Changes in functional connectivity associated with facial expression processing over the working adult lifespan

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Abstract

The recognition of negative emotions from facial expressions is shown to decline across the adult lifespan, with some evidence that this decline begins around middle age. While some studies have suggested ageing may be associated with changes in neural response to emotional expressions, it is not known whether ageing is associated with changes in the network connectivity associated with processing emotional expressions. In this study, we examined the effect of participant age on whole-brain connectivity to various brain regions that show connectivity during emotion processing, namely, the left and right amygdalae, medial prefrontal cortex (mPFC), and right posterior superior temporal sulcus (rpSTS). The study involved healthy participants aged 20-65 years who viewed facial expressions displaying anger, fear, happiness, and neutral expressions during functional magnetic resonance imaging (fMRI). We found that participant age was negatively associated with connectivity between the left amygdala and voxels in the left occipital pole, cerebellum, and middle frontal gyrus; between the rpSTS and voxels in the orbitofrontal cortex; and between the mPFC and cingulate cortex and right angular gyrus. Furthermore, most of these effects were due to a greater age-related decline in brain connectivity for negative expressions compared to happy and neutral expressions, providing further evidence for a specific age-related decline in the processing of negative emotions. These results indicate that changes in underlying functional connectivity might explain age-related changes in recognition of negative facial expressions across the adult lifespan.

Keywords

Facial expressions; Ageing; Functional connectivity

Introduction

The recognition of emotions from facial expressions changes across the adult lifespan. To date, two meta-analyses have shown that older adults (aged 60+) typically perform poorer than younger adults (aged approximately 18-30) at recognition tasks, with the largest group differences in the recognition of anger, sadness, and fear, followed by happiness and surprise (Gonçalves et al., 2018; Ruffman, Henry, Livingstone, & Phillips, 2008). Most studies included within these analyses examined differences in recognition between two distinct age groups, with fewer studies examining the changes in recognition that occur throughout the adult lifespan. Some studies suggest an 'inverted U-shape' for recognition accuracy that occurs over the developmental and adult lifespan, with the highest recognition accuracy in young and middle-aged adults (Horning, Cornwell, & Davis, 2012; Williams et al., 2009). Other studies have investigated how recognition changes over the adult lifespan only, reporting a linear age-related decrease in accuracy (Lambrecht, Kreifelts, & Wildgruber, 2012), with a specific decline in the recognition of anger and sadness beginning around age 40-45 (Brosgole & Weisman, 1995; Calder et al., 2003). Similarly, the recognition of emotional prosody from speech begins to decline during middle age (Lambrecht et al., 2012; Orbelo, Testa, & Ross, 2003; Paulmann, Pell, & Kotz, 2008), suggesting a modality-independent decline in emotion recognition across the adult lifespan.

Several studies have examined age differences in neural response to facial expressions, although again, most have tested differences in activation between distinct groups of younger and older adults (e.g. Zsoldos, Cousin, Klein-Koerkamp, Pichat, & Hot, 2016). A common result is that younger adults show higher activation in the amygdala and hippocampus than older adults for facial expressions of emotion, particularly in response to angry and fearful faces (Fischer, Nyberg, & Bäckman, 2010; Fischer et al., 2005; Gunning-Dixon et al., 2003; Iidaka et al., 2002; Keightley, Chiew, Winocur, & Grady, 2007; Tessitore et al., 2005), whereas older adults show higher activation than younger adults in prefrontal areas (Fischer et al., 2010; Gunning-Dixon et al., 2003; Tessitore et al., 2005; Zsoldos et al., 2016).

To our knowledge, only one study has examined differences in neural response to facial expressions that occur across the adult lifespan, where participants aged 12-79 were presented fearful, happy, and neutral faces during fMRI (Williams et al., 2006). Increasing age was linearly associated with a decrease in medial Prefrontal Cortex (mPFC) response to happy faces, and an increase in response to fearful faces. Amygdala response to happy faces was larger for participants aged 12-29 than 40-79, whereas for fearful faces amygdala response was larger in participants aged 20-49 than the younger and older participants. Together these results highlight that age differences in the neural response to facial expressions of specific emotions may develop linearly in some but not other brain regions over the adult lifespan.

The studies into the effect of age on neural response to facial expressions typically employ univariate statistics, assessing how the magnitude of activation differs between age groups (or across as examined by Williams et al., 2006), however research into face and emotion perception has often employed newer multivariate techniques for analysing fMRI data. Analysis of brain connectivity has emerged as a method for examining the statistical dependences (functional connectivity analysis), or causal interactions (effective connectivity analysis), between distinct regions or voxels. Such analyses can be conducted using resting-state data to assess underlying connectivity within or between brain networks in the absence of any specific task demands, or using task-based data to assess the patterns of connectivity that are associated with specific task demands.

Studies using both task-based and resting-state functional connectivity analysis have provided evidence that face perception is supported by synchronized activity between regions within both the core (the fusiform face area, occipital face area, and superior temporal sulcus) and extended (e.g. the amygdala and intraparietal sulcus) face processing network (Davies-Thompson & Andrews, 2012; Fairhall & Ishai, 2007; Lohse et al., 2016; Turk-Browne, Norman-Haignere, & Mccarthy, 2010; Wang, Zhen, et al., 2016; Zhang, Tian, Liu, Li, & Lee, 2009; Zhen, Fang, & Liu, 2013). Furthermore, the strength of this connectivity is subject to age-related increases over childhood and adolescence (Cohen Kadosh, Cohen Kadosh, Dick, & Johnson, 2011; Joseph et al., 2012) and is associated with performance in a number of behavioural face processing tasks (O'Neil, Hutchison, McLean, & Köhler, 2014; Zhu, Zhang, Luo, Dilks, & Liu, 2011).

Several studies have also examined the neural connectivity associated with the processing of facial expressions, with common results showing increased connectivity between the core and extended face processing regions, and particularly implementing connectivity of some regions involved in emotion processing and theory of mind – the right posterior STS (rpSTS), amygdala, and regions of the prefrontal cortex (Dima, Stephan, Roiser, Friston, & Frangou, 2011; Fairhall & Ishai, 2007; Foley, Rippon, Thai, Longe, & Senior, 2012; Furl, Henson, Friston, & Calder, 2013; Liang, Liu, Li, & Wang, 2018; Zhen et al., 2013). Importantly, some studies have linked this connectivity with behaviour, reporting that connectivity of the rpSTS to other face processing regions is correlated with emotion recognition accuracy (Wang, Song, Zhen, & Liu, 2016), amygdala connectivity is correlated with reaction time to identify angry faces (Marstaller, Burianová, & Reutens, 2016), and that coupling between the amygdala and vmPFC is associated with the engagement with emotional faces in a theory-of-mind task (Morawetz et al., 2016).

There are a wealth of studies investigating age-related changes in resting state and task-related connectivity, with common results showing reduced connectivity within the default mode network (Damoiseaux et al., 2008; Geerligs, Renken, Saliasi, Maurits, & Lorist, 2015; Meier et al., 2012) and reduced specificity of functional networks (Geerligs, Maurits, Renken, & Lorist, 2014) in comparison to younger adults. Some studies also showed that age differences in several behavioural tasks can be explained by age differences in connectivity of task-relevant regions (Chou, Chen, & Madden, 2013;

Madden et al., 2010; Sambataro et al., 2010). Furthermore, several studies have shown that these changes in connectivity may develop over the adult lifespan (Andrews-Hanna et al., 2007; Betzel et al., 2014; Biswal et al., 2010; Chan, Park, Savalia, Petersen, & Wig, 2014; Ferreira et al., 2016; Geerligs, Rubinov, et al., 2015; Onoda, Ishihara, & Yamaguchi, 2012; Rosenberg, Mennigen, Monti, & Kaiser, 2020), although as these studies often use correlational approaches with participants aged 18-90+, is it not clear at what age these changes in connectivity begin to develop.

