigorous battery of testing by a physician including a detailed history and physical examination, ECG, chest X-ray, complete blood count, kidney, liver, and thyroid function tests, cholesterol levels, visual fields and acuity. Those with suboptimal visual acuity wore corrective lenses during scanning (acuity mean ± SEM: Young right eye = 20/20.9 ± 1.29, left eye = 20/20 ± 1.44; Older right eye = 20/31.4 ± 2.89, left eye = 20/29.6 ± 2.12). All subjects also underwent an MRI exam of the brain to exclude those with structural anomalies, and those with cortical atrophy, ventricular enlargement and white matter hyperintensities outside the range associated with normal aging. Subjects with systemic disease that might affect brain function and subjects with psychiatric illness were excluded, as were those taking any psychoactive medication.

2.2. Visual stimulation

Many examples of two easily discriminable classes of achromatic textures (Fig. 1) were presented to subjects undergoing a series of PET scans. The two classes of textures differed in the organization of their constituent black and white pixels. In the random class of textures, pixels were randomly assigned the colors of black or white. In the even class, the colorings of special groupings of four pixels were restricted as follows: for any rectangle of pixels, the four pixels at the vertices of the rectangle had to have an even number of black and white pixels (e.g. all black, all white, or two black and two white). Thus, even textures were generated by a simple two-dimensional recursion rule from sets of randomly chosen values for the textures' initial rows and columns. If pixel color (black or white) was denoted in the i th and j th column of the two-dimensional array by ai, j and the colors of pixels in the initial row and column (a0, j and ai, 0) were randomly assigned values of $+1$ or -1, a recursion rule determined the assignment of the interior pixels of the texture from those previously assigned. The interior pixels of the even texture were assigned by the rule $+1 = ai, j \times ai - 1, j \times ai, j - 1 \times ai - 1, j - 1$.

As a consequence of this spatial correlation rule, the even textures exhibit extended rectilinear contours and rectangular blocks of a single color whereas the random textures do not. Because neither texture class had restrictions on how any two pixels or three pixels could be colored, the area of regions of a single color were the same in the random and even textures on average, but these regions always had a consistent and rectilinear shape in the even textures.

The subjects were given no prior exposure to the stimuli before beginning the scans nor given any instructions other

