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# Social perception drives eye-movement related brain activity: Evidence from pro- and anti-saccades to faces

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ABSTRACT

Social stimuli such as faces attract and retain attention to a greater extent than other objects. Using fMRI, we investigated how the activity of oculomotor and visual brain regions is modulated when participants look towards or away from visual stimuli belonging to different categories (faces and cars). We identified a region within the superior frontal sulcus showing greater difference between anti- and pro-saccades to faces than to cars, and thereby supporting inhibitory control in a social context. In contrast, ventral occipito-temporal regions and the amygdala, which are associated with face perception, showed higher activity for pro-saccades than anti-saccades for faces, but the reverse for cars, suggesting that contextual, top-down mechanisms modulate the functional specialisation of areas involved in perception. In addition, during saccades in the presence of faces, we found increased functional connectivity between the frontal eye-fields and other cortical and subcortical oculomotor structures, namely the inferior frontal eye field, the posterior parietal cortex and the basal ganglia, possibly reflecting the higher demand put on the oculomotor system to inhibit responses to socially salient stimuli. For the first time, these data highlight neural bases for the different orienting responses towards or away from faces as compared to other objects.

## 1. Introduction

Empirical behavioural studies have shown that social stimuli (mainly faces) impact on aspects of cognitive control. Faces grab attention more rapidly (Crouzet et al., 2010; Cerf et al., 2009) and automatically (Gilchrist and Proske, 2006; Devue and Brédart, 2008; Langton et al., 2008; Morand et al., 2010; Cerf et al., 2007) and retain attention more strongly (Bindemann et al., 2005) than other, non-social, stimuli. They are also detected more easily in crowded environments (Hershler and Hochstein, 2005; Simpson et al., 2015) and are fixated more often (Xu et al., 2014) than other objects during scene exploration. They influence the oculomotor planning system more than meaningless stimuli allowing for greater saccadic adaptation (Meermeier et al., 2016). They also act as powerful distractors for oculomotor (Devue et al., 2012) or manual (Awasthi et al., 2011) commands. Therefore, it appears that faces activate automatic reflexive processes, and thereby place greater demand on voluntary inhibitive cognitive control than other stimuli. The mechanism underlying this prioritisation of faces remains unclear, however. It involves physical salience (Honey et al., 2008), and is partly driven by low-level properties (VanRullen, 2006; Crouzet and Thorpe, 2011), but is also linked to the functional relevance of faces, either within a task or more generally due to their social significance (e.g. Devue et al., 2012). Some studies also show that faces (Laidlaw et al., 2015) or the anticipation of seeing a face (Xu-Wilson et al., 2009) affect the oculomotor command itself and not just its preparation. This is reflected in higher velocities or greater trajectory deviations of the eyes when a face is the target, or a distractor, for the saccadic eye movements, respectively. All these data point towards an interaction between the neural processing of faces and the different levels of control mechanisms of orienting responses.

The goal of the present study is to characterize the brain circuits that integrate face processing and oculomotor inhibitory control, using functional magnetic resonance imaging (fMRI). To this end we implemented a task requiring the voluntary inhibition of a reflexive action. In