Given the converging lines of evidence that (a) ageing is associated with both changes in expression recognition and changes in functional connectivity, and (b) that variability in expression recognition accuracy is associated with variability in connectivity strength, it is worth questioning whether there are any effects of age on the functional connectivity associated with the processing of facial expressions. Currently, it is not known whether the connectivity associated with the processing of facial expressions changes over the adult lifespan, a time during which the behavioural recognition of, and magnitude of neural activation in response to facial expressions begins to decline (Brosgole & Weisman, 1995; Calder et al., 2003; Horning et al., 2012; Lambrecht et al., 2012; Williams et al., 2006, 2009). Some studies have reported age-related changes in connectivity during the processing of social information that occur over adolescence, a period of life associated with increases in emotion recognition (Horning et al., 2012; Williams et al., 2009). For example, one study showed that connectivity between the amygdala and mPFC shifts from positive to negative during the viewing of emotional faces in participants aged 7-25 (Wu et al., 2016), and another reported greater connectivity between the mPFC and rpSTS/temporoparietal junction when mentalising the emotional state of others in adolescents compared to young adults (Burnett & Blakemore, 2009). Comparing younger adults to older adults, one study showed that when rating the valence of emotional images (IAPS; Lang, Bradley, & Cuthbert, 1997) older adults had greater functional connectivity between the amygdala and anterior cingulate cortex (St. Jacques, Dolcos, & Cabeza, 2010), which could reflect age differences in emotional evaluation. Perhaps the most relevant study to this question examined whether resting state connectivity could predict age differences in the learning of emotional faces (Sakaki, Nga, & Mather, 2013). Results showed an interaction between participant age, connectivity, and a positivity effect (the bias to remember positive facial expressions over negative), where inverse resting state connectivity between the amygdala and mPFC was associated with the positivity effect in older adults but not younger. Together, these results suggest that age differences in functional connectivity might underly age differences in the emotional evaluation of both faces and emotionally-valenced non-face stimuli, although it is still unknown at what age any changes in functional connectivity associated with the processing of facial expressions may develop.

In the current study we investigate whether there are any changes in connectivity during the viewing of facial expressions of emotion that occur over the working adult lifespan. Specifically, we examined whole-brain connectivity to the amygdala, rpSTS, and mPFC, as these regions have been implicated in emotion processing (Fusar-Poli et al., 2009), theory of mind (Dufour et al., 2013), and are subject to age-related changes in neural response to facial expressions (Williams et al., 2006) and resting state connectivity (for a review - Ferreira & Busatto, 2013). Importantly, increased connectivity to these regions is associated with better performance in behavioural measures of facial expression processing (Marstaller et al., 2016; Morawetz et al., 2016; Wang, Song, et al., 2016). We examined seed-to-voxel connectivity in a group of participants aged 20-65, using data collected as part of a larger project (Kumari et al., 2011, 2016). In this dataset, participants viewed angry, fearful, happy, and neutral facial expressions of emotion during fMRI. Should connectivity with the above regions act as an index of the ability to process emotions from facial expressions, we would expect to find reduced functional connectivity with these regions across the adult lifespan. Specifically, as the recognition of negative expressions begins to decline in middle age, we expect to find greater effects of age on connectivity to the above regions during the viewing of angry and fearful expressions than happy and neutral.

Methods

Participants

Data from 31 participants (22 males) were used. Participants were aged 20-65y (mean age = 33.8, S.D. = 11.46). All participants fell within the normal range across a range of neuropsychological tests, were not on any medication, and had no history of drug use. All participants provided written informed consent prior to their participation and were compensated for their time and travel. The study procedures for the larger project (Kumari et al., 2011, 2016) were approved by the ethics committee of the joint research ethics committee of the SLaM and the Institute of Psychiatry, London, and the use of these data for the current investigation was approved by the ethics committee of the College of Health and Life Sciences at Brunel University London .

fMRI task and protocol

Participants were presented with angry, fearful, happy, and neutral faces (from Ekman & Friesen, 1976), each in separate blocks lasting 30s. Each block contained 8 faces, presented for 3.75s each. Blocks for each facial expression category were presented 4 times each. After each block of faces, participants were presented with a 15s no face block during which an oval frame (matched for the luminance of the face but no face inside) appeared 4 times for 3.75 s each. During the face blocks, participants performed a gender discrimination task, where they indicated if each face was male or female using a button box. During the no face (oval frame) blocks, participants were asked to press a button when the blank oval frame appeared. Full details on the fMRI paradigm can be found in Kumari et al. (2011, 2016).

fMRI Image Acquisition

MRI data was collected with a 1.5T GE Signa System. 240 T2*-weighted images were collected for each participant, using an Echo Planar Imaging (EPI) sequence with 16 near-axial slices aligned parallel to the intercommisural plane (TR = 3000ms, TE = 40ms, flip angle = 90°, voxel size = 3.1mm x 3.1mm x 7mm, matrix size = 64 x 64, interslice gap = 0.7mm). In addition to these function images, a high-resolution 3D inversion recovery prepared spoiled gradient recalled acquisition in the steady state volume data set was acquired (TR = 12.2ms, TE = 5.3ms, inversion time = 300ms, voxel size = 0.94mm x 0.94mm x 1.5mm).

Data preprocessing

Data preprocessing was conducted using the Conn 2019 Toolbox in MATLAB 2016b (Whitfield-Gabrieli & Nieto-Castanon, 2012) using the “default MNI” pipeline. Functional images were realigned and unwarped (coregistered to the first image using b-spline interpolation). Outlier scans were identified using ART-based identification in which scans with a mean global-signal more than 5 standard deviations from the mean for the scanning session, or in which the motion was above 5mm in any direction, were identified and regressed out as nuisance covariates later in the analysis. Functional and structural images were then normalised to MNI space and segmented into grey matter, white matter, and cerebrospinal fluid (using the unified segmentation and normalisation procedure in SPM12) and resampled using 2mm isotropic voxels for the functional image and 1mm for the structural. Finally, functional data was smoothed using an 8mm FWHM Gaussian kernel.

Before conducting the connectivity analysis, Conn employs a denoising procedure by performing linear regression on the Blood Oxygen Level Dependent (BOLD) timeseries of each voxel, with principal components from the white matter and cerebrospinal fluid (Behzadi, Restom, Liau, & Liu, 2007; Chai, Castañón, Öngür, & Whitfield-Gabrieli, 2012), 12 motion parameters (3 translation, 3 rotation, and their first-order derivatives), and a variable number of noise components (one for each outlier detected during the outlier identification) as covariates. Additionally, the presentation of the four expression categories were modelled using a box-car function convolved with a canonical haemodynamic response function and were also included as covariates in the denoising procedure to ensure that functional connectivity measures did not reflect task-related effects (Whitfield-Gabrieli & Nieto-Castanon, 2012). After the linear regression the BOLD signal was band-pass filtered to remove temporal frequencies below 0.08Hz and above 0.9Hz.

fMRI data analysis

Two types of analyses were conducted with the fMRI data; standard univariate analysis and seed-based connectivity analysis. For both types of analysis, four subject-specific regions were defined (rpSTS, mPFC, and the left and right amygdala), using a group-constrained subject-specific (GSS) approach used (Fedorenko, Hsieh, Nieto-Castañón, Whitfield-Gabrieli, & Kanwisher, 2010; Julian, Fedorenko, Webster, & Kanwisher, 2012) in conjunction with a flood-fill algorithm (Coggan, Baker, & Andrews, 2019; Weibert et al., 2016), allowing for the definition of regions without any experimenter bias.

Region of Interest (ROI) Definition

First, a standard General Linear Model (GLM) was performed in SPM12 (http://www.fil.ion.ucl.ac.uk/spm/software/spm12/) on the timeseries of each voxel in the preprocessed (realigned, normalised, and smoothed) data, by modelling the four facial affect expression categories as box-car functions (convolved with a canonical haemodynamic response function), including the 6 realignment parameters as additional regressors and a 128 second high-pass filter, and contrasting the response to all faces against baseline. This contrast was chosen as we were interested in identifying the peak face-responsive voxel, rather than assessing the magnitude of face or emotion selectivity for the definition of ROIs. The resulting T-maps were then intersected with the group-level bilateral amygdala and mPFC ROIs defined by the Harvard-Oxford atlas (http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases) as implemented in Conn 2019. As the Harvard-Oxford atlas does not include a region for the rpSTS, this group-level mask was taken from an independent study in which face-selective regions were mapped for use with the GSS approach (Julian et al., 2012). Next, for each participant and each region, the voxel with the highest T-statistic (within the group-level mask) was used as the seed in a flood-fill algorithm, which defined a cluster of 100 spatially contiguous voxels by iteratively increasing the cluster from the seed by identifying the voxel with the largest T-statistic from the voxels surrounding the cluster at each iteration. The mean MNI coordinates of the seed voxels in the flood fill algorithm across participants were [53.0, -44.2, 11.4] for the rpSTS, [-1.2, 51.0, -10.6] for the mPFC, [-23.2, -4.4, -14.1] for the left amygdala and [19.7, -3.9, -13.7] for the right amygdala. The resulting clusters were used as subject-specific ROIs in both the univariate and seed-based connectivity analyses.