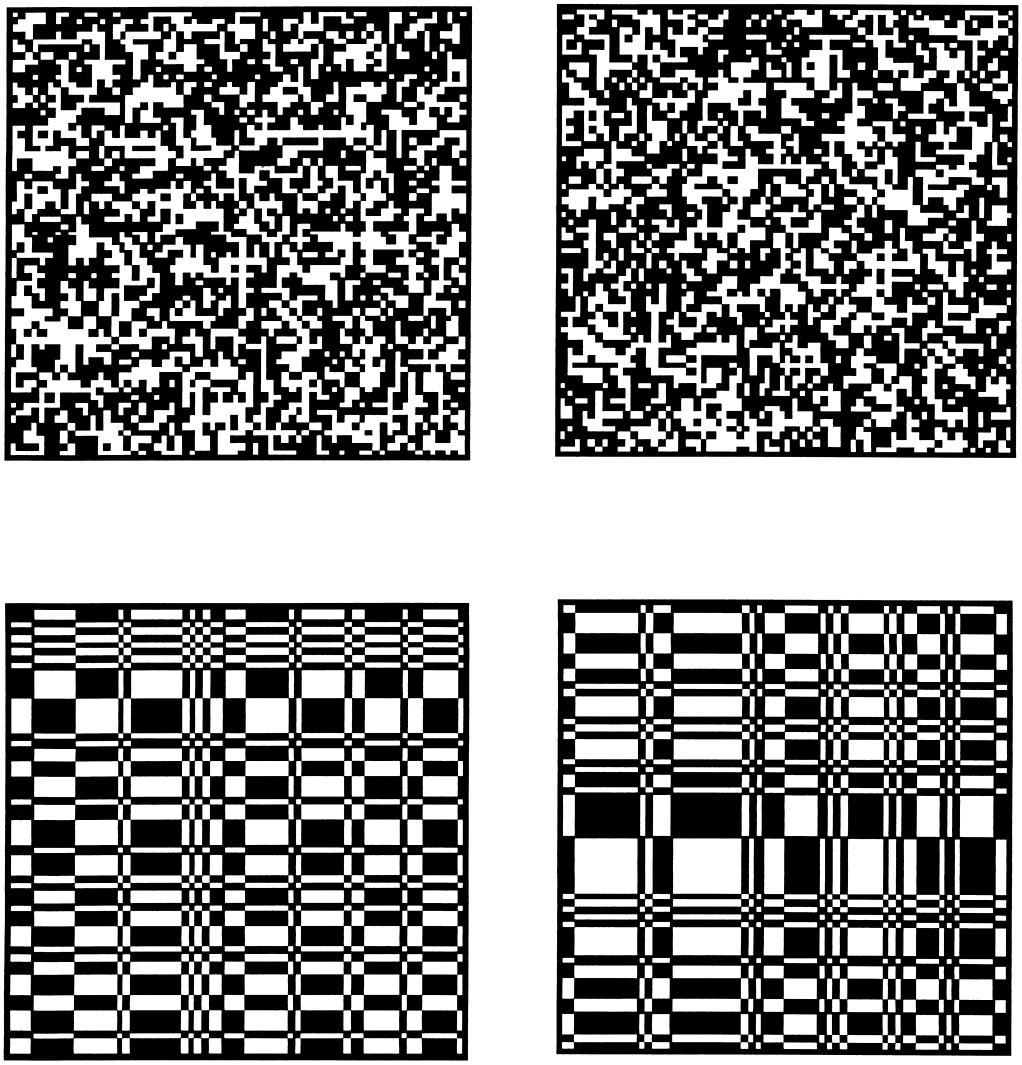

Fig. 1. Examples of random (top row) and even (bottom row) textures. The two classes share the same luminance and spatial frequency on average, yet the black and white checks are organized into extended contours and rectangular blocks in the even class.

than to keep their gaze centered on the visual display. The viewing of the textures was passive, and no performance was required for this task. The texture display subtended 22.5° × 28.3° of visual angle for all subjects. The smallest pixel (region of black or white) in the textures subtended 0.16° × 0.16° of visual angle. Four scans were collected during random texture viewing and four while viewing even textures. Scans were administered in an alternating fashion, with each pair of random/even scans counterbalanced across subjects to control for effects of presentation order. Novel textures were continuously shown every 0.5 s. Scans were conducted every 12 min. After the scanning session, the subjects were questioned regarding their perception of the texture stimuli.

2.3. Brain imaging

Each subject underwent a series of eight PET scans using radiolabeled water ($H_2{}^{15}0$) to measure regional cerebral blood flow (rCBF). All subjects fasted for at least 2 h and refrained from alcohol, caffeine and smoking for at least 24 h before the study. PET procedures were performed on a Scanditronix PC2048-15B tomograph (Upsala, Sweden) with a reconstructed resolution of 6.5 mm in both transverse and axial planes. Catheters were placed in a radial artery to obtain arterial blood samples and in an antecubital vein of the opposite arm for isotope injection. 37.5 mCi of $H_2{}^{15}0$ were injected i.v. per scan. Texture stimulation began one minute before bolus injections of the isotope and continued throughout the scan. Scanning began when the brain radioactive count rate reached a threshold level and continued for 4 min. Arterial blood radioactivity was determined continuously using an automated blood counter. The arterial time activity curve and scan data were used for image reconstruction with a rapid least squares algorithm [8].

