



## Age-related dedifferentiation and compensatory changes in the functional network underlying face processing

Hana Burianová<sup>a,b,c,\*</sup>, Yunjo Lee<sup>c,d</sup>, Cheryl L. Grady<sup>c,d,e</sup>, Morris Moscovitch<sup>c,d</sup>

<sup>a</sup> Centre for Advanced Imaging, University of Queensland, Brisbane, Australia

<sup>b</sup> ARC Centre of Excellence in Cognition and its Disorders, Department of Cognitive Science, Macquarie University, Sydney, Australia

<sup>c</sup> Rotman Research Institute at Baycrest, Toronto, Ontario, Canada

<sup>d</sup> Department of Psychology, University of Toronto, Ontario, Canada

<sup>e</sup> Department of Psychiatry, University of Toronto, Ontario, Canada

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### ABSTRACT

Recent evidence has shown that older adults fail to show adaptation in the right fusiform gyrus (FG) to the same face presented repeatedly, despite accurate detection of the previously presented face. We used functional magnetic resonance imaging to investigate whether this phenomenon is associated with age-related reductions in face specificity in brain activity and whether older adults compensate for these face-processing deficiencies by increasing activity in other areas within the face-processing network, or outside this network. A comparison of brain activity across multiple stimulus categories showed that, unlike young adults who engaged a number of brain regions specific to face processing, older adults generalized these patterns of activity to objects and houses. Also, young adults showed functional connectivity between the right FG and its homologous region during face processing, whereas older adults did not engage the left FG but showed a functional connection between the right FG and left orbitofrontal cortex. Finally, this frontotemporal functional connection was activated more strongly in older adults who performed better on a face-matching task (done outside of the scanner), suggesting increased involvement of this functional link for successful face recognition with increasing age. These findings suggest that 2 neural mechanisms, dedifferentiation and compensatory neural recruitment, underlie age differences in face processing.

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### 1. Introduction

Recent neuroimaging studies have yielded evidence for 2 distinct phenomena in the aging brain: (1) neural representations of different cognitive processes become less selective and their neural signature less distinct (Li et al., 2001); and (2) older adults often have greater brain activity than young adults during cognitive tasks, particularly in the frontal cortex, that might compensate for age-related processing deficiencies (Cabeza et al., 2002; Duvernoy et al., 2009; Grady, 2012; Reuter-Lorenz et al., 2000). The first finding is consistent with the idea of dedifferentiation, which in terms of brain activity refers to reduced distinctiveness of neural representations in domain-specific areas. For instance, ventral occipital visual areas show reduced category selectivity to faces, places, and words in older relative to younger adults (Park et al., 2004). Dedifferentiation has also been reported in domain-general

cognitive areas, including the parietal and prefrontal cortices, during memory encoding and retrieval (Carp et al., 2010a, 2010b), and in areas active specifically for retrieval of autobiographical and episodic memories (St-Laurent et al., 2011). Although such results might indicate reductions in the integrity of the aging brain, other neuroimaging studies have reported an increased engagement of prefrontal and other brain areas, which is interpreted as a compensatory mechanism when associated with maintained performance in older adults (Davis et al., 2008; Grady, 2002; Grady et al., 2002, 1994; Madden et al., 2004; Schiavetto et al., 2002), or when activity in these “over-recruited” areas is correlated with behavior in older adults (Davis et al., 2008; Grady et al., 2005). Indeed, some have suggested that the strongest evidence for compensation is this latter finding, in which a link can be made between more brain activity and better performance in older adults who show the most overrecruitment (Cabeza and Dennis, 2012; Grady, 2008). Albeit 2 distinct phenomena, the dedifferentiation and compensation processes are unlikely to be mutually exclusive. Rather, it is possible that the brain might show reduced neural selectivity in some domain-specific regions and, at the same time or as a consequence, use other task-specific regions, or even a different

\* Corresponding author at: Centre for Advanced Imaging, Department of Cognitive Science, The University of Queensland, Brisbane, QLD 4072, Australia. Tel.: (+61) 7 3346 9963; fax: (+61) 7 3346 0330.

E-mail address: [hana.burianova@cai.uq.edu.au](mailto:hana.burianova@cai.uq.edu.au) (H. Burianová).

network of areas, to compensate for this deficiency in neural distinctiveness, evincing remarkable brain plasticity or reserve in old age. The purpose of the current study was to investigate this question by exploring age-related neural changes during face processing, using functional magnetic resonance imaging (fMRI).

Many behavioral studies have reported that older adults show reduced recognition and perception of familiar and unfamiliar faces relative to younger adults (Bartlett et al., 1991; Boutet and Faubert, 2006; Habak et al., 2008; Lott et al., 2005; Searcy et al., 1999). On the neural level, age-related deficits in face processing are likely to be observed in multiple areas (Carp et al., 2010a; Goh et al., 2010; Lee et al., 2011), because face processing is distributed widely over many functionally interacting areas that show serial and parallel processing (Barbeau et al., 2008; Gobbin and Haxby, 2007; Haxby et al., 2000). Importantly, deficiencies at early stages of face processing might cascade downstream and yield changes in the entire functional brain network (Davis et al., 2008; Grady, 2000, 2008). Thus, we aimed to examine (1) whole-brain activations during processing of faces and objects, to assess neural selectivity to different categories of objects; and (2) functional connectivity of the distributed face processing network, using multivariate partial least squares (PLS) analysis.

In our recent study (Lee et al., 2011), older adults showed no adaptation in the right fusiform gyrus (FG), 1 of the regions considered to be crucial for face recognition (Clarke et al., 1997; Kanwisher et al., 1997; Nestor et al., 2011; Steeves et al., 2006), to repeatedly presented faces, even when facial identity and view were kept constant. Contrary to these deficiencies in neural adaptation, on a behavioral level older adults performed similarly to young adults in matching the same facial identity shown in the same view outside the scanner (also consistent with previous behavioral data of Habak et al., 2008 and Searcy et al., 1999). Additionally, we found that older adults recruited a unique set of brain regions in which activity correlated with their behavioral performance. It has been suggested that older adults compensate for processing deficits because of decreased activity in the occipital lobe by increasing frontal activity (Davis et al., 2008; Grady et al., 2002). If compensation occurs, 1 possible frontal area of compensatory recruitment might be the orbitofrontal cortex (OFC), in which activity has been often observed during processing of faces and nonfacial objects (Bar, 2009; Bar et al., 2006; Fairhall and Ishai, 2007; Ishai, 2007, 2008; Johnson, 2005; Kveraga et al., 2007; Li et al., 2010). The OFC is argued to be a part of the extended cortical network for face processing (Fairhall and Ishai, 2007; Haxby et al., 2000) and is involved in a variety of face tasks, including assessment of facial attractiveness (Ishai, 2007), facial sex categorization (Freeman et al., 2010), facial emotion recognition (Harmer et al., 2001), and detection of blurred faces (Li et al., 2010; Summerfield et al., 2006). More activity or stronger functional connectivity in the OFC in older adults would be consistent with the compensation-related utilization of neural circuits hypothesis (Reuter-Lorenz and Cappell, 2008). The compensation-related utilization of neural circuits hypothesis is based on the idea that as task demands increase, reliance on neural resources increases regardless of age, but that this demand/resource function is shifted to the left in older adults. That is, older adults recruit more resources at lower levels of cognitive load. For basic face recognition, this increased reliance on neural resources could involve task-specific regions, such as the OFC, which younger adults might only recruit when the cognitive demands are greater or more complex processing of faces is required. Additional domain-general resources might also be recruited by older adults. Both of these types of recruitment could be compensatory, especially if this additional engagement of brain activity was associated with improved performance in older adults (Grady, 2012).