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the anti-saccade task (Hallett, 1978), participants are asked to suppress the automatic tendency to look towards a salient visual stimulus that appears abruptly in the periphery and instead to program a voluntary eye movement to its mirror location. This paradigm is well suited to address just how face processing and inhibitory control interact as (i) behaviourally, it reveals robust and significant increases in anti-saccade error rates for faces (compared to inverted faces - Gilchrist and Proske, 2006 - or other visual objects - Morand et al., 2010, 2014); and (ii) the brain regions involved in anti and pro-saccades are well characterized (Everling and Munoz, 2000; Hutton, 2008; Grosbras et al., 2005; rev. In McDowell et al., 2008; Jamadar et al., 2013). These regions include the frontal and supplementary eye-fields (FEF, SEF), the intraparietal sulcus (IPS), the thalamus (pulvinar) and the basal ganglia as well as the superior colliculi. Although these regions are engaged in all types of saccades, whether endogenously triggered or reactive, they are usually engaged to a greater extent during the execution of anti-saccades than during pro-saccades (Curtis and D'Esposito, 2003). In addition, some prefrontal regions, like the pre-SEF, are recruited specifically for anti-saccades and not pro-saccades (Curtis and D'Esposito, 2003). Our first goal was therefore to test whether anti-saccade-related activity in these regions is modulated by the nature of the visual target (face vs. other stimulus). We wanted to investigate to what extent the nature of the stimulus may modulate task-related activity, first in the context of a natural response towards a stimulus, and second in the context of having to inhibit this automatic response. As the two tasks differ in terms of their cognitive demand (inhibition of prepotent response or not), motor programming (volitional planning *versus* more reflexive visuomotor transformation) and visual processing (peripheral *versus* foveal), the interaction between task and stimulus category could potentially be expressed in brain circuits involved in any of these domains.

More specifically, as the anti-saccades task is seemingly harder for faces than cars, we might expect increased activity in brain regions involved in cognitive control and known to be modulated by cognitive effort, such as the dorsal prefrontal cortex or the anterior cingulate cortex. In addition, since the stimulus category influences latencies, and thus supposedly aspects of motor programming including decision making and visual guidance, we could expect oculomotor regions (FEF, SEF, IPS) to be affected by stimulus category. Lastly, as only in the pro-saccades condition the target is foveated, we would expect the stimulus effect on visual regions to be stronger in this case.

We also investigated whether the functional coupling between the nodes of this extended oculomotor network was modified by the visual content of the target. A number of studies in humans (Gitelman et al., 2002; Bressler et al., 2008; Hwang et al., 2010; Tu et al., 2010; Alkan et al., 2011; Pa et al., 2014; Vossel et al., 2015) and non-human primates (Koval et al., 2014) have indeed indicated that context and/or task difficulty modulate the functional connectivity within the brain network involved in anti-saccades. Therefore, we assessed whether the nature of the stimulus had an impact on the functional coupling between the nodes of the oculomotor network, as well as between the oculomotor regions and regions known to be specifically engaged in the perceptual processing of faces, such as the fusiform face area (FFA; Kanwisher et al., 1997), the occipital face area (OFA) in the inferior occipital cortex (e.g., Rossion et al., 2003), the posterior superior temporal sulcus (pSTS - Grill-Spector et al., 2004) and the amygdala (e.g., Ishai et al., 2005; Fusar-Poli et al., 2009). A strengthened functional connectivity between frontal/prefrontal oculomotor regions and occipito-temporal face regions would support the stronger involuntary orienting responses for faces compared to other objects. In summary, we expected to observe an interaction between the task (i.e., anti-vs. pro-saccades) and the stimulus (i.e., face and car) in regions involved in anti-saccade programming as well as in their functional connectivity with regions of the face network.

## 2. Methods

### 2.1. Participants

Nineteen healthy participants naive to the aim of the study took part in the fMRI experiment with eye tracking. Four participants, who exhibited a within-run maximal amplitude of translational or rotational between-volumes displacement that was above 3 mm and 3°, respectively in at least one run, were discarded from the analysis. Another participant had to be excluded due to technical problems with the eye tracking data. Consequently, 14 datasets were included in the final analysis (mean age ± 27.1, SD ± 2.7 years; 7 females; all right-handed). An informed consent form was signed and everyone received 40 euros as compensation. The study was approved by the research ethics committee Sud-Mediterranée and is in line with the 1964 Declaration of Helsinki.