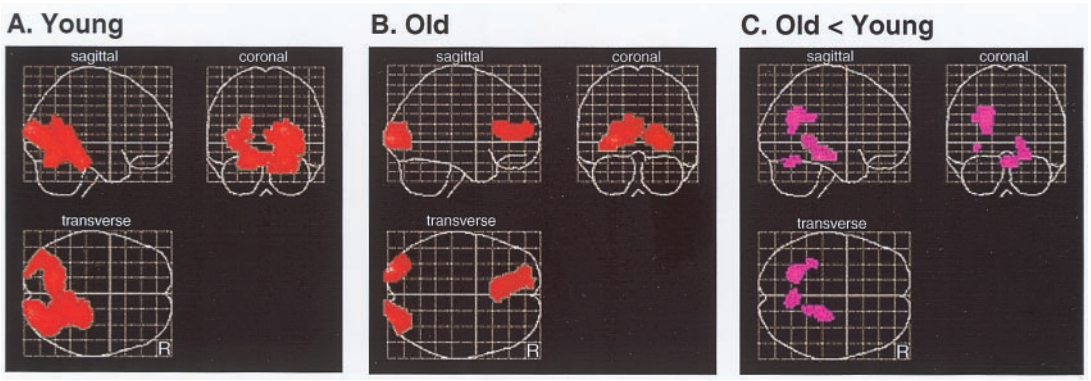

Fig. 2. Projection maps illustrating significant differences in rCBF during even texture perception relative to random texture perception (Z-score threshold 2.36; spatial extent $P < 0.05$). (A) rCBF increases within the young group. (B) rCBF increases within the older group. (C) Between-group interaction illustrating significantly smaller rCBF increases in older subjects relative to young subjects (($young_{even}$ - $young_{random}$) - (old_{even} - old_{random})) in the precuneus, middle temporal, and posterior cingulate gyri of the left hemisphere and parahippocampal gyrus of the right.

2.4. Data analysis

All scans were registered and spatially normalized [16] into the stereotactic space of Talairach and Tournoux [42]. Images were smoothed with a full width at half maximum of $20 \times 20 \times 12$ mm in the x, y, and z planes. Pixel rCBF values were scaled using the ratio adjustment method [14]. The image data were analyzed using Statistical Parametric Mapping (SPM97; Welcome Department of Cognitive Neurology, London, England), where voxel by voxel comparisons determined significant changes in rCBF during even stimulation relative to baseline random stimulation ($P < 0.01$). Data from all even scans were analyzed relative to all random scans for both young and older subjects. These data represent within-group activation patterns. To determine significant differences in activation patterns related to aging, group by texture type interactions were tested. These data represent between-group differences in activation. To control for multiple comparisons, cluster analyses were performed on each contrast to determine the significance of each cluster of activated voxels based on the magnitude of activation ($Z = 2.36$) and spatial extent ($P < 0.05$) [15].

3. Results

Statistically significant brain areas activated on a within-group basis will be presented first followed by brain areas that showed significantly different activation patterns between groups. In the young subjects, cerebral activation during even texture stimulation relative to random texture stimulation occurred in visual extrastriate regions of the brain. Bilateral activation was observed in the fusiform (BA 19) and lingual gyri (BA 19). Activation of the middle occipital gyrus (BA 18/19) was also seen in the right hemisphere. Regions anterior to the occipital lobe were also stimulated by even textures relative to random. These regions included bilateral inferior temporal (BA 37) and posterior cingulate gyri (BA 30/23). Additional activation of the parahippocampal gyrus (BA 35/36) was seen in the right hemisphere and precuneus in the left (BA 31). Bilateral activation was observed in the cerebellum. The results are presented in Fig. 2A. Local maxima are presented in Table 1.

In the older subjects, cerebral activation during even texture stimulation relative to random texture stimulation also involved the visual extrastriate regions. These regions included bilateral activation of the cuneus (BA 18) and left hemisphere activation of the inferior occipital gyrus (BA 18). In addition, the activation pattern involved anterior regions of the brain including anterior cingulate (BA 32/24), medial frontal (BA 10), middle frontal (BA 46/10), and superior frontal gyri (BA 10) in the left hemisphere. The results are presented in Fig. 2B.

Between-group interactions (Fig. 2C) revealed significantly smaller rCBF increases in older subjects relative to young during even texture stimulation [($young_{even}$ - $young_{random}$) - (old_{even} - old_{random})]. These differences were observed in the precuneus (BA 7), middle temporal (BA 39), and posterior cingulate (BA 31/23) gyri of the left hemisphere. In the right hemisphere, significant differences were observed in the parahippocampal gyrus (BA 28/35). Older subjects did not demonstrate significantly greater rCBF increases relative to young subjects [(old_{even} - old_{random}) - ($young_{even}$ - $young_{random}$)].