To measure functional connectivity between the frontal cortex and the fusiform areas, we identified seed regions in the fusiform gyri and in the left medial OFC. Activity in this latter area has been found during viewing of famous and emotional faces in young adults (Fairhall and Ishai, 2007; Ishai et al., 2005). We expected that age-related deficiencies at early processing stages (i.e., in the FG) would cascade downstream and alter the face-processing network (Davis et al., 2008; Grady, 2002, 2008). We hypothesized that: (1) older adults would exhibit a general decrease in neural specificity across activated face-processing areas; (2) young and older adults would show differences in the functional connectivity of the face-processing network, with older adults showing stronger connectivity with OFC; and (3) activity in the face-processing network specific to older adults would correlate with their behavioral performance (i.e., reaction times [RTs] and accuracy), reflecting the importance of the OFC in face-matching performance with increasing age.

## 2. Methods

### 2.1. Participants

Fifteen healthy older adults (mean age, 68 years; SD, 4.2; range, 61–75 years; 6 men) and 14 healthy young adults (mean age, 24 years; SD, 4.9; range, 8–32 years; 7 men) participated in the study. Older adults were screened via a detailed phone interview for general health (e.g., cardiovascular disease or stroke), medications, and normal vision (e.g., cataract or glaucoma, eye exam within a year). They achieved an average score of 29.3 (SD, 1.1) on the Mini-Mental State Examination (Folstein et al., 1975), and all had undergraduate or graduate-level education. Young adults were undergraduate or graduate students attending the University of Toronto. All participants had normal or corrected-to-normal vision and no history of eye disease or neurological or psychiatric problems. All participants provided written informed consent approved by the Baycrest Centre Research Ethics Board.

### 2.2. Study design

The study consisted of: (1) an imaging experiment; and (2) a postscan behavioral test. The imaging experiment was block-designed and consisted of 2 runs of the face/object same/different task. The postscan test was conducted outside the scanner on a different day (on average, within a month) and involved sequential matching of unfamiliar faces across identity and/or viewpoints (Lee et al., 2011).

### 2.3. Experimental procedure

Stimuli for the same/different task consisted of gray-scaled photographs of natural faces (frontal, 20° side views), houses (frontal, 20° side views), and common household objects. For the postscan face-matching task, we used novel, natural faces that were not presented during the fMRI experiment. In each trial, a fixation cross was displayed for 250 ms, followed by a first stimulus displayed for 750 ms, a fixation cross for 250 ms, a second stimulus for 2000 ms, and a blank screen for 750 ms. Participants were asked to indicate whether the 2 stimuli were identical during the same/different task.

### 2.4. fMRI data acquisition

Anatomical and functional images were acquired at the Rotman Research Institute, Baycrest Centre, Toronto, Ontario, using a 3 Tesla Siemens Magnetom Trio scanner with a matrix 12-channel head

coil. Anatomical images were acquired using a T1-weighted 3-D magnetization-prepared rapid gradient-echo sequence (160 oblique axial slices, repetition time [TR] = 2 seconds, echo time [TE] = 2.63 s, field of view = 256 mm, voxel size = 1 mm<sup>3</sup>, acquisition matrix = 256 × 256). Brain activation was assessed using the blood oxygenation level-dependent (BOLD) effect (Ogawa et al., 1990) with optimal contrast. Functional images were obtained using a whole-head T2\*-weighted echo-planar image sequence (30 oblique axial slices with interleaved acquisition, 0 gap, TR = 2 seconds, TE = 30 ms, flip angle = 70°, field of view = 200 mm, voxel size = 3.125 × 3.125 × 5 mm, acquisition matrix = 64 × 64). Physiological data (cardiac and respiratory rate) were acquired during the scanning session to use in the removal of physiological noise from the fMRI time-series data.

### 2.5. fMRI data preprocessing

The initial 5 time points from each image volume, during which participants viewed the experimental instructions on the screen, were removed from the analyses to allow for the brain magnetization to stabilize. Images were reconstructed and motion-corrected using the Analysis of Functional Neuroimages (Cox, 1996). We discarded any run in which a peak range of the head motion exceeded 1.5 mm. Further preprocessing of the time-series data involved correction for physiological noise and slice timing. To enable group comparisons, each brain scan was spatially normalized, i.e., scaled and warped to match a standard (the Montreal Neurological Institute) template, and smoothed with a 6-mm Gaussian filter, which, acting as a low-pass filter, makes the data less noisy by reducing the images' high-frequency components. The voxel size, after preprocessing, was 2 × 2 × 2 mm.

### 2.6. fMRI data analysis

The procedure of the fMRI analysis was 3-fold. First, we tested for modulations of brain activity attributable to the experimental conditions, and identified brain areas that would serve as the reference (i.e., seed) regions for further functional connectivity analyses. The choice of the seed regions was based on 2 criteria: (1) reliable modulation of activity during face processing in both groups; and (2) previous empirical evidence for a role of these regions in face processing. Second, we delineated a large-scale network that was active during face processing by determining areas of the brain in which activity was correlated with that of the seed regions (i.e., its functional connectivity; Friston et al., 1993; Horwitz, 1994; McIntosh, 1999). Finally, we examined whether activity in this face-processing network was correlated with behavioral performance on the face-matching task. Here we tested the hypothesis that the network identified in the preceding functional connectivity analysis would be correlated with RTs and accuracy.

These analytical steps are based on the assumption that cognition is the result of integrated and coordinated activity of groups of brain regions (i.e., distributed brain networks) rather than the independent activity of any single brain region. To delineate these networks, we chose a multivariate analytical technique called PLS (McIntosh et al., 1996, 2004; for a detailed tutorial and review of PLS, see Krishnan et al., 2011), which is designed to identify groups of brain regions distributed over the entire brain in which activity changes as a function of task demands (task PLS), are correlated with behavioral performance (behavior PLS), or correlated with activity in a given 'seed' region (seed PLS). This assessment of activity patterns across all brain voxels is in contrast to the more typically used univariate analysis that assesses the significance of each voxel separately. An additional advantage of the PLS technique

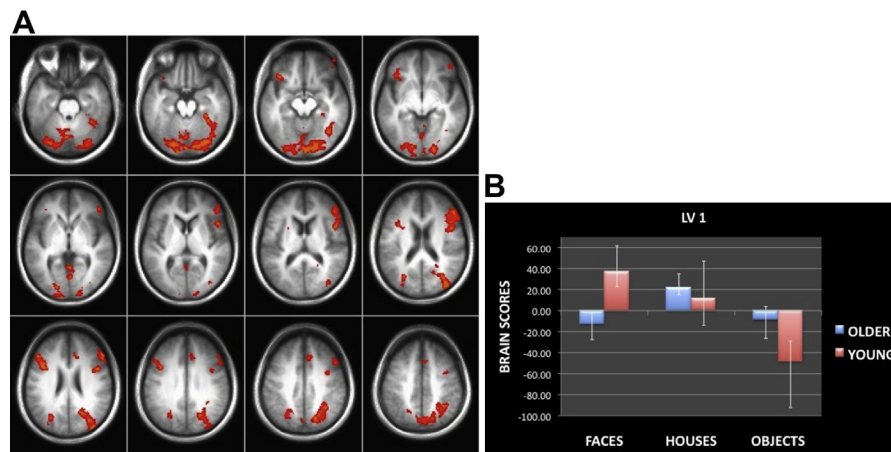
is that all task conditions can be entered simultaneously into the analysis, thus facilitating the identification of common patterns of brain activity across conditions, and patterns unique to specific experimental conditions or groups.