### 2.2. Stimuli

We employed the same sets of neutral Western Caucasian faces and cars images as used in previous studies (Morand et al., 2010, 2014). Faces consisted of 6 males and 6 females and were cropped within a common oval frame. For object stimuli, we used images of 12 different models of cars taken from a database by Schweinberger et al. (2007). Faces and cars (image size: 128 × 128 pixels, corresponding to about 4 × 4 degrees of visual angle, 8 bits/pixel) were grayscale photographs on a uniform gray background (see Fig. 1A). All 24 images were normalized for mean amplitude spectrum, luminance and root mean square contrast. Therefore, their global visual properties were equivalent (see Morand et al., 2010 for more details). One image appeared in each trial at one of two possible peripheral locations on the horizontal meridian, either 10° to the left or right of the center of the screen. Over the course of the experiment, each photograph (among the 12 face and 12 car photographs) was presented 10 times (5 times to the right and 5 times to the left of the fixation cross). A central gray cross, on a black background, was used to mark central fixation.

### 2.3. Experimental paradigm and set-up (see Fig. 1B)

We implemented an event-related design intermixing pro- and anti-saccades trials. Each trial started with the presentation of the fixation cross for periods ranging from 2000 ms to 8000 ms (jitter sampled on an exponential distribution; Hagberg et al., 2001). Then, a cue, whose color instructed the participant to generate subsequently either a pro-saccade (green dot) or an anti-saccade (red dot), was presented for 1300 ms in the center of the screen. A gap interval of 200 ms during which a blank screen was presented preceded the stimulus (a face or a car unpredictably), which appeared for 1000 ms randomly in the left or right hemifield. The central fixation cross for the next trial reappeared just at target extinction. Participants had to generate a saccade either in the direction of the stimulus appearing on the screen (pro-saccade if the cue had been green) or in the opposite direction away from the stimulus (anti-saccade for a red cue). The gap was introduced as it is well established that the removal of the fixation point before target onset helps disengaging attention from the center and reduces reaction times for both pro- and anti-saccades (Munoz and Everling, 2004). Participants were instructed to perform the saccade as quickly and accurately as possible, and revert back (at their own pace) to central fixation. For the anti-saccades trials, they were instructed to look at the mirror location of the stimulus with respect to the midline (before reverting back to fixation). Participants practiced outside the scanner to ensure that they understood the task.

Each participant completed 6 runs of 40 trials. Each run lasted 5 min followed by a few minutes rest. Within a run, 20 face and 20 car photographs were presented, with half pro- and half anti-saccade instructions. We created six different schedules optimizing both the transitions between different conditions (i.e. anti- or pro-saccades