In terms of deactivations, the young group demonstrated decreased blood flow in the middle frontal gyrus of the left hemisphere (BA 9; Talairach coordinate: −46 6 40). The older group demonstrated decreased blood flow in the inferior parietal lobule (BA 40; Talairach coordinate: 56 −36 32) of the right hemisphere. No significant differences were found between the two groups.

Due to the passive nature of the task, the subjects were asked what they perceived and thought about during the scanning session using a standardized questionnaire. Both young and older subjects gave similar descriptions of their experiences. All subjects recognized that two types of tex-

Table 1
Local maxima within clusters demonstrating significant increases in rCBF during Even texture stimulation relative to Random stimulation*

Group	Region	Talairach coordinate			Z-score
		x	y	z	
Young	R Lingual gyrus (19)	30	−66	−4	3.60
	L Lingual gyrus (19)	−28	−64	−4	2.90
	R Fusiform gyrus (19)	26	−62	−8	3.58
	L Fusiform gyrus (19)	−26	−56	−8	2.74
	R Mid occipital gyrus (18/19)	30	−78	4	3.54
	L Precuneus (31)	−22	−62	20	2.89
	R Inf temporal gyrus (37)	28	−70	0	3.68
	L Inf temporal gyrus (37)	−42	−72	0	2.43
	R Parahippocampal gyrus (35/36)	24	−36	−8	3.66
	R Posterior cingulate (29/30)	14	−48	8	3.78
	L Posterior cingulate (30/23)	−22	−62	12	2.52
	R Cerebellum	4	−62	−16	3.15
	L Cerebellum	−8	−64	−16	3.54
Old	L Cuneus (18)	−26	−90	4	4.13
	R Cuneus (18)	26	−94	4	4.03
	L Inf occipital gyrus (18)	−36	−84	0	2.96
	L Med frontal gyrus (10)	−20	52	8	3.15
	L Mid frontal gyrus (46/10)	−32	54	16	2.93
	L Sup frontal gyrus (10)	−18	56	16	3.19
	L Anterior cingulate (32/24)	−20	42	12	2.58
Old versus young	L precuneus (7)	−22	−58	32	3.44
Decreased rCBF	L mid temporal gyrus (39)	−26	−58	24	3.52
	R parahippocampal gyrus (28/35)	20	−20	−16	3.39
	L posterior cingulate (31/23)	−24	−64	12	3.07

*Brodmann areas are indicated in parentheses from the atlas of Talairach and Tournoux (1988)

tures were shown and described the types as either exhibiting small black and white squares (random textures) or patterns with larger squares, rectangles and long lines (even textures). Most subjects recognized that the two texture types were presented in an alternating fashion across scans. Most subjects also stated that even textures were "easier to look at," yet some found no difference between the two types. Some subjects saw recognizable shapes in the even textures, the most common reported being letters, maps and quilt shapes. Of the subjects that reported seeing these shapes, all stated that the shapes "just appeared" and that they did not actively try to see objects in the textures. The one difference between young and older subjects relates to thought processes during scanning. Although all subjects reported concentrating on the center of the viewing screen during the start of each scan, young subjects reported that their mind drifted toward the end of the scan more often than older subjects. For those subjects that did report extraneous thoughts, most stated that their minds drifted to a similar degree throughout the session with no difference between early and late scans.

4. Discussion

Isodipole textures have been used to study visual perception in both monkeys and humans. Non-human primate studies [35] have shown that the striate cortex (V1) extracts higher order spatial correlations from visual textures. When monkeys are shown textures such as those used in the present study, even and random texture interchange produces a prominent form specific signal in the visual evoked potential (VEP) recorded epicortically from V1. Multielectrode recordings also show that this form specific signal is generated in many layers of striate cortex. Finally, single-unit recordings from simple and complex cells within V1 demonstrate that differential responses to even/random texture interchange can be produced at the level of single receptive fields.