In short, PLS analysis uses singular value decomposition of a single matrix that contains all participants' data to find a set of latent variables (LVs), which are mutually orthogonal dimensions that reduce the complexity of the data set. In other words, PLS does not force contrasts but rather decomposes the data to maximize the amount of covariance of an LV with respect to the experimental conditions. Thus, akin to principal component analysis (e.g., Friston et al., 1993), PLS enables us to differentiate the degree of contribution of different brain regions associated with task or performance. Each LV consists of a singular image of voxel saliences (i.e., a spatiotemporal pattern of brain activity that reflects task-related changes or brain-behavior correlations seen across conditions), a singular profile of task saliences (i.e., a set of weights that indicate how brain activity in the singular image is expressed in each of the experimental conditions), and a singular value (i.e., the amount of covariance accounted for by the LV). The first LV always accounts for the largest amount of covariance (i.e., has the largest singular value), with subsequent LVs accounting for progressively smaller amounts. For each condition in each LV, we calculated summary measures of how strongly each participant expresses the particular pattern of activity seen on the LV. These measures, called brain scores, are the products of the weighted salience of each voxel and BOLD signals summed across the entire brain for each participant in each condition on a given LV. Saliency indicates the degree to which a voxel is related to the LV and can be positive or negative, depending on the voxel's relation to the pattern of task-dependent differences identified using the LV.

The significance for each LV was determined using a permutation test, which assesses the significance of each LV by determining the probability that a singular value from permuted data (resampled 500 times) is larger than the obtained value (McIntosh et al., 1996). In addition to the permutation test, a second and independent step was to determine the reliability of the saliences (or weights) for each brain voxel that characterizes a given spatiotemporal pattern identified by the LVs. To do so, we estimated the standard error of each voxel's salience on each LV by 100 bootstrap resampling steps (Efron and Tibshirani, 1985). Peak voxels with a bootstrap ratio (i.e., salience/standard error) > 3.0 were considered to be reliable, as these approximate  $p < 0.005$  (Sampson et al., 1989). Because extraction of the LVs and corresponding brain images is done in a single analytic step, no correction for multiple comparisons is required.

In the current study, we used task PLS analysis to examine modulation of brain activity during the 3 conditions of the same/different task (i.e., faces, houses, and objects) to establish whether the 2 groups of participants show neural activations that are specific to face processing, and to identify the seed regions in which BOLD values were subsequently entered into seed PLS analysis to assess task-related functional connectivity (i.e., the relation of activity in the selected seed regions and activity in the rest of the brain during face processing; Della-Maggiore et al., 2000; McIntosh, 1999; McIntosh et al., 1997; Schreurs et al., 1997). We identified 3 seed regions that showed highly reliable task-related changes in both groups of participants in the faces versus houses conditions: the right FG (44, -44, -18), left FG (-40, -46, -16), and medial OFC (-2, 58, -6). These areas were shown to be important for face processing in a number of studies (Fairhall and Ishai, 2007; Haxby et al., 2000; Kanwisher et al., 1997).

To delineate the face-processing network in the 2 groups of participants, we extracted the BOLD values from the 3 seeds (i.e.,



**Fig. 1.** Task PLS results: LV1, faces, houses, objects. (A) A pattern of whole-brain activity. (B) Brain scores related to whole-brain activity seen in (A), across 3 conditions (faces, houses, objects) and 2 groups (older and young adults). Error bars denote 95% confidence intervals for the correlations calculated using the bootstrap procedure. Top left corner slice  $z = -22$ , bottom right corner slice  $z = 44$ . Abbreviations: LV, latent variable; PLS, partial least squares.

from the peak voxels) for the faces condition and correlated them with activity in all other brain voxels, across the participants (seed PLS). These correlations were then combined into a matrix and decomposed with singular value decomposition, resulting in a set of LVs characterizing the set of regions where activity was correlated with seed activity in young and older adults during face processing. The significance and reliability of the LVs were determined by permutation tests and bootstrap resampling, as described earlier in text. Finally, to examine the relation of the face-processing network with behavioral performance, we used seed/behavior PLS analysis, adding 2 more variables in a subsequent seed-behavior analysis, which allowed us to assess whether activity in the network, defined according to the areas correlating with the right FG, left FG, and OFC, was also correlated with accuracy and RTs on the facial identity-matching task, which was done outside the scanner (McIntosh et al., 1996; Zhu et al., 2011). This task, unlike the same/different task in the scanner, assessed face perception per se, so that we could correlate brain activity with a sensitive measure of behavioral performance.

In all of the analyses, the bootstrap procedure calculated the 95% confidence intervals of either the mean-centered brain scores for each condition and group (for task PLS), or the correlations between brain scores and seed activity (or behavior) for each condition and group (in the seed and seed/behavior analyses). To obtain a conservative measure of the differences in activity between conditions and age groups, we determined these differences via a lack of overlap in the confidence intervals. That is, nonoverlapping intervals between conditions within a group, or between groups within a condition, indicated a significant difference.

### 3. Results

#### 3.1. Behavioral performance

In both behavioral tasks, there was no significant difference in either accuracy or RT between young and older adults. In the scanner (same/different task), older adults' RT was 814.87 ms (standard error [SE] = 38.09) and accuracy 0.95 (SE = 0.02), whereas young adults' RT was 739.57 ms (SE = 28.92) and accuracy 0.95 (SE = 0.01). Outside the scanner (facial identity-matching task), older adults' RT was 797.50 ms (SE 47.94) and accuracy 0.97 (SE = 0.01), whereas young adults' RT was 708.87 ms (SE = 42.58) and accuracy 0.98 (SE = 0.01).