Univariate Analysis

The univariate analysis was conducted to examine the response to each expression category within each of the ROIs. For each expression category, the average beta estimate across voxels within each subject-specific region was calculated, for each participant. For each ROI, means for each expression were then calculated across participants. Paired-sample T-tests were then conducted between pairs of betas within each ROI, controlling for multiple comparisons with the Bonferroni adjustment ($\alpha = 0.05/6 = 8.33E\text{-}3$). Additionally, a Pearson correlation between participant age and response to each expression within each region was conducted to assess the relationship between participant age and univariate response to expressions. Multiple comparisons were corrected for using the Bonferroni adjustment (α = 0.05/4 = 1.25E-2).

Functional Connectivity Analysis

Seed-based connectivity analysis was conducted using the Conn toolbox, using the four subject-specific ROIs as seeds. Connectivity was measured as the Fischer Z-transformed bivariate correlation coefficient between the BOLD timeseries within the ROI and each voxel in the brain, then mapped to the voxel to create the seed-based connectivity maps, separately for each of the regions and expression categories.

Second level GLMs were used to assess significance of (a) the average effect of participant age across expressions on connectivity with each of the four ROIs, and (b) interactions between expression category and age on connectivity with each of the four ROIs. To do so, the connectivity maps of the four expression categories were modelled as within-subject covariates and participant age as a between-subject covariate. One-sample T-tests (to examine average effects across expressions) and F-tests (to examine differences between the expressions) were then conducted, using $p<.005$ (uncorrected) at the voxel level p(FWE-corrected)<.05 at the cluster level. Any significant age-expression interactions were followed up with post-hoc t-tests between every pair of expressions, using $p<.005$ (uncorrected) at the voxel level for voxels only within the mask of the ANOVA results. Significance was assessed using the cluster-level p-value, correcting for multiple comparisons with the Bonferroni adjustment (α = 0.05/6 = 8.33E-3).

Data availability

The data that support the findings of this study will be made available in anonymised form upon reasonable request to the authors. All metadata (activation maps, connectivity matrices) generated for the study will be available openly through Brunel University Research Archive (BURA).

Results

Univariate analysis

Results of the univariate analysis are presented in Figure 1, and Supplementary Table S1. The left and right amygdalae showed similar patterns of results, where the largest response was to Angry and Fearful faces, followed by Happy and Neutral faces. The largest, but negative, response in the mPFC was also to Fearful and Angry faces. The largest, but negative, response in the rpSTS was to happy faces.

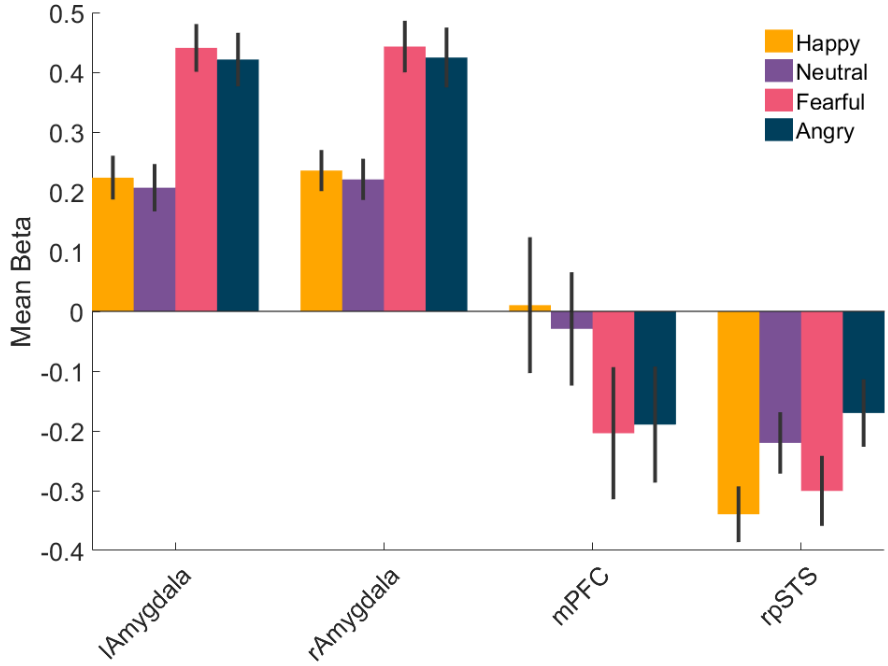

Figure 1: Mean response to each expression category, within each region. Error bars show one ± 1 standard error of the mean.

After controlling for multiple comparisons with the Bonferroni correction ($\alpha = 0.05/6 = 8.33E-3$), no significant differences in response to the expressions was found in any region, although the fearful-happy difference was marginal in the left ($t(28) = 2.632$, $p = .013$) and right ($t(28) = -2.618$, $p = .014$) amygdalae. Results of the paired-sample T-tests are presented in Supplementary Table S2. After correcting for multiple comparisons with the Bonferroni adjustment ($\alpha = 0.05/4 = 1.25E-2$), no significant relationship was found between participant age and the response to any expression in any region, although the relationship between age and left amygdala response to fearful faces was marginal ($r = -0.407$, $p = .023$). Results of the correlations are presented in Supplementary Table S3.

Left amygdala connectivity

There was no effect of participant age (averaged across expression categories) on connectivity with the left amygdala. There were, however, differences between the expression categories on the effect of age on connectivity between the left amygdala and three clusters. One cluster covered regions of the occipital pole and intracalcarine sulcus, and post-hoc comparisons revealed that increasing participant age was associated with a greater reduction in connectivity between this region and the left amygdala for both angry ($T(29) = 5.34$, $p < .001$) and fearful ($T(29) = 5.52$, $p = .002$) faces compared to happy faces. The second cluster covered regions of the middle frontal and precentral gyri, where there was a greater age-related reduction in connectivity for happy faces compared to fearful faces ($T(29) = 6.34$, $p = .003$). The third cluster covered regions in the cerebellum, where post-hoc comparisons showed a greater age-related reduction in connectivity for fearful ($T(29) = 5.22$, $p = .004$) compared to happy, and similar trend for angry faces compared to happy, although this just failed to reach significance after the Bonferroni correction ($T(29) = 4.27$, $p = .009$). Statistical maps are presented in Figure 2, and results of the ANOVA are presented in Table 1.

Table 1: Results of the second-level GLMs examining the effect of age on connectivity with the left amygdala. Degrees of freedom for the t-tests = 29. Degrees of freedom for the F-tests = [3, 27].

Side	Region	Voxels (n)	MNI			F	p(FWE)
			X	Y	Z		
L	Occipital pole Intracalcarine cortex Lingual gyrus	398	-10	-90	-2	12.16	<.001
R	Middle frontal gyrus Precentral gyrus	227	42	-2	50	13.88	.030
L	Cerebelum 6 Vermis 6 Cerebelum 4 5 Lingual gyrus Vermis 4 5	207	-4	-66	-12	12.46	.048

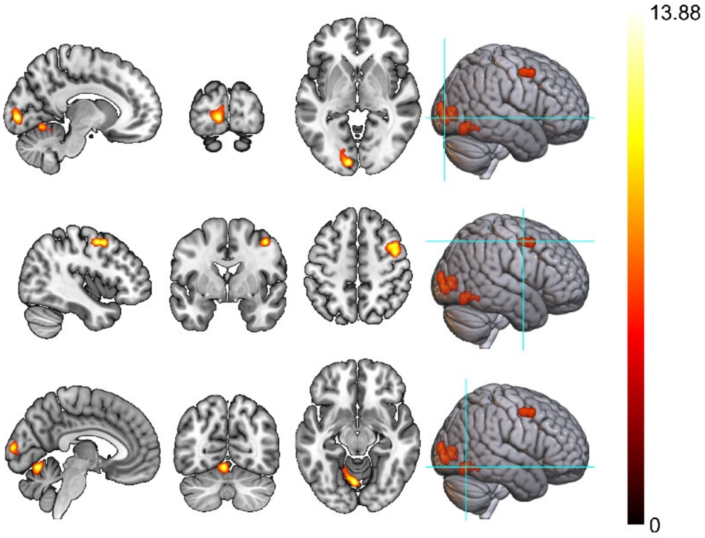

Figure 2: Three clusters showing significant interactions between expression and age on connectivity with the left amygdala. Each row displays sagittal, axial, and coronal slices for each peak coordinate within the cluster. Colourbar displays F-values.