Human VEP studies also demonstrate a differential response to even textures relative to random textures [47,48]. The antisymmetric or form specific component of the VEP signal increases in amplitude when even textures are shown. Using functional neuroimaging, we have also shown that stimulation with random textures relative to a fixation condition results in activation primarily of the striate cortex in young subjects, whereas stimulation with even textures results in activation primarily of extrastriate and temporal regions [4]. This finding suggests that increased recruitment of regions along the occipital temporal pathway of the brain occurs in response to visually salient features contained within the even textures.

The present study extends our previous neuroimaging studies [3,4,5] where stimulation with visual textures dif-

fering in the presence of salient form elements produced differential levels of activation in the ventral occipitotemporal pathway of young adults. Here we demonstrate that there are differences in form perception associated with aging.

The within-group activation pattern in the young subjects involves both cerebral hemispheres. Activation resulting from even texture stimulation relative to random stimulation includes extrastriate regions of the brain, such as bilateral lingual and fusiform gyri, the precuneus of the left hemisphere and middle occipital gyrus of the right hemisphere. Other areas activated include the parahippocampal gyrus of the right hemisphere, bilateral inferior temporal and posterior cingulate gyri. These occipitotemporal areas are part of the ventral visual pathway. Involvement of this pathway in the present study indicates the ability of these brain areas to extract differences in salient form elements.

The within-group activation pattern in the older subjects involves both cerebral hemispheres posteriorly and the left hemisphere anteriorly. The activation includes posterior extrastriate regions, such as the cuneus of both hemispheres as well as the inferior occipital gyrus of the left hemisphere. These subjects also exhibit areas of activation outside the occipitotemporal pathway. These include regions in the medial, middle and superior frontal lobe, and the anterior cingulate gyrus of the left hemisphere.

Between-group interactions reveal significant rCBF differences in older relative to young subjects. Regions demonstrating differences include the precuneus, middle temporal, and posterior cingulate gyri of the left hemisphere and the parahippocampal gyrus of the right hemisphere. These areas all showed decreased cerebral blood flow in the older compared to the young group. The frontal lobe regions activated in the older subjects alone, however, did not show statistically significant differences in blood flow between the two groups.

Prior functional neuroimaging studies in humans have assessed age-related changes in rCBF during the processing of both nonverbal and verbal visual tasks. These tasks involve high level cognitive processes such as perception and location of faces [17,18], memory for faces [20] or words [6,38], word identification [29], and card sorting [32]. These studies have all shown age-related differences in visual processing. The differences often include either decreased occipitotemporal activation [20,29] and/or additional activation outside of the occipitotemporal pathway [6,17,18].

Current literature suggests several hypotheses for the differences in activation patterns seen in young and old. First, age-related regional decreases in activation in some brain regions reflect less efficient cognitive processing with aging, that is "processing deficiency" [18,20,38]. Grady et al. [18] interprets age-related differences in rCBF during a face-matching/location matching task (a nonmemory, visual task) as more efficient use of occipital visual areas by young, whereas old subjects rely on other cortical networks including frontal regions to compensate for the "reduced processing efficiency" of the occipital cortex. In the present study, older subjects show decreased blood flow in occipital, temporal and cingulate regions relative to the young subjects. Furthermore, using photic stimulation to assess the response of the visual cortex, a functional MRI study [36] has shown a significantly decreased amplitude of response in old compared to young normals, suggesting an age-related alteration in coupling of blood oxygenation to focal activation. Together, these findings suggest that processing of visual information may be compromised with aging.

Secondly, age-related increases in activation in other brain regions reflect "functional compensation" [18]. Studies have shown activation outside of the ventral visual pathway with aging. Grady et al. [17,18] showed that although both young and older subjects activated the occipitotemporal pathway during a face matching task, older subjects had additional areas of activation in the superior parietal and prefrontal cortices. Additionally, Cabeza et al. [6] found age-related decreases in activation during encoding of word pairs in bilateral occipitotemporal regions and the prefrontal cortex of the left hemisphere, with an associated age-related increase in activation in bilateral insular regions. In the present study, older subjects also activate areas outside the occipitotemporal pathway. Although these differences were not statistically significant, within-group activation patterns revealed that older subjects activate the inferior, middle, and superior regions of the frontal lobe whereas the young do not.