#### 3.2. Whole-brain analysis

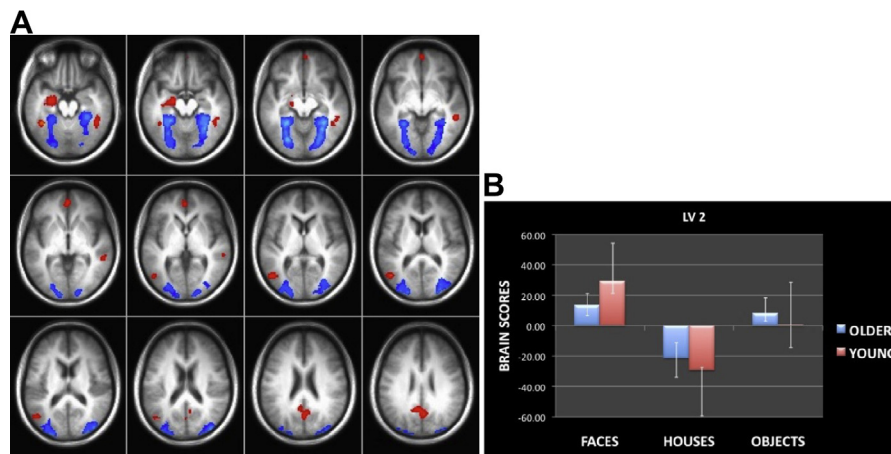
The task PLS analysis of the same/different task yielded 1 significant LV that accounted for 49% of covariance in the data ( $p < 0.01$ ) and a second LV that showed a statistical trend and accounted for 26% covariance in the data ( $p = 0.07$ ). Both LVs reflected patterns of activity related to the processing of faces in the young participants, but these were less specific for the older adults. LV1 identified a set of regions with increased activity during the face condition, relative to the object condition, in the young participants, but in the older adults this pattern of activity was seen in the house condition, compared with faces and objects. These areas included right FG, bilateral occipitotemporal gyrus, middle occipital gyrus, inferior frontal gyrus, medial frontal gyrus, and precuneus (Fig. 1 and Table 1; see Supplementary Fig. 1 for a comparable result from a univariate analysis). LV2 yielded an activation pattern differentiating the face condition from the house condition in both groups of participants (Fig. 2 and Table 2; see Supplementary Fig. 2 for a comparable result from a univariate analysis). However, the older adults also recruited these brain regions in the object condition. The areas with increased activity during the face condition in both groups (and object condition in older adults) included bilateral FG, left hippocampus, orbitofrontal gyrus, posterior cingulate gyrus, and left middle temporal gyrus. The brain regions with increased activity during the house condition were bilateral occipitotemporal gyrus, FG, and middle occipital gyrus. Considering both of these

**Table 1**  
Whole-brain analysis: LV1

Region	Hem	BA	MNI Coordinates			Ratio <sup>a</sup>
			x	y	z	
Fusiform gyrus	R	37	42	-54	-16	4.32
Occipitotemporal gyrus	R	18/19	32	-76	-16	5.38
	L	18/19	-18	-80	-16	5.68
Middle occipital gyrus	R	19	34	-72	24	5.11
	L	19	-28	-68	22	5.10
Inferior frontal gyrus	R	44/45	48	8	22	5.02
	L	44/9	-38	12	28	6.86
Medial frontal gyrus		8	8	24	36	4.09
Precuneus	R	7	22	-62	52	5.61
	L	7	-16	-62	54	3.65

Key: BA, Brodmann area; Hem, hemisphere; L, left; LV, latent variable; MNI, Montreal Neurological Institute; R, right; SE, standard error.

<sup>a</sup> Salience/SE ratio using the bootstrap analysis.



**Fig. 2.** Task PLS results: LV2, faces, houses, objects. (A) A pattern of whole-brain activity. (B) Brain scores related to whole-brain activity seen in (A), across 3 conditions (faces, houses, objects) and 2 groups (older and young adults). Error bars denote 95% confidence intervals for the correlations calculated using the bootstrap procedure. Top left corner slice  $z = -16$ , bottom right corner slice  $z = 28$ . Abbreviations: LV, latent variable; PLS, partial least squares.

patterns together, younger adults show brain activity for faces that is distinct from houses and objects. In contrast, these results suggest reduced face specificity in the brains of older adults, in that neither pattern differentiated faces from objects in the older group.

### 3.3. Functional connectivity

The seed PLS analysis was carried out using only the data from the face condition in the same/different task. It assessed functional connectivity among the right FG, left FG, and OFC regions that were identified in LV2 of the task analysis (with more activity for faces than houses in both groups), and the rest of the brain. This analysis yielded 1 significant LV that accounted for 46% of covariance in the data ( $p < 0.001$ ). The delineated face-processing network was engaged in young and older adults, but differed between them in critical functional connections (Fig. 3 and Table 3). In young adults, this network was functionally connected (i.e., positively correlated) with the right and left FG, but not the OFC. In older adults, this set of regions was functionally connected with the right FG and the OFC, but not the left FG. This distributed network included previously identified face-processing areas, inferior frontal gyrus, medial frontal gyrus, insula, and precuneus. Additional areas of the functional network included bilateral inferior parietal lobule, anterior

and posterior cingulate gyrus, and superior temporal gyrus. The main age-related difference in the functional connectivity of these regions during face processing was that only older adults recruited OFC into this network.

### 3.4. Behavior correlations

The seed-behavior analysis assessed whether activity in the face network (i.e., regions functionally connected to the right FG, left FG, and OFC during viewing of natural faces in the same/different task) was correlated with behavioral performance (accuracy and RTs) on the face-matching task obtained outside of the scanner. This analysis yielded 1 significant LV that accounted for 46% of covariance in the data ( $p < 0.001$ ). The brain regions identified using this LV (Fig. 4) were quite similar to those seen when only the 3 seeds were included in the analysis (Fig. 3 and Table 3), as would be expected. Again, in young adults, this network was functionally connected to both the right and left FG (but not to the OFC), and in older adults it was functionally connected to the right FG and OFC, but not the left FG. Crucially, this additional analysis showed that activity in the face-processing network was not correlated with either behavioral measure in young adults, but was significantly correlated with accuracy (a positive correlation of  $r = 0.4$ ) in older adults, indicating that more accurate older adults recruited this functional network more strongly. Interestingly, there was no significant correlation between the functional network and RTs in older adults. These results suggest that the age-related compensatory recruitment of the OFC is directly linked to accurate face recognition in older adults, rather than response speed.

**Table 2**  
Whole-brain analysis: LV2

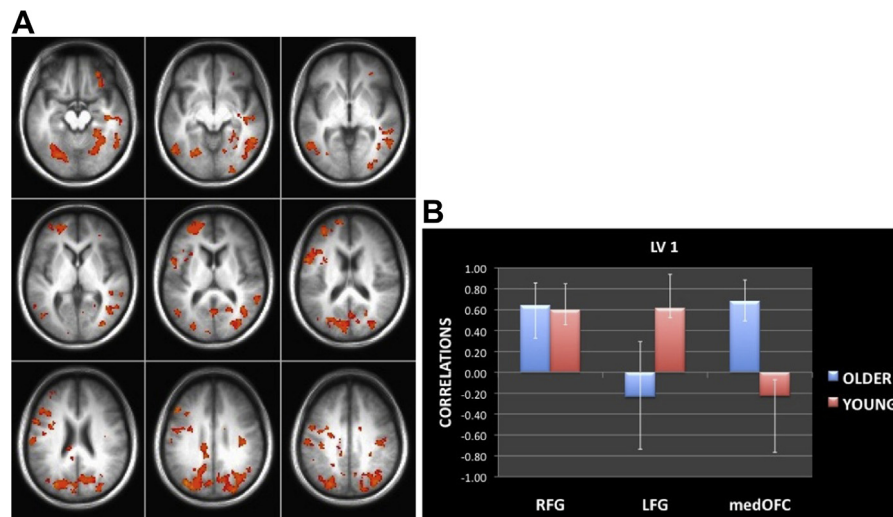
Region	Hem	BA	MNI Coordinates			Ratio <sup>a</sup>
			x	y	z	
<b>Positive correlations</b>						
Fusiform gyrus	R	37	44	-44	-18	5.35
	L	37	-40	-46	-16	8.10
Medial orbitofrontal cortex	L	11	-2	58	-6	4.15
Hippocampus	L		-22	-14	-14	5.45
Posterior cingulate gyrus	R	31	4	-60	28	5.86
Middle temporal gyrus	L	39	-48	-64	10	6.62
<b>Negative correlations</b>						
Fusiform gyrus	R	37	32	-48	-10	-9.62
	L	37	-26	-44	-10	-9.41
Middle occipital gyrus	R	19	42	-82	18	-7.98
	L	19	-28	-90	18	-6.49
Occipitotemporal gyrus	R	18/19	22	-74	-6	6.87
	L	18/19	-22	-74	-6	-8.23