Right amygdala connectivity

Averaged across expression categories, we found no effect of age on connectivity with the right amygdala. We also found no effect of expression category on the effect of age on connectivity with the right amygdala.

rpSTS

There was no effect of participant age (averaged across expression categories) on connectivity with the rpSTS. We did, however, find an interaction showing the effect of expression category on the effect of age on connectivity between the rpSTS and a cluster of voxels covering regions of the frontal orbital cortex and subcallosal cortex (Table 2). However, no post-hoc comparisons between the expressions reached significance, although there was a trend for a greater age-related reduction in connectivity for fearful ($T(29) = 5.34$, $p = .013$) and angry ($T(29) = 5.28$, $p = .011$) faces compared to neutral. Statistical maps are presented in Figure 3.

Table 2: Effect of age on connectivity with rpSTS

Side	**Region**	**Voxels (n)**	**MNI**			**F**	**p(FWE)**
			X	*Y*	*Z*		
L	Frontal orbital cortex Subcallosal cortex	247	-14	24	-20	8.42	.020

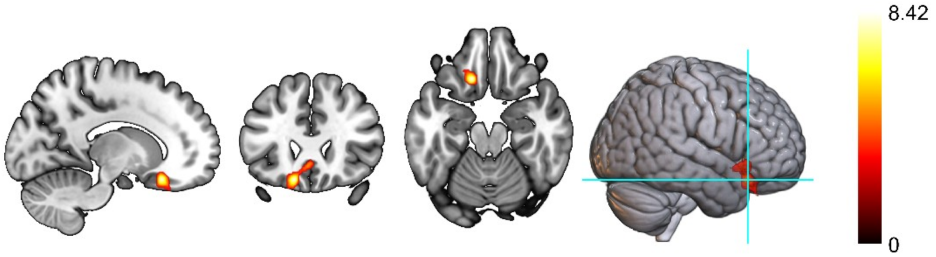

Figure 3: Cluster showing significant interactions between expression and age on connectivity with the rpSTS. Sagittal, axial, and coronal slices display the peak coordinate within the cluster. Colourbar displays F-values.

mPFC

There was no effect of participant age (averaged across expression categories) on connectivity with the mPFC. There were, however, differences between the expression categories on the effect of age on connectivity between the mPFC and two clusters. One cluster covered regions of the anterior cingulate, paracingulate, and superior frontal gyri, where the pattern of post-hoc comparisons suggested a greater age-related decline in connectivity for the negative expressions compared to happy and neutral. Participant age was associated with a greater decline in connectivity for fearful ($T(29) = 5.34$, $p < .001$) and angry ($T(29) = 5.72$, $p < .001$) faces compared to neutral, and a greater decline for fearful ($T(29) = 4.85$, $p = .001$) and angry ($T(29) = 4.49$, $p = .001$) faces compared to happy.

The second cluster covered regions of the right lateral occipital cortex, and angular and supramarginal gyri, where post-hoc comparisons showed a greater age-related reduction in connectivity for both angry faces ($T(29) = 4.89$, $p = .004$) and happy ($T(29) = 5.37$, $p = .001$) faces compared to neutral. Statistical maps are presented in Figure 4, and results of the ANOVA are presented in Table 3.

Table 3: Effect of age on connectivity with mPFC

Side	Region	Voxels (n)	MNI			F	p(FWE)
			X	*Y*	*Z*		
	Cingulate gyrus, anterior division	962	8	20	32	20.60	<.001
Left	Paracingulate gyrus Frontal pole Superior frontal gyrus						
Right	Paracingulate gyrus						
Right	Angular gyrus Supramarginal gyrus, posterior division Lateral occipital cortex, superior division Superior parietal lobule	319	36	-54	42	12.36	.005

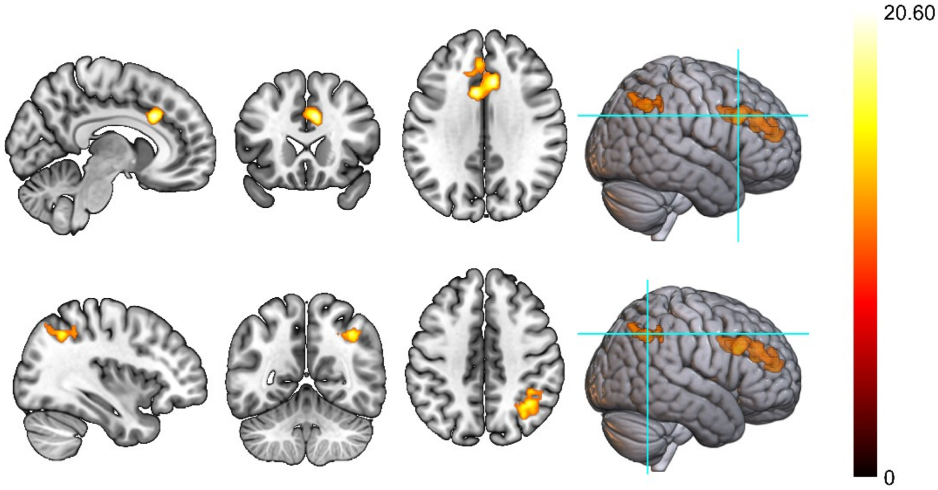

Figure 4: Two clusters showing significant interactions between expression and age on connectivity with the mPFC. Each row displays sagittal, axial, and coronal slices for each peak coordinate within the cluster. Colourbar displays F-values.

Discussion

The aim of this study was to examine whether there are any effects of participant age on functional connectivity strength during the processing of facial expressions of emotion in working age adults. We found significant effects of participant age on connectivity to the left amygdala, the rpSTS, and to the mPFC, but not to the right amygdala. We found an age-related reduction in connectivity between the left amygdala and left occipital pole for negative expressions compared to happy faces. In other words, participant age was more greatly associated with reduced connectivity strength for angry and fearful faces than happy faces. Similarly, we found a greater age-related reduction in connectivity between the left amygdala and parts of the cerebellum for negative faces compared to happy faces, and between the left amygdala and partis of the middle frontal and precentral gyri for happy faces compared to fearful. For the rpSTS, we found a greater age-related reduction in connectivity with the left OFC for angry and fearful faces compared to neutral faces. For the mPFC, we found a greater age-related conduction with anterior regions of the cingulate cortex for negative expressions compared to happy and neutral, and between the mPFC and right supramarginal and angular gyri for angry faces compared to neutral.

Given that the recognition of emotions from facial expressions begins to decline during the working adult lifespan (Calder et al., 2003; Horning et al., 2012; Lambrecht et al., 2012; Williams et al., 2009), ageing is associated with changes in functional connectivity (Ferreira & Busatto, 2013), and connectivity strength is associated with emotion processing ability (Marstaller et al., 2016; Wang, Song, et al., 2016), these results could suggest that age-related reductions in connectivity contribute to the age-related reduction in the processing of facial expressions of emotion. This suggestion is further supported by the trend in results that the age-related reduction in connectivity with the left amygdala, rpSTS, and mPFC is greater for negative expressions than for happy and neutral expressions, as ageing is associated with a reduction in the recognition of angry and fearful faces (Gonçalves et al., 2018; Ruffman et al., 2008).