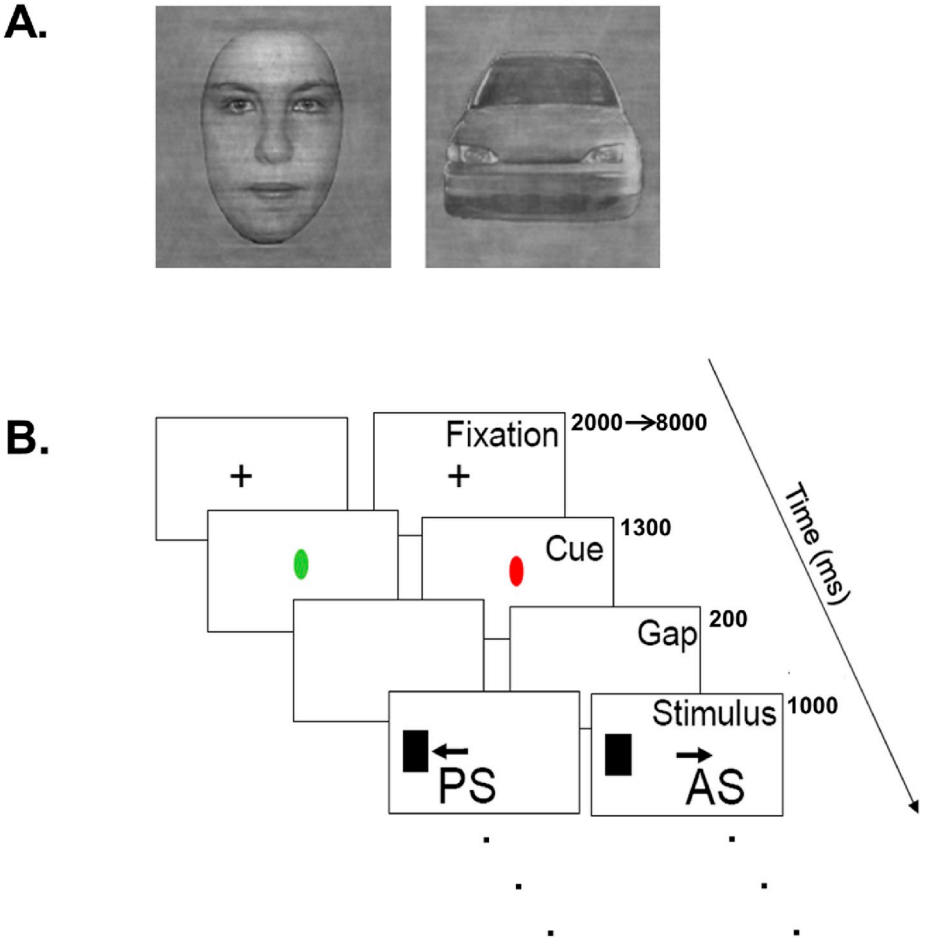



**Fig. 1. Schematic representation of the anti-saccade task**. A. Examples of the images used. B. Within a block, participants had to generate either a pro-saccade (PS) or an anti-saccade (AS) depending on the color of the cue: a green dot informed the participant to perform a saccade towards the stimulus (PS) while a red dot instructed the participant to generate a saccade in the opposite direction (AS) towards the virtual mirror location of the stimulus. Stimuli were faces or cars as shown in A. and were presented in random order. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

towards faces or cars presented in either the left or right hemifield) and the timing (jitter) between events to maximise global design efficiency (Dale, 1999). The order of these six predefined runs was counterbalanced across participants.

Stimuli were back projected onto a frosted screen placed at the back of the scanner and viewed by the participants through a mirror. They were presented using a program based on LabVIEW (National Instruments, Austin, TX). Participants' eye-gaze location was continuously monitored using a custom-made video-based eye tracker mounted on to plastic framed googles (resolution 1–2°; 60 Hz). This allowed us to ensure that participants completed the task as instructed, and to identify error trials off-line. We explained the task outside the scanner and participants completed a practice session of 30 trials. The whole experiment lasted about 1 h.

### 2.4. Eye tracking data analysis

We parsed and analysed the eye tracking data using in-house Matlab (The Mathworks, Inc.) scripts. We detected saccades using a threshold of 30 deg/s, identified the first saccade after target onset that was larger than two degrees, determined its latency and whether its direction was correct. Trials where the signal was lost due to a blink, or where no horizontal saccade could be detected, were excluded from the analysis.

### 2.5. FMRI recordings

Functional images were acquired using a 3-T scanner (Medspec 30/80 AVANCE, Bruker, Ettlingen, Germany) with a T2*-weighted gradient echo-planar imaging sequence (36 axial slices; 3 mm thickness; 1 mm inter-slice gap; reconstruction matrix = 64 × 64; repetition time = 2.4 s; echo time = 30 ms, flip angle = 81.6°). The scanning planes were parallel to the anterior commissure-posterior commissure and covered the whole brain. Each run consisted of 122 brain volumes. A high-resolution structural MRI was acquired using a three-dimensional T1-weighted sequence (MPRAGE; repetition time = 9.4 ms; echo time = 4.4 ms; inversion time = 800 ms; resolution 1 × 1x1 $mm^3$). We also acquired a field map to assess geometric distortions in the echo-planer images (reconstruction matrix = 64 × 64 × 64; field of view = 192 mm × 192 mm x 192 mm; repetition time = 30 ms; echo time = 3.7 ms, flip angle = 30°).

### 2.6. FMRI analysis

Analyses were performed using SPM12 (Wellcome Department of Imaging Neuroscience, London, UK) and in-house scripts running in Matlab 2012a) (Mathworks Inc., Natick, USA).