Key: BA, Brodmann area; Hem, hemisphere; L, left; LV, latent variable; MNI, Montreal Neurological Institute; R, right; SE, standard error.

<sup>a</sup> Saliency/SE ratio using the bootstrap analysis.

## 4. Discussion

In our recent study (Lee et al., 2011), we found that when viewing repeatedly presented faces of same identity and viewpoint, in contrast to their young counterparts, older adults failed to show adaptation in the right FG, despite accurate face matching. The purpose of the current study was to examine further how age-related differences in the neural underpinnings of face processing influence behavior. Our findings provide evidence for the involvement of 2 critical phenomena, a generalized age-related reduction in neural specificity to faces (i.e., dedifferentiation) and a change in the functional connectivity of the face-processing network that consisted of an age-related increase in the engagement of medial



**Fig. 3.** Seed PLS results. (A) A pattern of correlated whole-brain activity. (B) Correlations between activity in right FG, left FG, left medial OFC, and scores representing activity in the regions seen in (A). Error bars denote 95% confidence intervals for the correlations calculated using the bootstrap procedure. Top left corner slice  $z = -12$ , bottom right corner slice  $z = 34$ . Abbreviations: FG, fusiform gyrus; L, left; med, medial; OFC, orbitofrontal cortex; PLS, partial least squares; R, right.

frontal cortex. Moreover, we show that the age difference in functional connections is related to better accuracy in older adults, suggesting that this altered connectivity is compensatory in nature and highlighting its critical role in face recognition as one ages.

#### 4.1. Dedifferentiation

The whole-brain analysis showed that young adults recruit a number of brain regions previously shown to be involved in face processing (Haxby et al., 2000). These areas include bilateral occipitotemporal gyrus, FG, inferior frontal gyrus, middle occipital gyrus, medial frontal gyrus, and precuneus, and are activated primarily during face processing in young adults, in direct contrast to processing of houses or other objects. Older adults recruit the same areas; however, some of this activity is found for houses, rather than faces, and some is seen for faces and other objects, suggesting a lack of specificity in the neural signature of older adults for faces. These findings parallel previous neuroimaging studies that show age-related reductions in neural sensitivity to

different stimulus categories (faces, places, or words) in the ventral and dorsal visual pathways (Carp et al., 2010a, 2010b; Park et al., 2004; Schiavetto et al., 2002). Similarly, Grady et al. (1992, 1994) found that older adults activate ventral occipital areas during face-matching and location-matching, suggesting that the ventral and dorsal visual pathways for object identity and location, respectively, are less functionally segregated in older adults (see also Park et al., 2004; Schiavetto et al., 2002). Our results, along with these earlier studies, indicate that some dedifferentiation of category-specific activity to visual stimuli occurs in older adults. In addition, our data indicate that this dedifferentiation is not limited to visually responsive regions of cortex, but occurs in frontal cortex as well, as others have noted for memory tasks (Carp et al., 2010a, 2010b; St-Laurent et al., 2011) and for auditory processing (Grady et al., 2011).

#### 4.2. Compensatory recruitment

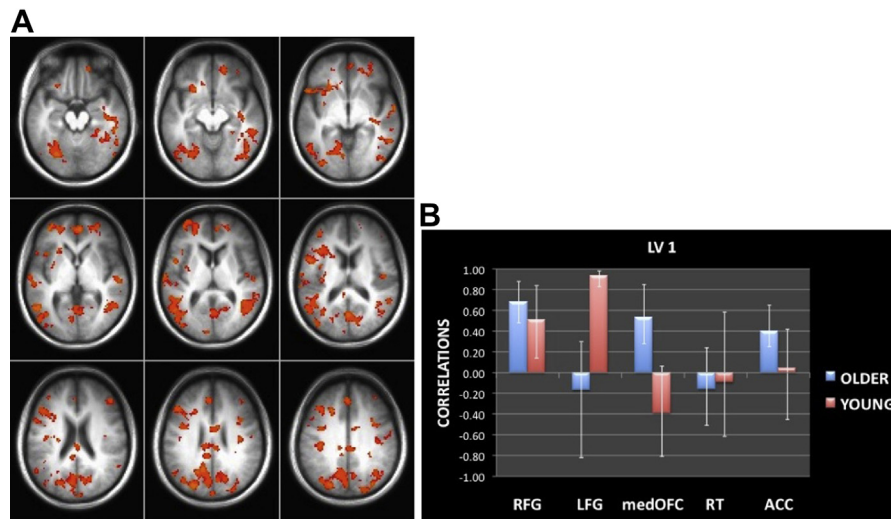
The functional connectivity analysis yielded 2 interesting findings. First, young and older adults recruit the same neural network during face processing, but this network differs significantly in its functional connections with fusiform regions and the OFC. In young adults, the face-processing network is functionally connected to the right FG and its homologous region, whereas in older adults this network is functionally connected only to the right FG. However, older adults also recruit the orbitofrontal gyrus, perhaps to compensate for the loss of the functional connection between the fusiform gyri. Second, activity in the face-processing network positively correlates with performance of the older adults, but not of the young adults. These findings suggest that compensatory mechanisms in the prefrontal cortex are recruited to counteract altered domain-specific processing in posterior regions (Davis et al., 2008; Schiavetto et al., 2002), such as the reduced adaptation in FG that we found in these older adults (Lee et al., 2011). In our view, the strongest evidence for compensation is that there is recruitment of additional neural resources in older adults, whether it be higher levels of mean activity or stronger functional connectivity, and this recruitment is related to performance in older adults. In the current study we found such evidence; that is, both age groups recruit OFC activity for faces, but the older adults have stronger functional connections between OFC and the rest of the face-processing

**Table 3**  
Seed PLS analysis: LV1

Region	Hem	BA	MNI Coordinates			Ratio <sup>a</sup>
			x	y	z	
Fusiform gyrus	R	37	44	-44	-18	8.12
	L	37	-40	-46	-16	5.21
Medial orbitofrontal cortex	L	11	-2	58	-6	4.23
Occipitotemporal gyrus	L	18/19	-20	-66	-8	7.10
Middle occipital gyrus	R	19	18	-70	24	5.10
	L	19	-28	-74	24	6.93
Inferior frontal gyrus	R	44	34	6	30	5.17
	L	44/45	-54	8	16	6.23
Medial frontal gyrus		8	0	38	36	5.14
Insula	R	13	30	-2	14	5.08
Precuneus	L	7	-10	-56	58	5.54
Inferior parietal lobule	R	40	42	-34	56	6.64
	L	40	-40	-36	54	7.00
Cingulate gyrus	Anterior	24	10	-12	40	4.90
	Posterior	31	-10	-36	30	5.22
Superior temporal gyrus	L	22	-56	-24	4	6.02

Key: BA, Brodmann area; Hem, hemisphere; L, left; LV, latent variable; MNI, Montreal Neurological Institute; PLS, partial least squares; R, right; SE, standard error.