Our finding that participant age is associated with connectivity between the left amygdala and left occipital pole might be explained in terms of the 'modulatory' role of the amygdala on early visual processing. It has been suggested that the amygdala provides top-down signals that modulate representations of emotional stimuli in the Early Visual Cortex (EVC), and guide attention toward emotionally salient, and particularly negative, information (Barrett & Bar, 2009; Vuilleumier, 2005). Regarding the processing of facial expressions, several studies have shown that amygdala activity predicts expression-specific activity in the EVC (Morris et al., 1998), patients with amygdala lesions show reduced activity in the fusiform and occipital cortex when viewing fearful faces (Vuilleumier, Richardson, Armony, Driver, & Dolan, 2004), and disruption of EVC activity 120ms after the initial presentation of emotional faces selectively disrupts the perception of negative facial expressions (Guo, Calver, Soornack, & Bourke, 2020). It is possible, therefore, that our result that ageing is associated with a greater reduction in connectivity between the amygdala and occipital pole for angry faces compared to happy faces could reflect age differences in amygdala modulation of EVC activity for emotionally salient stimuli. Further research is needed to examine effects of age on any causal association between amygdala and EVC activity for negative facial expressions.

We found an age-related reduction in connectivity between the rpSTS and OFC, for angry and fearful faces compared to neutral. The OFC contains face-selective cells that represent social categories (including age, gender, and facial expression; Barat, Wirth, & Duhamel, 2018), and this region is shown to play a role in implementing top-down predictions that shape representations in visual areas during object recognition (Bar et al., 2006). Furthermore, given the neuroanatomical connections between this region and temporal recognition regions (Cavada, Compañy, Tejedor, Cruz-Rizzolo, & Reinoso-Suárez, 2000; Kahnt, Chang, Park, Heinzle, & Haynes, 2012) a model of social perception has proposed that the OFC is involved offering top-down guidance that shape representations of faces in the fusiform gyrus (Freeman & Johnson, 2016). Our result of an age-related reduction in connectivity between the rpSTS and OFC might, therefore, reflect changes in top-down visual processing of facial expressions that could occur across the lifespan, although it is currently not clear why this explains the specific reduction in connectivity for negative faces compared to neutral.

Previous research has shown connectivity between the mPFC, anterior cingulate, supramarginal gyrus, and other face-responsive regions during face processing (Zhen et al., 2013). The present results add to this, by showing that the connectivity between these regions during the processing of facial expressions varies as a function of observer age. Specifically, we found a greater age-related reduction in connectivity between the mPFC and anterior cingulate for negative faces compared to happy and neutral, and between the mPFC and parts of the supramarginal and angular gyri for both happy and angry faces compared to neutral. e age-related reduction in connectivity with the supramarginal and angular gyri could be interpreted in terms of age-related changes in theory of mind. The temporoparietal junction covers areas of the supramarginal and angular gyri and is frequently reported to be recruited during tasks requiring theory of mind, along with the mPFC (Dodell-Feder, Koster-Hale, Bedny, & Saxe, 2011). Furthermore, performance on tasks requiring the attribution of another's mental state declines over the adult lifespan (Kemp, Després, Sellal, & Dufour, 2012). We found a greater age-related decline in connectivity for both happy and angry faces compared to neutral faces, suggesting that the age-related changes in connectivity are not valence-specific, but instead relate to the processing of emotional faces more broadly. As emotion processing is associated with theory of mind (Mitchell & Phillips, 2015), such changes in connectivity could reflect age-related changes in theory of mind, although further research is needed to directly test whether any age-related changes in tasks requiring theory of mind is associated with changes in connectivity between the mPFC, TPJ, and other regions recruited during such tasks.

While the results of this research suggest that changes in functional connectivity, especially to the amygdala and rpSTS, might contribute in part to age-related changes in expression recognition, it is unknown whether these measures of connectivity directly relate to recognition accuracy. Participants in the dataset used in this study were also tested on recognition accuracy, however ceiling effects were observed across all four expression categories, so these measures were not used within this analysis. Perhaps future research could investigate the contribution of differences in connectivity to the effects of age on expression recognition using a suitably challenging test of facial expression perception.

A further question for future research to address is whether any age differences in segregation of functional networks contributes to age differences in expression recognition. A common result of studies using resting state connectivity is that functional networks become less segregated over the adult lifespan, characterised by reduced within-network and increased between-network connectivity (Betzel et al., 2014; Chan et al., 2014; Ferreira et al., 2016; Geerligs et al., 2014; Geerligs, Renken, et al., 2015; Rosenberg et al., 2020). Conversely, cognitive development is accompanied by increased segregation of functional networks over adolescence (Dosenbach et al., 2010; Stevens, 2016). Given that the strength of connectivity within the face processing network is associated with behavioural measures for the perception of emotion and identity in faces (O'Neil et al., 2014; Wang, Song, et al., 2016; Zhu et al., 2011), it is possible that the age-related changes in expression recognition could be explained in terms of reduced specificity of the face-processing network.

The present study has found several age-related reductions in functional connectivity associated with the processing of facial expressions that occur over the working adult lifespan, namely between the left amygdala and regions in the left occipital pole, cerebellum, and right middle frontal gyrus, between the rpSTS and left OFC, and between the mPFC and supramarginal and angular gyri, and cingulate cortex. Furthermore, most of these effects were due to a greater age-related reductions connectivity for negative expressions compared to happy and neutral expressions, providing support for a theory of the effect of age on expression recognition that encompasses changes in functional connectivity.

Declarations of interest: none

References

Andrews-Hanna, J. R., Snyder, A. Z., Vincent, J. L., Lustig, C., Head, D., Raichle, M. E., & Buckner, R. L. (2007). Disruption of Large-Scale Brain Systems in Advanced Aging. *Neuron*, *56*(5), 924–935. https://doi.org/10.1016/j.neuron.2007.10.038

Bar, M., Kassam, K. S., Ghuman, A. S., Boshyan, J., Schmidt, A. M., Dale, A. M., … Halgren, E. (2006).

Top-down facilitation of visual recognition. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(2), 449–454. https://doi.org/10.1073/pnas.0507062103

Barat, E., Wirth, S., & Duhamel, J. R. (2018). Face cells in orbitofrontal cortex represent social categories. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(47), E11158–E11167. https://doi.org/10.1073/pnas.1806165115

Barrett, L. F., & Bar, M. (2009). See it with feeling: Affective predictions during object perception. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1521), 1325–1334. https://doi.org/10.1098/rstb.2008.0312

Behzadi, Y., Restom, K., Liau, J., & Liu, T. T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *NeuroImage*, *37*(1), 90–101. https://doi.org/10.1016/j.neuroimage.2007.04.042

Betzel, R. F., Byrge, L., He, Y., Goñi, J., Zuo, X. N., & Sporns, O. (2014). Changes in structural and functional connectivity among resting-state networks across the human lifespan. *NeuroImage*, *102*(P2), 345–357. https://doi.org/10.1016/j.neuroimage.2014.07.067

Biswal, B. B., Mennes, M., Zuo, X. N., Gohel, S., Kelly, C., Smith, S. M., … Milham, M. P. (2010). Toward discovery science of human brain function. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(10), 4734–4739. https://doi.org/10.1073/pnas.0911855107

Brosgole, L., & Weisman, J. (1995). Mood recognition across the ages. *International Journal of Neuroscience*, *82*(3–4), 169–189. https://doi.org/10.3109/00207459508999800

Burnett, S., & Blakemore, S. J. (2009). Functional connectivity during a social emotion task in adolescents and in adults. *European Journal of Neuroscience*, *29*(6), 1294–1301. https://doi.org/10.1111/j.1460-9568.2009.06674.x

Calder, A. J., Keane, J., Manly, T., Sprengerlmeyer, R., Scott, S., Nimmo-Smith, I., & Young, A. W. (2003). Facial expression recognition across the adult life span. *Neuropsychologia*, *41*, 195–202.