#### 2.6.1. Pre-processing

The first five volumes were discarded to ensure magnetic field saturation. The remaining images were (1) slice-time corrected using the middle slice as the reference slice, (2) realigned to the mean image of the time series to correct for head movement within run, (3) unwarped based on field-map images, (4) co-registered to the high-resolution structural image, (5) transformed into the MNI152 T1 template using the parameters derived from the spatial normalization of the structural high resolution image, (6) resampled to 3-mm isotropic voxel size and (7) smoothed with a 6-mm-FWHM Gaussian kernel.

#### 2.6.2. Main analysis

We analysed the data voxel-wise using the general linear model

(GLM) approach (Friston et al., 1995). As we did not expect any effect of saccade direction for our question of interest (i.e., the interaction between saccade programming and stimulus nature), and for the sake of statistical power, we ignored laterality. For correct trials we defined one regressor for each of the four conditions: pro-saccades towards faces (pro face) or cars (pro car) and anti-saccades away from faces (anti face) or cars (anti car). We grouped the remaining trials, i.e. trials containing errors and trials contaminated by blinks as a separate condition of no-interest. Indeed, we wanted to focus on correct trials and, as we did not have enough power to analyse brain activity in relation to errors, we excluded those trials from our analysis. For each condition, we modelled the stimulus-evoked neural response first by defining a boxcar function, with each event starting at target onset and lasting 1 s. These boxcar functions were convolved with the default canonical hemodynamic response function of SPM12 to provide a function representing each condition. In addition, we included one constant term and the six realignment parameters (3 translations, 3 rotations) as covariates into our model, to account for changes in signal level across runs and influence of head motion on BOLD signal, respectively. We also applied a high-pass filter (cut off period = 128 s) to remove low-frequency drifts.

We first estimated the model for each individual yielding one map of parameter estimates per condition (i.e. pro face, pro car, anti face, anti car) per participant. At the group level, we conducted a mixed-effect 2 × 2 factorial ANOVA, with stimulus (face or car) and task (anti- or pro-saccade) as independent factors, subject as random factor, and the individual pro face, pro car, anti face and anti car parameter-estimates images as dependant variables. We investigated the main effects of stimulus and task. Positive and negative interactions (faces/cars x anti/pro) were also investigated to examine whether the difference between anti- and pro-saccades was larger for faces than for cars or *vice versa*, respectively.

We performed whole-brain analyses. We applied a voxel-level threshold at $p < .001$, uncorrected for multiple comparisons and a cluster level threshold at $p < .05$, with family wise errors correction (Forman et al., 1995). For the interactions, for which we expected more restricted effects, we considered only voxels where we could observe an overall activity in any saccades condition (pro face, pro car, anti face or anti car; $p < .001$, uncorrected), effectively reducing the search volume.

#### 2.6.3. Psycho-physiologic interaction (PPI) analysis

We conducted a PPI analysis to investigate how the pattern of functional connectivity of regions involved in anti-saccades is modulated by the nature of the visual stimulus. For that, we first determined seed regions in the oculomotor network based on the peaks of activity identified in the group analysis of the contrast anti > pro-saccades. We defined spheres of 12 mm radius centred on the following voxels' coordinates (x, y, z in mm): right FEF [15–3 69], left FEF [-15 3 69], right parietal [12–63 60], left parietal [-15 -63 60]. We did the same for the face network: we defined spheres centred on the right amygdala [12–6 -18], the left amygdala [-21 0–18], and the right post STS [51–66 9]. Although the fusiform cortex was not identified in our study, for completeness we also included a region centred on this region at [36–57 -15] (Rossion et al., 2012).