<sup>a</sup> Salience/SE ratio using the bootstrap analysis.



**Fig. 4.** Seed/behavior PLS results. (A) A pattern of correlated whole-brain activity. (B) Correlations between activity in right FG, left FG, left medial OFC, reaction times, accuracy during the face-matching task, and scores representing activity in the regions seen in (A). Error bars denote 95% confidence intervals for the correlations calculated from the bootstrap procedure. Top left corner slice  $z = -14$ , bottom right corner slice  $z = 34$ . Abbreviations: ACC, accuracy; FG, fusiform gyrus; L, left; med, medial; OFC, orbitofrontal cortex; PLS, partial least squares; R, right; RT, reaction time.

network, and activity in this network of regions is associated with better face processing performance only in the older adults. The specificity of the connection between functional connectivity and accuracy to only the older group is good evidence for an age difference in how the faces are processed that might compensate for reduced modulation of activity in the FG.

Research shows that increased activity in frontal areas is associated with: (1) compromised face detection because of noise added to face stimuli (Grady et al., 2000; Ishai, 2008; Li et al., 2010; Summerfield et al., 2006; for objects, see Kveraga et al., 2007); or (2) reduced domain-specificity in older adults (Grady et al., 1994; Schiavetto et al., 2002). Specifically, evidence shows that orbitofrontal areas boost their coupling with the FG as perceptual ambiguity increases (Bar et al., 2006; Summerfield et al., 2006), indicating that a top-down signal from the frontal cortex to the ventral visual area might help resolve perceptual ambiguity (Summerfield et al., 2006). Thus, it is reasonable to suggest that the age-related reduction in selectivity of face processing in occipito-temporal cortex is tantamount to adding noise to the entire system (Wilson et al., 2011) and that frontal areas are consequently recruited to help strengthen the weakened signal, making faces more recognizable. As discussed in the introduction, OFC is involved in various aspects of face processing, such as detection of blurred faces (Li et al., 2010; Summerfield et al., 2006) and objects (Bar et al., 2006; Kveraga et al., 2007), and linking external input to existing representation in memory given uncertain external input (Bar, 2009). It seems to be involved in cognitive aspects of face processing (e.g., judgment of the value or linking the perceived face to stored representation), which assist perception and recognition of the face. Thus, our data suggest that older adults rely more on cognitive processes (e.g., assessing the value of faces) to compensate for their compromised fusiform connection. Further support for this interpretation comes from the strong relation between OFC recruitment and behavioral performance of the older adults, in that high-performing older adults show greater increases in connectivity between the temporal and frontal regions. In a similar vein, Thomas et al. (2008) reported an association between face discrimination performance and the integrity of the right inferior fronto-occipital fasciculus, a white matter tract, which passes through the FG and projects to the frontal cortex. Their results

suggest that connectivity between the frontal cortex and ventral visual areas contributes to behavioral performance involving face perception.

To recapitulate, our results show that functional connectivity between the left and right FG is not significant in older adults and that the right, not left FG, is functionally connected to the prefrontal areas to support behavioral performance. It is important to state that these results appear to contradict the right hemisphere hypothesis of aging (e.g., Meudell and Greenhalgh, 1987), which proposes that aging affects functions associated with the right hemisphere to a greater degree than those involving the left hemisphere (see review in Dolcos et al., 2002; also see Thomas et al., 2008). Similarly, in our previous study (Lee et al., 2011), older adults showed more activity, compared with young adults, in the left FG and left middle occipital gyrus. It has been shown that activity in FG during a face-matching task positively correlates with FG gray matter volume in healthy older adults (Teipel et al., 2007), implying that the brain-behavior relation might be an index of gray matter integrity. Although we can only speculate, we propose 2 possible interpretations of the age-related loss of functional connectivity between left and right FG. The first potential explanation involves age-related weakening of white matter tracts between left and right FG. Although reductions in white matter connectivity of the ventral stream have been linked to age-related changes in face perception (Thomas et al., 2008), to our knowledge no study has examined white matter connectivity between the left and right FG in the aged population. The other possibility to interpret these findings is in line with the Hebbian principle of synaptic plasticity, which states that the weight between 2 neurons increases if the 2 neurons activate simultaneously and reduces if they activate separately (Hebb, 1949). In other words, neurons that fire together wire together and those that are out of sync lose their link. We propose that as one ages, the functioning in the right FG might be reduced, which is reflected by abnormal adaptation to repeatedly presented faces (Goh et al., 2010; Lee et al., 2011). The functioning in the left FG remains relatively spared, resulting in “negative weighting” between right and left FG and a subsequent weakening of their functional connection. To compensate for the loss of this connection, the right FG strengthens its functional connection with OFC. This connection is further strengthened over time, making the

functional connection between the right and left FG less important. Evidence comes from Teipel et al. (2007), who examined voxelwise correlations between FG activity during a face-matching task and regional gray matter density, showing that activity in the right FG significantly correlates with left FG gray matter density, whereas activity in the left FG does not significantly correlate with the right FG gray matter density. Moreover, their results suggest that preservation of the cortical density in the ventral visual pathway determines to what extent an alternate pathway would be involved in the maintenance of task performance. Thus, the findings of Teipel et al. (2007) strongly indicate that the preservation of the right FG might be directly related to the left FG. The loss of functional connectivity between the left and right FG in our study might, therefore, reflect a deterioration of right FG function.

In summary, our results indicate that dedifferentiation and functional compensation are not incompatible. Using multivoxel pattern analysis, Carp et al. (2010b) found that older adults show less distinctive multivoxel activation patterns to different object categories in a number of regions, including early and ventral visual cortices, inferior parietal cortex, and medial and lateral prefrontal cortex. However, they found no evidence of compensation by increased selectivity in anterior regions. In contrast, our results clearly demonstrate reduced specificity and compensation in the brains of older adults. Dedifferentiation was evident in age-related reduced sensitivity to different object categories across a number of brain areas and compensation was evident in the functional connectivity between the right FG and OFC, which was associated with behavioral accuracy.

## Disclosure statement

All authors have no conflicts of interest.

The study and all experimental procedures were conducted with the approval of the Baycrest Centre Research Ethics Board.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.neurobiolaging.2013.06.016>.