Cavada, C., Compañy, T., Tejedor, J., Cruz-Rizzolo, R. J., & Reinoso-Suárez, F. (2000). The anatomical connections of the macaque monkey orbitofrontal cortex. A review. *Cerebral Cortex*, *10*(3), 220–242. https://doi.org/10.1093/cercor/10.3.220

Chai, X. J., Castañón, A. N., Öngür, D., & Whitfield-Gabrieli, S. (2012). Anticorrelations in resting state networks without global signal regression. *NeuroImage*, *59*(2), 1420–1428. https://doi.org/10.1016/j.neuroimage.2011.08.048

Chan, M. Y., Park, D. C., Savalia, N. K., Petersen, S. E., & Wig, G. S. (2014). Decreased segregation of brain systems across the healthy adult lifespan. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(46), E4997–E5006. https://doi.org/10.1073/pnas.1415122111

Chou, Y., Chen, N., & Madden, D. J. (2013). Functional brain connectivity and cognition: effects of adult age and task demands. *Neurobiology of Aging*, *34*(8), 1925–1934. https://doi.org/10.1016/j.neurobiolaging.2013.02.012

Coggan, D. D., Baker, D. H., & Andrews, T. J. (2019). Selectivity for mid-level properties of faces and places in the fusiform face area and parahippocampal place area. *European Journal of Neuroscience*, *49*(12), 1587–1596. https://doi.org/10.1111/ejn.14327

Cohen Kadosh, K., Cohen Kadosh, R., Dick, F., & Johnson, M. H. (2011). Developmental Changes in Effective Connectivity in the Emerging Core Face Network. *Cerebral Cortex*, *21*(6), 1389–1394.

https://doi.org/10.1093/cercor/bhq215

Damoiseaux, J. S., Beckmann, C. F., Arigita, E. J. S., Barkhof, F., Scheltens, P., Stam, C. J., … Rombouts, S. A. R. B. (2008). Reduced resting-state brain activity in the “default network” in normal aging. *Cerebral Cortex*, *18*(8), 1856–1864. https://doi.org/10.1093/cercor/bhm207

Davies-Thompson, J., & Andrews, T. J. (2012). Intra- and interhemispheric connectivity between face-selective regions in the human brain. *Journal of Neurophysiology*, *108*(11), 3087–3095. https://doi.org/10.1152/jn.01171.2011

Dima, D., Stephan, K. E., Roiser, J. P., Friston, K. J., & Frangou, S. (2011). Effective connectivity during processing of facial affect: Evidence for multiple parallel pathways. *Journal of Neuroscience*, *31*(40), 14378–14385. https://doi.org/10.1523/JNEUROSCI.2400-11.2011

Dodell-Feder, D., Koster-Hale, J., Bedny, M., & Saxe, R. (2011). FMRI item analysis in a theory of mind task. *NeuroImage*, *55*(2), 705–712. https://doi.org/10.1016/j.neuroimage.2010.12.040

Dosenbach, N. U. F., Nardos, B., Cohen, A. L., Fair, D. A., Power, J. D., Church, J. A., … Schlaggar, B. L. (2010). Prediction of individual brain maturity using fMRI. *Science*, *329*(5997), 1358–1361. https://doi.org/10.1126/science.1194144

Dufour, N., Redcay, E., Young, L., Mavros, P. L., Moran, J. M., Triantafyllou, C., … Saxe, R. (2013). Similar Brain Activation during False Belief Tasks in a Large Sample of Adults with and without Autism. *PLoS ONE*, *8*(9), e75468. https://doi.org/10.1371/journal.pone.0075468

Ekman, P., & Friesen, W. V. (1976). *Pictures of facial affect*. Palo Alto, CA: Consulting Psychologists Press.

Fairhall, S. L., & Ishai, A. (2007). Effective connectivity within the distributed cortical network for face perception. *Cerebral Cortex*, *17*(10), 2400–2406. https://doi.org/10.1093/cercor/bhl148

Fedorenko, E., Hsieh, P. J., Nieto-Castañón, A., Whitfield-Gabrieli, S., & Kanwisher, N. (2010). New method for fMRI investigations of language: Defining ROIs functionally in individual subjects. *Journal of Neurophysiology*, *104*(2), 1177–1194. https://doi.org/10.1152/jn.00032.2010

Ferreira, L. K., & Busatto, G. F. (2013). Resting-state functional connectivity in normal brain aging. *Neuroscience and Biobehavioral Reviews*, *37*(3), 384–400. https://doi.org/10.1016/j.neubiorev.2013.01.017

Ferreira, L. K., Regina, A. C. B., Kovacevic, N., Martin, M. D. G. M., Santos, P. P., Carneiro, C. D. G., … Busatto, G. F. (2016). Aging effects on whole-brain functional connectivity in adults free of cognitive and psychiatric disorders. *Cerebral Cortex*, *26*(9), 3851–3865. https://doi.org/10.1093/cercor/bhv190

Fischer, H., Nyberg, L., & Bäckman, L. (2010). Age-related differences in brain regions supporting successful encoding of emotional faces. *Cortex*, *46*(4), 490–497. https://doi.org/10.1016/j.cortex.2009.05.011

Fischer, H., Sandblom, J., Gavazzeni, J., Fransson, P., Wright, C. I., & Bäckman, L. (2005). Age-differential patterns of brain activation during perception of angry faces. *Neuroscience Letters*, *386*(2), 99–104. https://doi.org/10.1016/j.neulet.2005.06.002

Foley, E., Rippon, G., Thai, N. J., Longe, O., & Senior, C. (2012). Dynamic facial expressions evoke distinct activation in the face perception network: A connectivity analysis study. *Journal of Cognitive Neuroscience*, *24*(2), 507–520. https://doi.org/10.1162/jocn_a_00120

Freeman, J. B., & Johnson, K. L. (2016). More Than Meets the Eye: Split-Second Social Perception.

Trends in Cognitive Sciences, *20*(5), 362–374. https://doi.org/10.1016/j.tics.2016.03.003

Furl, N., Henson, R. N., Friston, K. J., & Calder, A. J. (2013). Top-down control of visual responses to fear by the amygdala. *Journal of Neuroscience*, *33*(44), 17435–17443. https://doi.org/10.1523/JNEUROSCI.2992-13.2013

Fusar-Poli, P., Placentino, A., Carletti, F., Landi, P., Allen, P., Surguladze, S., … Politi, P. (2009). Functional atlas of emotional faces processing: A voxel-based meta-analysis of 105 functional magnetic resonance imaging studies. *Journal of Psychiatry and Neuroscience*, *34*(6), 418–432. https://doi.org/10.1016/S1180-4882(09)50077-7

Geerligs, L., Maurits, N. M., Renken, R. J., & Lorist, M. M. (2014). Reduced specificity of functional connectivity in the aging brain during task performance. *Human Brain Mapping*, *35*(1), 319–330. https://doi.org/10.1002/hbm.22175

Geerligs, L., Renken, R. J., Saliasi, E., Maurits, N. M., & Lorist, M. M. (2015). A Brain-Wide Study of Age-Related Changes in Functional Connectivity. *Cerebral Cortex*, *25*(7), 1987–1999. https://doi.org/10.1093/cercor/bhu012

Geerligs, L., Rubinov, M., Tyler, L. K., Brayne, C., Bullmore, E. T., Calder, A. C., … Henson, R. N. (2015). State and trait components of functional connectivity: Individual differences vary with mental state. *Journal of Neuroscience*, *35*(41), 13949–13961. https://doi.org/10.1523/JNEUROSCI.1324-15.2015

Gonçalves, A. R., Fernandes, C., Pasion, R., Ferreira-Santos, F., Barbosa, F., & Marques-Teixeira, J. (2018). Effects of age on the identification of emotions in facial expressions: A metaanalysis. *PeerJ*, *2018*(7), 1–19. https://doi.org/10.7717/peerj.5278

Gunning-Dixon, F. M., Gur, R. C., Perkins, A. C., Schroeder, L., Turner, T., Turetsky, B. I., … Gur, R. E. (2003). Age-related differences in brain activation during emotional face processing. *Neurobiology of Aging*, *24*(2), 285–295. https://doi.org/10.1016/S0197-4580(02)00099-4

Guo, K., Calver, L., Soornack, Y., & Bourke, P. (2020). Valence-dependent Disruption in Processing of Facial Expressions of Emotion in Early Visual Cortex—A Transcranial Magnetic Stimulation Study. *Journal of Cognitive Neuroscience*, *32*(5), 906–916. https://doi.org/10.1162/jocn_a_01520

Horning, S. M., Cornwell, R. E., & Davis, H. P. (2012). The recognition of facial expressions: An investigation of the influence of age and cognition. *Aging, Neuropsychology, and Cognition*, *19*(6), 657–676. https://doi.org/10.1080/13825585.2011.645011