Thirdly, Cabeza et al. [6] has interpreted age-related changes in activation during a memory encoding and retrieval task as a difference in the way young and old subjects perform—either by using a different strategy or by implementing the same strategy using different brain regions. Recent work by Hazlett et al. [23] supports the "same strategy-different ways" hypothesis in a PET study where young and old performed a verbal memory task. Good performers were compared in both groups and were shown to activate different cortical regions (frontal in the young and occipital in the old) using the same cognitive strategy. Although the subjects in the present study were not required to perform overt cognitive operations, post-scan interviews reveal that both young and older subjects perceived differences between the two texture types and that these perceptions—or at least the ability to describe what they saw and thought about the stimuli—were similar for both groups. The similarity in "performance," or perception in the present case, and the resultant differences in activation during texture perception could be explained by Hazlett's theory of a dynamic brain region reallocation with aging. The possibility should be noted, however, that endogenous factors such as differences in drifts in attention or extraneous thought during the "passive" viewing of the textures may also play a role in the differences observed between groups.

Thus, previous neuroimaging studies reveal that changes

occur during the performance of visual tasks with healthy aging. These changes include decreased cortical activation patterns relative to that observed in young control subjects, suggesting that processing of visual stimuli may be compromised with age. Furthermore, activation patterns that deviate from those seen in young subjects also suggest that some form of cortical reorganization likely occurs with age. Using path analysis on PET data from young and old subjects encoding and recalling word pairs, Cabeza et al. [7] has provided support for the hypothesis that age-related changes in activation are due to age-related changes in effective connectivity in the neural network underlying the task. Until this point, these age-related differences in brain activation could be attributed to differences in high-level visual and cognitive processes required for the performance of the specific task. The present study, however, suggests that these differences may result, at least in part, from changes in early or low-level visual processes such as those needed for the perception or extraction of more basic form elements.

These processing differences may result from changes in a visual receptive field mechanism that operates at different spatial scales at various stages along the ventral occipitotemporal pathway [3–5,47,48]. This receptive field mechanism carries out a spatial linking operation in two stages [47]. First, local edge detection is performed by neurons with receptive fields as small as the smallest texture elements. Second, a stage of integration occurs that cooperatively links the outputs of neighboring local edge detectors sharing a common orientation preference. This second 'nonlinear' stage involves a function that restricts the recruitment of edge detector subunits unless these subunits are aligned along an extended contour or the perimeter of a larger block and share the same orientation preference. The outputs of many such nonlinear stages may be summed into larger receptive fields in the extrastriate visual cortical areas. A more precise description of how the intermediate nonlinear stage behaves as the outputs from the subunit inputs are changed has been formulated in a recent psychophysical study [21] which suggests that many visual perceptual phenomena may be understood, in part, by the operation of this intermediate nonlinearity. What is unique about the perception of even and random textures is that the nonlinearity seems to act through a particular type of spatial pooling, i.e. between subunits with similar orientation tuning preferences in specific spatial arrangements. It is not clear from the present study, however, whether the change that comes with aging is a change in the intermediate nonlinearity, or in the organization of linkages between receptive fields with similar orientation preferences. Further psychophysical and imaging studies of texture and motion perception in normal older adults could help isolate the component of visual processing that changes with age.

References

[1] Ball K, Sekuler R. Improving visual perception in older observers. J Gerontol 1986;41(2):176–82.

[2] Ball MJ. Neuronal loss, neurofibrillary tangles and granulovacuolar degeneration in the hippocampus with aging and dementia. A quantitative study. Acta Neuropathol (Berl) 1977;37(2):111–18.

[3] Beason–Held LL, Purpura KP, Krasuski JS, et al. Striate cortex in humans demonstrates relationship between activation and variations in visual form. Exp Brain Res, 2000;130(2):221–6.