## References

- Bar, M., 2009. The proactive brain: memory for predictions. *Philos. Trans. Roy. Soc. B Biol. Sci.* 364, 1235–1243.
- Bar, M., Kassam, K., Ghuman, A., Boshyan, J., Dale, A., Hämäläinen, M., Marinkovic, K., Schacter, D.L., Rosen, B., Halgren, E., 2006. Top-down facilitation of visual recognition. *Proc. Natl. Acad. Sci. U.S.A.* 103, 449–454.
- Barbeau, E.J., Taylor, M.J., Regis, J., Marquis, P., Chauvel, P., Liegeois-Chauvel, C., 2008. Spatio-temporal dynamics of face recognition. *Cereb. Cortex* 18, 997–1009.
- Bartlett, J.C., Strater, L., Fulton, A., 1991. False recency and false fame of faces in young adulthood and old age. *Mem. Cogn.* 19, 177–188.
- Boutet, I., Faubert, J., 2006. Recognition of faces and complex objects in younger and older adults. *Mem. Cogn.* 34, 854–864.
- Cabeza, R., Anderson, N.D., Locantore, J.K., McIntosh, A.R., 2002. Aging gracefully: compensatory brain activity in high-performing older adults. *Neuroimage* 17, 1394–1402.
- Cabeza, R., Dennis, N.A., 2012. Frontal lobes and aging: deterioration and compensation. In: Stuss, D.T., Knight, R.T. (Eds.), *Principles of Frontal Lobe Function*. Oxford University Press, New York, pp. 628–652.

- Carp, J., Gmeindl, L., Reuter-Lorenz, P.A., 2010a. Age differences in the neural representation of working memory revealed by multi-voxel pattern analysis. *Front. Hum. Neurosci.* 4, 217.
- Carp, J., Park, J., Polk, T.A., Park, D.C., 2010b. Age differences in neural distinctiveness revealed by multi-voxel pattern analysis. *Neuroimage* 56, 736–743.
- Clarke, S., Lindemann, A., Maeder, P., Borruat, F.X., Assal, G., 1997. Face recognition and postero-inferior hemispheric lesions. *Neuropsychologia* 35, 1555–1563.
- Cox, R.W., 1996. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Comp. Biomed. Res.* 29, 162–173.
- Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., Cabeza, R., 2008. Que PASA? The posterior-anterior shift in aging. *Cereb. Cortex* 18, 1201–1209.
- Della-Maggiore, V., Sekuler, A.B., Grady, C.L., Bennett, P.J., Sekuler, R., McIntosh, A.R., 2000. Corticolimbic interactions associated with performance on a short-term memory task are modified by age. *J. Neurosci.* 20, 8410–8416.
- Dolcos, F., Rice, H.J., Cabeza, R., 2002. Hemispheric asymmetry and aging: right hemisphere decline or asymmetry reduction. *Neurosci. Biobehav. Rev.* 26, 819–825.
- Duvernois, S., Motamedinia, S., Rugg, M.D., 2009. The relationship between aging, performance, and the neural correlates of successful memory encoding. *Cereb. Cortex* 19, 733–744.
- Efron, B., Tibshirani, R., 1985. The bootstrap method for assessing statistical accuracy. *Behaviormetrika* 17, 1–35.
- Fairhall, S.L., Ishai, A., 2007. Effective connectivity within the distributed cortical network for face perception. *Cereb. Cortex* 17, 2400–2406.
- Folstein, M.F., Folstein, S.E., McHugh, P.R., 1975. Mini-mental state: a practical method for grading the cognitive state of patients for the clinician. *J. Psychiatric Res.* 12, 189–198.
- Freeman, J.B., Rule, N.O., Adams Jr., R.B., Ambady, N., 2010. The neural basis of categorical face perception: graded representations of face gender in fusiform and orbitofrontal cortices. *Cereb. Cortex* 20, 1314–1322.
- Friston, K.J., Frith, C.D., Frackowiak, R.S., 1993. Principal component analysis learning algorithms—a neurobiological analysis. *Proc. Roy. Soc. London B Biol. Sci.* 254, 47–54.
- Gobbini, M.D., Haxby, J.V., 2007. Neural systems for recognition of familiar faces. *Neuropsychologia* 45, 32–41.
- Goh, J.O., Suzuki, A., Park, D.C., 2010. Reduced neural selectivity increases fMRI adaptation with age during face discrimination. *Neuroimage* 51, 336–344.
- Grady, C.L., 2000. Functional brain imaging and age-related changes in cognition. *Biol. Psychology* 54, 259–281.
- Grady, C.L., 2002. Age-related differences in face processing: a meta-analysis of three functional neuroimaging experiments. *Can. J. Exp. Psychol.* 56, 208–220.
- Grady, C.L., 2008. Cognitive neuroscience of aging. *Ann. N. Y. Acad. Sci.* 1124, 127–144.
- Grady, C.L., 2012. The cognitive neuroscience of ageing. *Nat. Rev. Neurosci.* 13, 491–505.
- Grady, C.L., Bernstein, L.J., Beig, S., Siegenthaler, A.L., 2002. The effects of encoding task on age-related differences in the functional neuroanatomy of face memory. *Psychol. Aging* 17, 7–23.
- Grady, C.L., Charlton, R., He, Y., Alain, C., 2011. Age differences in fMRI adaptation for sound identity and location. *Front. Hum. Neurosci.* 5, 24.
- Grady, C.L., Haxby, J.V., Horwitz, B., Schapiro, M.B., Rapoport, S.I., Ungerleider, L.G., Mishkin, M., Carson, R.E., Herscovitch, P., 1992. Dissociation of object and spatial vision in human extrastriate cortex: age-related changes in activation of regional cerebral blood flow measured with [<sup>15</sup>O] water and positron emission tomography. *J. Cogn. Neurosci.* 4, 23–34.
- Grady, C.L., Maisog, J.M., Horwitz, B., Ungerleider, L.G., Mentis, M., Salerno, J.A., Pietrini, P., Wagner, E., Haxby, J.V., 1994. Age-related changes in regional blood flow activation during visual processing of faces and location. *J. Neurosci.* 14, 1450–1462.
- Grady, C.L., McIntosh, A.R., Craik, F.I.M., 2005. Task-related activity in prefrontal cortex and its relation to recognition memory performance in young and old adults. *Neuropsychologia* 43, 1466–1481.
- Grady, C.L., McIntosh, A.R., Horwitz, B., Rapoport, S.I., 2000. Age-related changes in the neural correlates of degraded and nondegraded face processing. *Cogn. Neuropsychol.* 17, 165–186.
- Habak, C., Wilkinson, F., Wilson, H.R., 2008. Aging disrupts the neural transformations that link facial identity across views. *Vision Res.* 48, 9–15.
- Harmer, C.J., Thillo, K.V., Rothwell, J.C., Goodwin, G.M., 2001. Transcranial magnetic stimulation of medial-frontal cortex impairs the processing of angry facial expressions. *Nat. Neurosci.* 4, 17–18.
- Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2000. The distributed human neural system for face perception. *Trends Cogn. Sci.* 4, 223–233.
- Hebb, D.O., 1949. *The Organization of Behavior*. Wiley & Sons, New York.
- Horwitz, B., 1994. Data analysis paradigms for metabolic-flow data: Combining neural modeling and functional neuroimaging. *Human Brain Mapping* 2, 112–122.
- Ishai, A., 2007. Sex, beauty and the orbitofrontal cortex. *Int. J. Psychophysiol.* 63, 181–185.
- Ishai, A., 2008. Let's face it: it's a cortical network. *Neuroimage* 40, 415–419.
- Ishai, A., Schmidt, C.F., Boesiger, P., 2005. Face perception is mediated by a distributed cortical network. *Brain Res. Bull.* 67, 87–93.
- Johnson, M.H., 2005. Subcortical face processing. *Nat. Rev. Neurosci.* 6, 766–774.
- Kanwisher, N., McDermott, J., Chun, M.M., 1997. The fusiform face area: a module in human extrastriate cortex specialized for face perception. *J. Neurosci.* 17, 4302–4311.