Iidaka, T., Okada, T., Murata, T., Omori, M., Kosaka, H., Sadato, N., & Yonekura, Y. (2002). Age-related differences in the medial temporal lobe responses to emotional faces as revealed by fMRI. *Hippocampus*, *12*(3), 352–362. https://doi.org/10.1002/hipo.1113

Joseph, J. E., Swearingen, J. E., Clark, J. D., Benca, C. E., Collins, H. R., Corbly, C. R., … Bhatt, R. S. (2012). The changing landscape of functional brain networks for face processing in typical development. *NeuroImage*, *63*(3), 1223–1236. https://doi.org/10.1016/j.neuroimage.2012.08.021

Julian, J. B., Fedorenko, E., Webster, J., & Kanwisher, N. (2012). An algorithmic method for functionally defining regions of interest in the ventral visual pathway. *NeuroImage*, *60*(4), 2357–2364. https://doi.org/10.1016/j.neuroimage.2012.02.055

Kahnt, T., Chang, L. J., Park, S. Q., Heinzle, J., & Haynes, J. D. (2012). Connectivity-based parcellation of the human orbitofrontal cortex. *Journal of Neuroscience*, *32*(18), 6240–6250. https://doi.org/10.1523/JNEUROSCI.0257-12.2012

Keightley, M. L., Chiew, K. S., Winocur, G., & Grady, C. L. (2007). Age-related differences in brain activity underlying identification of emotional expressions in faces. *Social Cognitive and Affective Neuroscience*, *2*(4), 292–302. https://doi.org/10.1093/scan/nsm024

Kemp, J., Després, O., Sellal, F., & Dufour, A. (2012). Theory of Mind in normal ageing and neurodegenerative pathologies. *Ageing Research Reviews*, *11*(2), 199–219. https://doi.org/10.1016/j.arr.2011.12.001

Kumari, V., Fannon, D., Peters, E. R., Ffytche, D. H., Sumich, A. L., Premkumar, P., … Kuipers, E. (2011). Neural changes following cognitive behaviour therapy for psychosis: A longitudinal study. *Brain*, *134*(8), 2396–2407. https://doi.org/10.1093/brain/awr154

Kumari, V., Peters, E., Guinn, A., Fannon, D., Russell, T., Sumich, A., … Ffytche, D. H. (2016). Mapping depression in schizophrenia: A functional magnetic resonance imaging study. *Schizophrenia Bulletin*, *42*(3), 802–813. https://doi.org/10.1093/schbul/sbv186

Lambrecht, L., Kreifelts, B., & Wildgruber, D. (2012). Age-related decrease in recognition of emotional facial and prosodic expressions. *Emotion*, *12*(3), 529–539. https://doi.org/10.1037/a0026827

Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (1997). International affective picture system (IAPS): Technical manual and affective ratings. *NIMH Center for the Study of Emotion and Attention*, 39–58.

Liang, Y., Liu, B., Li, X., & Wang, P. (2018). Multivariate pattern classification of facial expressions based on large-scale functional connectivity. *Frontiers in Human Neuroscience*, *12*(March), 1–12. https://doi.org/10.3389/fnhum.2018.00094

Lohse, M., Garrido, L., Driver, J., Dolan, R. J., Duchaine, B. C., & Furl, N. (2016). Effective connectivity from early visual cortex to posterior occipitotemporal face areas supports face selectivity and predicts developmental prosopagnosia. *Journal of Neuroscience*, *36*(13), 3821–3828. https://doi.org/10.1523/JNEUROSCI.3621-15.2016

Madden, D. J., Costello, M. C., Dennis, N. A., Davis, S. W., Shepler, A. M., Spaniol, J., … Cabeza, R. (2010). Adult age differences in functional connectivity during executive control. *NeuroImage*, *52*(2), 643–657. https://doi.org/10.1016/j.neuroimage.2010.04.249

Marstaller, L., Burianová, H., & Reutens, D. C. (2016). Individual differences in structural and functional connectivity predict speed of emotion discrimination. *Cortex*, *85*, 65–74. https://doi.org/10.1016/j.cortex.2016.10.001

Meier, T. B., Desphande, A. S., Vergun, S., Nair, V. A., Song, J., Biswal, B. B., … Prabhakaran, V. (2012). Support vector machine classification and characterization of age-related reorganization of functional brain networks. *NeuroImage*, *60*(1), 601–613. https://doi.org/10.1016/j.neuroimage.2011.12.052

Mitchell, R. L. C., & Phillips, L. H. (2015). The overlapping relationship between emotion perception and theory of mind. *Neuropsychologia*, *70*, 1–10. https://doi.org/10.1016/j.neuropsychologia.2015.02.018

Morawetz, C., Kellermann, T., Kogler, L., Radke, S., Blechert, J., & Derntl, B. (2016). Intrinsic functional connectivity underlying successful emotion regulation of angry faces. *Social Cognitive and Affective Neuroscience*, *11*(12), 1980–1991. https://doi.org/10.1093/scan/nsw107

Morris, J. S., Friston, K. J., Büchel, C., Frith, C. D., Young, A. W., Calder, A. J., & Dolan, R. J. (1998). A neuromodulatory role for the human amygdala in processing emotional facial expressions.

Brain, *121*(1), 47–57. https://doi.org/10.1093/brain/121.1.47

O'Neil, E. B., Hutchison, R. M., McLean, D. A., & Köhler, S. (2014). Resting-state fMRI reveals functional connectivity between face-selective perirhinal cortex and the fusiform face area related to face inversion. *NeuroImage*, *92*, 349–355. https://doi.org/10.1016/j.neuroimage.2014.02.005

Onoda, K., Ishihara, M., & Yamaguchi, S. (2012). Decreased functional connectivity by aging is associated with cognitive decline. *Journal of Cognitive Neuroscience*, *24*(11), 2186–2198. https://doi.org/10.1162/jocn_a_00269

Orbelo, D. M., Testa, J. A., & Ross, E. D. (2003). Age-Related Impairments in Comprehending Affective Prosody with Comparison to Brain-Damaged Subjects. *Journal of Geriatric Psychiatry and Neurology*, *16*(1), 44–52. https://doi.org/10.1177/0891988702250565

Paulmann, S., Pell, M. D., & Kotz, S. A. (2008). How aging affects the recognition of emotional speech. *Brain and Language*, *104*(3), 262–269. https://doi.org/10.1016/j.bandl.2007.03.002

Rosenberg, B. M., Mennigen, E., Monti, M. M., & Kaiser, R. H. (2020). Functional Segregation of Human Brain Networks Across the Lifespan: An Exploratory Analysis of Static and Dynamic Resting-State Functional Connectivity. *Frontiers in Neuroscience*, *14*(December). https://doi.org/10.3389/fnins.2020.561594

Ruffman, T., Henry, J. D., Livingstone, V., & Phillips, L. H. (2008). A meta-analytic review of emotion recognition and aging: Implications for neuropsychological models of aging. *Neuroscience and Biobehavioral Reviews*, *32*(4), 863–881. https://doi.org/10.1016/j.neubiorev.2008.01.001

Sakaki, M., Nga, L., & Mather, M. (2013). Amygdala Functional Connectivity with Medial Prefrontal Cortex at Rest Predicts the Positivity Effect in Older Adults' Memory. *Journal of Cognitive Neuroscience*, *25*(8), 1206–1224. https://doi.org/10.1162/jocn_a_00392

Sambataro, F., Murty, V. P., Callicott, J. H., Tan, H.-Y., Das, S., Weinberger, D. R., & Mattay, V. S. (2010). Age-related alterations in default mode network: Impact on working memory performance. *Neurobiology of Aging*, *31*(5), 839–852. https://doi.org/10.1016/j.neurobiolaging.2008.05.022

St. Jacques, P., Dolcos, F., & Cabeza, R. (2010). Effects of aging on functional connectivity of the amygdala during negative evaluation: A network analysis of fMRI data. *Neurobiology of Aging*, *31*(2), 315–327. https://doi.org/10.1016/j.neurobiolaging.2008.03.012

Stevens, M. C. (2016). The contributions of resting state and task-based functional connectivity studies to our understanding of adolescent brain network maturation. *Neuroscience and Biobehavioral Reviews*, *70*, 13–32. https://doi.org/10.1016/j.neubiorev.2016.07.027