[4] Beason–Held LL, Purpura KP, Krasuski JS, et al. Cortical regions involved in visual texture perception: a fMRI study. Cogn Brain Res 1998;7(2):111–8.

[5] Beason–Held LL, Purpura KP, Van Meter JW, et al. PET reveals occipitotemporal pathway activation during elementary form perception in humans. Vis Neurosci 1998;15(3):503–10.

[6] 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(1):391–400.

[7] Cabeza R, McIntosh AR, Tulving E, Nyberg L, Grady CL. Age-related differences in effective neural connectivity during encoding and recall. Neuroreport 1997;8(16):3479–83.

[8] Carson RE, Berg GW, Finn RD, et al. Tomographic measurement of rCBF with high-resolution PET and $H_2{}^{15}0$: comparison of methods. J Cereb Blood Flow Metab1987;7:S578.

[9] Cherry KE, St Pierre C. Age-related differences in pictorial implicit memory: role of perceptual and conceptual processes. Exp Aging Res 1998;24(1):53–62.

[10] Coffey CE, Wilkinson WE, Parashos IA, et al. Quantitative cerebral anatomy of the aging human brain: a cross-sectional study using magnetic resonance image. Neurology 1992;42:527–536.

[11] Damasio AR, Damasio H, Van Hoesen GW. Prosopagnosia: anatomic basis and behavioral mechanisms. Neurology 1982;32(4):331–41.

[12] Elliott DB, Yang KC, Whitaker D. Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. Optom Vis Sci 1995;72(3):186–91.

[13] Folk CL, Hoyer WJ. Aging and shifts of visual spatial attention. Psychol Aging 1992;7(3):453–65.

[14] Fox PT, Mintun MA, Reiman EM, Raichle ME. Enhanced detection of focal brain responses using intersubject averaging and change-distribution analysis of subtracted PET images. J Cereb Blood Flow Metab 1988;8(5):642–53.

[15] Friston K, Worsley K, Frackowiak R, Mazziotta J, Evans A. Assessing the significance of focal activations using their spatial extent. Hum Brain Mapp 1994;1:210–20.

[16] Friston KJ, Ashburner J, Frith CD, JBP, Heather JD, Frackowiak RSJ. Spatial realignment and normalization of images. Hum Brain Mapp 1995;3:165–89.

[17] Grady C, Haxby J, Horwitz B, et al. Dissociation of object and spatial vision in human extrastriate cortex: age-related changes in activation of regional cerebral blood flow measured with 15-O water and positron emission tomography. J Cogn Neurosci 1992;4(1):23–34.

[18] 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(3):1450–1462.

[19] Grady CL, McIntosh AR, Bookstein F, Horwitz B, Rapoport SI, Haxby JV. Age-Related Changes in Regional Cerebral Blood Flow during Working Memory for Faces. Neuroimage 1998;8(4):409–425.

[20] Grady CL, McIntosh AR, Horwitz B, et al. Age-related reductions in human recognition memory due to impaired encoding. Science 1995; 269:218–221.

[21] Graham N, Sutter A. Spatial summation in simple (Fourier) and complex (non-Fourier) texture channels. Vis Res 1998;38:231–57.

[22] Haxby JV, Grady CL, Horwitz B, et al. Dissociation of object and spatial visual processing pathways in human extrastriate cortex. Proc Natl Acad Sci USA 1991;88(5):1621–5.