- Krishnan, A., Williams, L.J., McIntosh, A.R., Abdi, H., 2011. Partial least squares (PLS) methods for neuroimaging: a tutorial and review. *Neuroimage* 56, 455–475.
- Kveraga, K., Boshyan, J., Bar, M., 2007. Magnocellular projections as the trigger of top-down facilitation in recognition. *J. Neurosci.* 27, 13232–13240.
- Lee, Y., Grady, C.L., Habak, C., Wilson, H.R., Moscovitch, M., 2011. Face processing changes in normal aging revealed by fMRI adaptation. *J. Cogn. Neurosci.* 23, 3433–3447.
- Li, J., Liu, J., Liang, J., Zhang, H., Zhao, J., Rieth, C.A., 2010. Effective connectivities of cortical regions for top-down face processing: a dynamic causal modeling study. *Brain Res.* 1340, 40–51.
- Li, S.C., Lindenberger, U., Sikstrom, S., 2001. Aging cognition – from neuro-modulation to representation. *Trends Cogn. Sci.* 5, 479–486.
- Lott, L.A., Haegerstrom-Portnoy, G., Schneck, M.E., Brabyn, J.A., 2005. Face recognition in the elderly. *Optom. Visi. Sci.* 82, 874–881.
- Madden, D.J., Whiting, W.L., Provenzale, J.M., Huettel, S.A., 2004. Age-related changes in neural activity during visual target detection measured by fMRI. *Cereb. Cortex* 14, 143–155.
- McIntosh, A.R., 1999. Mapping cognition to the brain through neural interactions. *Memory* 7, 523–548.
- McIntosh, A.R., Bookstein, F.L., Haxby, J.V., Grady, C.L., 1996. Spatial pattern analysis of functional brain images using partial least squares. *Neuroimage* 3, 143–157.
- McIntosh, A.R., Chau, W.K., Protzner, A.B., 2004. Spatiotemporal analysis of event-related fMRI data using partial least squares. *Neuroimage* 23, 764–775.
- McIntosh, A.R., Nyberg, L., Bookstein, F.L., Tulving, E., 1997. Differential functional connectivity of prefrontal and medial temporal cortices during episodic memory retrieval. *Hum. Brain Mapp.* 5, 323–327.
- Meudell, P.R., Greenhalgh, M., 1987. Age related differences in left and right hand skill and in visuo-spatial performance: their possible relationships to the hypothesis that the right hemisphere ages more rapidly than the left. *Cortex* 23, 431–445.
- Nestor, A., Plaut, D.C., Behrmann, M., 2011. Unraveling the distributed neural code of facial identity through spatiotemporal pattern analysis. *Proc. Natl. Acad. Sci. U.S.A.* 108, 9998–10003.
- Ogawa, S., Lee, T.M., Kay, A.R., Tank, D.W., 1990. Brain magnetic-resonance-imaging with contrast dependent on blood oxygenation. *Proc. Natl. Acad. Sci. U.S.A.* 87, 9868–9872.
- Park, D.C., Polk, T.A., Park, R., Minear, M., Savage, A., Smith, M.R., 2004. Aging reduces neural specialization in ventral visual cortex. *Proc. Natl. Acad. Sci. U.S.A.* 101, 13091–13095.
- Reuter-Lorenz, P.A., Cappell, K., 2008. Neurocognitive aging and the compensation hypothesis. *Curr. Dir. Psychol. Sci.* 18, 177–182.
- Reuter-Lorenz, P.A., Jonides, J., Smith, E.E., Hartley, A., Miller, A., Marshuetz, C., Koeppel, R.A., 2000. Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *J. Cogn. Neurosci.* 12, 174–187.
- Sampson, P.D., Streissguth, A.P., Barr, H.M., Bookstein, F.L., 1989. Neurobehavioral effects of prenatal alcohol: part II. Partial least squares analysis. *Neurotoxicol. Teratol.* 11, 477–491.
- Schiavetto, A., Kohler, S., Grady, C.L., Winocur, G., Moscovitch, M., 2002. Neural correlates of memory for object identity and object location: effects of aging. *Neuropsychologia* 40, 1428–1442.
- Schreurs, B., McIntosh, A.R., Bahron, M., Herscovitch, P., Sunderland, T., Molchan, S., 1997. Lateralization and behavioural correlation of changes in regional cerebral blood flow. *77*, 2153–2163.
- Searcy, J.H., Bartlett, J.C., Menon, A., 1999. Age differences in accuracy and choosing in eyewitness identification and face recognition. *Mem. Cogn.* 27, 538–552.
- Steeves, J.K., Culham, J.C., Duchaine, B.C., Pratesi, C.C., Valyear, K.F., Schindler, I., Humphrey, G.K., Milner, A.D., Goodale, M.A., 2006. The fusiform face area is not sufficient for face recognition: evidence from a patient with dense prosopagnosia and no occipital face area. *Neuropsychologia* 44, 594–609.
- St-Laurent, M., Abdi, H., Burianová, H., Grady, C., 2011. Influence of aging on the neural correlates of autobiographical, episodic, and semantic memory retrieval. *J. Cogn. Neurosci.* 23, 4150–4163.
- Summerfield, C., Egner, T., Greene, M., Koechlin, E., Mangels, J., Hirsch, J., 2006. Predictive codes for forthcoming perception in the frontal cortex. *Science* 314, 1311–1314.
- Teipel, S.J., Bokde, R.L., Born, C., Meindl, T., Reiser, M., Moller, H.J., Hampel, H., 2007. Morphological substrate of face matching in healthy ageing and mild cognitive impairment: a combined MRI-fMRI study. *Brain* 130, 1745–1758.
- Thomas, C., Moya, L., Avidan, G., Humphreys, K., Jung, K.J., Peterson, M.A., Behrmann, M., 2008. Reduction in white matter connectivity, revealed by diffusion tensor imaging, may account for age-related changes in face perception. *J. Cogn. Neurosci.* 20, 268–284.
- Wilson, H.R., Mei, M., Habak, C., Wilkinson, F., 2011. Visual bandwidths for face orientation increase during healthy aging. *Vision Res.* 51, 160–164.
- Zhu, Q., Zhang, J., Luo, Y.L., Dilks, D.D., Liu, J., 2011. Resting-state neural activity across face-selective cortical regions is behaviorally relevant. *J. Neurosci.* 31, 10323–10330.