Tessitore, A., Hariri, A. R., Fera, F., Smith, W. G., Das, S., Weinberger, D. R., & Mattay, V. S. (2005). Functional changes in the activity of brain regions underlying emotion processing in the elderly. *Psychiatry Research - Neuroimaging*, *139*(1), 9–18. https://doi.org/10.1016/j.pscychresns.2005.02.009

Turk-Browne, N. B., Norman-Haignere, S. V., & Mccarthy, G. (2010). Face-specific resting functional connectivity between the fusiform gyrus and posterior superior temporal sulcus. *Frontiers in Human Neuroscience*, *4*(September), 1–15. https://doi.org/10.3389/fnhum.2010.00176

Vuilleumier, P. (2005). How brains beware: Neural mechanisms of emotional attention. *Trends in Cognitive Sciences*, *9*(12), 585–594. https://doi.org/10.1016/j.tics.2005.10.011

Vuilleumier, P., Richardson, M. P., Armony, J. L., Driver, J., & Dolan, R. J. (2004). Distant influences of amygdala lesion on visual cortical activation during emotional face processing. *Nature Neuroscience*, *7*(11), 1271–1278. https://doi.org/10.1038/nn1341

Wang, X., Song, Y., Zhen, Z., & Liu, J. (2016). Functional integration of the posterior superior temporal sulcus correlates with facial expression recognition. *Human Brain Mapping*, *37*(5), 1930–1940. https://doi.org/10.1002/hbm.23145

Wang, X., Zhen, Z., Song, Y., Huang, L., Kong, X., & Liu, J. (2016). The hierarchical structure of the face network revealed by its functional connectivity pattern. *Journal of Neuroscience*, *36*(3), 890–900. https://doi.org/10.1523/JNEUROSCI.2789-15.2016

Weibert, K., Harris, R. J., Mitchell, A., Byrne, H., Young, A. W., & Andrews, T. J. (2016). An image-invariant neural response to familiar faces in the human medial temporal lobe. *Cortex*, *84*, 34–42. https://doi.org/10.1016/j.cortex.2016.08.014

Whitfield-Gabrieli, S., & Nieto-Castanon, A. (2012). Conn: A Functional Connectivity Toolbox for Correlated and Anticorrelated Brain Networks. *Brain Connectivity*, *2*(3), 125–141. https://doi.org/10.1089/brain.2012.0073

Williams, L. M., Brown, K. J., Palmer, D., Liddell, B. J., Kemp, A. H., Olivieri, G., … Gordon, E. (2006). The Mellow Years?: Neural Basis of Improving Emotional Stability over Age. *Journal of Neuroscience*, *26*(24), 6422–6430. https://doi.org/10.1523/JNEUROSCI.0022-06.2006

Williams, L. M., Mathersul, D., Palmer, D. M., Gur, R. C., Gur, R. E., & Gordon, E. (2009). Explicit identification and implicit recognition of facial emotions: I. Age effects in males and females across 10 decades. *Journal of Clinical and Experimental Neuropsychology*, *31*(3), 257–277. https://doi.org/10.1080/13803390802255635

Wu, M., Kujawa, A., Lu, L. H., Fitzgerald, D. A., Klumpp, H., Fitzgerald, K. D., … Phan, K. L. (2016). Age-related changes in amygdala-frontal connectivity during emotional face processing from childhood into young adulthood. *Human Brain Mapping*, *37*(5), 1684–1695. https://doi.org/10.1002/hbm.23129

Zhang, H., Tian, J., Liu, J., Li, J., & Lee, K. (2009). Intrinsically organized network for face perception during the resting state. *Neuroscience Letters*, *454*(1), 1–5. https://doi.org/10.1016/j.neulet.2009.02.054

Zhen, Z., Fang, H., & Liu, J. (2013). The Hierarchical Brain Network for Face Recognition. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0059886

Zhu, Q., Zhang, J., Luo, Y. L. L., Dilks, D. D., & Liu, J. (2011). Resting-state neural activity across face-selective cortical regions is behaviorally relevant. *Journal of Neuroscience*, *31*(28), 10323–10330. https://doi.org/10.1523/JNEUROSCI.0873-11.2011

Zsoldos, I., Cousin, E., Klein-Koerkamp, Y., Pichat, C., & Hot, P. (2016). Age-related differences in brain activity during implicit and explicit processing of fearful facial expressions. *Brain Research*, *1650*, 208–217. https://doi.org/10.1016/j.brainres.2016.09.004

Supplementary Info

Table S1: Mean and standard deviation of the average beta estimation across voxels, within each subject-specific ROI.

ROI	Expression	Mean beta	S.D.
lAmygdala	Neutral	0.207	0.441
	Fearful	0.441	0.445
	Happy	0.224	0.407
	Anger	0.421	0.499
rAmygdala	Neutral	0.221	0.384
	Fearful	0.443	0.481
	Happy	0.235	0.383
	Anger	0.425	0.558
mPFC	Neutral	-0.029	1.056
	Fearful	-0.204	1.231
	Happy	0.010	1.265
	Anger	-0.189	1.080
rpSTS	Neutral	-0.220	0.573
	Fearful	-0.300	0.652
	Happy	-0.340	0.519
	Anger	-0.170	0.629

Table S2: Results of the pairwise comparisons between the responses to expressions within each region, with uncorrected p-values. Multiple comparisons were corrected for using the Bonferroni adjustment ($\alpha = 0.05/6 = 8.33E\text{-}3$).

ROI	Comparison	T-test
lAmygdala	Neutral-Fearful	$t(30) = 2.286$, $p = .029$
	Neutral-Happy	$t(30) = 0.176$, $p = .861$
	Fearful-Happy	$t(30) = -2.632$, $p = .013$
	Neutral-Anger	$t(30) = 1.774$, $p = .086$
	Fearful-Anger	$t(30) = -0.226$, $p = .823$
	Happy-Anger	$t(30) = 1.625$, $p = .115$
rAmygdala	Neutral-Fearful	$t(30) = 2.499$, $p = .018$
	Neutral-Happy	$t(30) = 0.172$, $p = .865$
	Fearful-Happy	$t(30) = -2.618$, $p = .014$
	Neutral-Anger	$t(30) = 1.849$, $p = .074$
	Fearful-Anger	$t(30) = -0.206$, $p = .838$
	Happy-Anger	$t(30) = 1.587$, $p = .123$
mPFC	Neutral-Fearful	$t(30) = -0.544$, $p = .590$
	Neutral-Happy	$t(30) = 0.126$, $p = .901$
	Fearful-Happy	$t(30) = 1.320$, $p = .197$
	Neutral-Anger	$t(30) = -0.574$, $p = .570$
	Fearful-Anger	$t(30) = 0.077$, $p = .939$
	Happy-Anger	$t(30) = -0.993$, $p = .329$
rpSTS	Neutral-Fearful	$t(30) = -0.894$, $p = .378$
	Neutral-Happy	$t(30) = -1.722$, $p = .095$
	Fearful-Happy	$t(30) = -0.469$, $p = .642$
	Neutral-Anger	$t(30) = 0.658$, $p = .516$
	Fearful-Anger	$t(30) = 1.413$, $p = .168$
	Happy-Anger	$t(30) = 2.135$, $p = .041$

Table S3: Relationship between the response to each expression and age. Multiple comparisons were corrected for using the Bonferroni adjustment (α = 0.05/4 = 1.25E-2).

ROI	**Expression**	**Pearson Correlation**
lAmygdala	Neutral	r = 0.084, p = .654
	Fearful	r = -0.407, p = .023
	Happy	r = -0.363, p = .045
	Angry	r = -0.134, p = .472
rAmygdala	Neutral	r = -0.032, p = .863
	Fearful	r = -0.301, p = .100
	Happy	r = -0.213, p = .250
	Angry	r = -0.195, p = .294
mPFC	Neutral	r = -0.069, p = .712
	Fearful	r = -0.226, p = .222
	Happy	r = -0.190, p = .307
	Angry	r = -0.096, p = .608
rpSTS	Neutral	r = 0.050, p = .788
	Fearful	r = 0.107, p = .566
	Happy	r = -0.023, p = .904
	Angry	r = 0.036, p = .846