[23] Hazlett EA, Buchsbaum MS, Mohs RC, et al. Age-related shift in brain region activity during successful memory performance. Neurobiol Aging 1998;19(5):437–45.
[24] Julesz B, Gilbert EN, Victor JD. Visual discrimination of textures with identical third-order statistics. Biol Cybern 1978;31(3):137–40.
[25] Madden DJ. Four to ten milliseconds per year: age-related slowing of visual word identification. J Gerontol 1992;47(2):59–68.
[26] Madden DJ. Selective attention and visual search: revision of an allocation model and application to age differences. J Exp Psychol Hum Percept Perform 1992;18(3):821–36.
[27] Madden DJ, Pierce TW, Allen PA. Age-related slowing and the time course of semantic priming in visual word identification. Psychol Aging 1993;8(4):490–507.
[28] Madden DJ, Pierce TW, Allen PA. Adult age differences in the use of distractor homogeneity during visual search. Psychol Aging 1996; 11(3):454–74.
[29] Madden DJ, Turkington TG, Coleman RE, Provenzale JM, DeGrado TR, Hoffman JM. Adult age differences in regional cerebral blood flow during visual word identification: evidence from $H_2{}^{15}O$ PET. Neuroimage 1996;3(2):127–42.
[30] McIntosh AR, Grady CL, Ungerleider LG, Haxby JV, Rapoport SI, Horwitz B. Network analysis of cortical visual pathways mapped with PET. J Neurosci 1994;14(2):655–66.
[31] Moschner C, Baloh RW. Age-related changes in visual tracking. J Gerontol 1994;49(5):M235–8.
[32] Nagahama Y, Fukuyama H, Yamauchi H, et al. Age-related changes in cerebral blood flow activation during a card sorting test. Exp Brain Res 1997;114(3):571–7.
[33] Plude DJ, Hoyer WJ. Age and the selectivity of visual information processing. Psychol Aging 1986;1(1):4–10.
[34] Puglisi JT, Morrell RW. Age-related slowing in mental rotation of three-dimensional objects. Exp Aging Res 1986;12(4):217–20.
[35] Purpura K, Victor J, Katz E. Striate cortex extracts higher-order spatial correlations from visual textures. Proc Natl Acad Sci USA 1994;91:8482–8486.
[36] Ross MH, Yurgelun–Todd DA, Renshaw PF, et al. Age-related reduction in functional MRI response to photic stimulation. Neurol 1997;48:173–6.
[37] Salthouse TA. Adult age differences in integrative spatial ability. Psychol Aging 1987;2(3):254–60.
[38] Schacter DL, Savage CR, Alpert NM, Rauch SL, Albert MS. The role of hippocampus and frontal cortex in age-related memory changes: a PET study. Neuroreport 1996;7(6):1165–9.
[39] Sekuler R, Ball K. Visual localization: age and practice. J Opt Soc Am [a] 1986;3(6):864–7.
[40] Sekuler R, Owsley C, Hutman L. Assessing spatial vision of older people. Am J Optom Physiol Opt 1982;59(12):961–8.
[41] Smith AD, Park DC, Cherry K, Berkovsky K. Age differences in memory for concrete and abstract pictures. J Gerontol 1990;45(5): 205–9.
[42] Talairach J, Tournoux P. Co-planar stereotaxic atlas of the human brain. New York: Thieme, 1988.
[43] Terry R, DeTeresa R, Hansen L. Neocortical cell counts in normal human adult aging. Ann Neurol 1987;21(6):530–539.
[44] Ungerleider LG, Mishkin M. Two cortical visual systems. In: Ingle DJ, Goodale MA, Mansfield RJW, editors. Analysis of visual behavior. Cambridge: MIT Press, 1982. p. 549–86.
[45] Vaina LM. Functional segregation of color and motion processing in the human visual cortex: clinical evidence. Cereb Cortex 1994;4(5): 555–72.
[46] Van Essen DC. Functional organization of the primate visual cortex. In: Peters A, Jones EG, editors. Cerebral cortex (Vol. 3) New York: Plenum Press, 1985. p. 259–320.
[47] Victor JD, Conte MM. Cortical interactions in texture processing: scale and dynamics. Vis Neurosci 1989;2:297–313.
[48] Victor JD, Conte MM. Spatial organization of nonlinear interactions in form perception. Vis Res 1991;31:1457–88.
[49] West MJ. Regionally specific loss of neurons in the aging human hippocampus. Neurobiol Aging 1993;14(4):287–93.
[50] Wickens CD, Braune R, Stokes A. Age differences in the speed and capacity of information processing: 1. A dual-task approach. Psychol Aging 1987;2(1):70–8.
[51] Zhang L, Sturr JF. Aging, background luminance, and threshold-duration functions for detection of low spatial frequency sinusoidal gratings. Optom Vis Sci 1995;72(3):198–204.