We then conducted one analysis for each of these regions. This included several steps:

1 At the individual level, we extracted the time-course, concatenated across the six runs, of the voxel showing the highest difference between anti- and pro-saccades (or pro-saccades to faces vs. cars in case of the amygdala and pSTS).
2 We set up the interaction term between this seed time-course and the experimental treatment that is: faces > cars contrast in case of the FEF and parietal areas, and anti-saccades > pro-saccades contrast for the amygdala, pSTS and fusiform. These analyses test whether inter-regional correlation of nodes of the oculomotor network is modulated by the stimulus category and whether the inter-regional correlation of nodes of the face network is modulated by the task.
3 We computed a new GLM analysis including this interaction term, the mean time course and the experimental design, as well as all the other regressors included in the original model (session effects, motion parameters).
4 To investigate group effects, the parameter estimates associated with the interaction term were entered into a one-sample *t*-test. These analyses reveal where in the brain the functional connectivity with the seed region is different while viewing faces as compared to cars (or performing an anti-vs. a pro-saccade). The voxel-level threshold was set at $p < .001$, uncorrected for multiple comparisons, with an extent threshold larger than 4 contiguous voxels. This more liberal threshold was chosen to balance type I and type II errors in this specific analysis (Lieberman and Cunningham, 2009).

## 3. Results

### 3.1. Behavioural data

An average of 17.8 trials per participant were excluded due to signal loss (i.e., due to blinks or artefacts) with no differences between conditions. The mean error rates computed on the remaining trials are presented in Fig. 2. An analysis of variance (computed on the arctangent of the percent correct scores in order to meet normality assumption) revealed a main effect of task ($F(1,18) = 30.3$, $p < .001$), with, unsurprisingly, more errors for anti-saccades than for pro-saccades; a main effect of stimulus ($F(1,18) = 5.2$, $p < .034$) and a stimulus × task interaction ($F(1,18) = 6.9$, $p <. 017$). Post-hoc tests (Bonferroni corrected) showed that participants made significantly more anti-saccades direction errors when the stimulus was a face than when it was a car (14.9% vs. 11%, $t(17) = 2.85$, $p = .011$). There was no difference for the pro-saccades condition (3.49% vs. 3.72%, $t(17) = 0.30$, $p = .77$). Regarding latencies, as expected, they were longer for anti-than pro-saccades (280 ms vs. 238 ms, $F(1,18) = 46.8$, $p < .001$) but we did not observe any effect of stimulus category ($F(1,18) = 0.003$, $p = .99$) nor an interaction between task and stimulus ($F(1,18) = 0.77$, $p = .391$).

Lastly, we observed that in 90.9% of trials (with no differences between conditions), participants waited for the reappearance of the fixation point to return their gaze to the center.

### 3.2. FMRI main analysis

#### 3.2.1. Main effect of saccade type

We observed a main effect of task in several brain regions. Post-hoc contrasts showed significantly greater activation for anti-compared to pro-saccades in regions within the superior parietal cortex and the dorsal precentral cortex, corresponding to the FEF, bilaterally, the posterior part of the left fusiform cortex, the bilateral lingual gyrus and the superior part of the lateral occipital gyrus (see Table 1 & Fig. 2B). Changing the threshold to voxel-level $p < .001$ (uncorrected) revealed additional activation peaks within the left anterior cingulate ($t = 3.77$; 9 voxels), the pre-SEF ($t = 5.07$, 13 voxels), the caudate nucleus ($t = 3.67$, 9 voxels) and the bilateral middle temporal gyrus (right: $t = 4.56$, 17 voxels and left: $t = 4.01$ 9 voxels). The contrast pro > anti-saccades revealed activation in the occipital lobe, mainly in regions within the inferior and middle occipital gyri, extending into the occipital pole (see Table 1).

#### 3.2.2. Main effect of stimulus

The faces > cars contrast revealed foci of activation within the left amygdala and basal ganglia (see Table 2 & Fig. 2B). No above-threshold activation was noticed for the cars > faces contrast. As the visual stimulation is quite different in the pro- and anti-saccades conditions, respectively, we also examined activity separately for the two tasks. For the pro-saccades, we observed higher activity for faces than cars in the

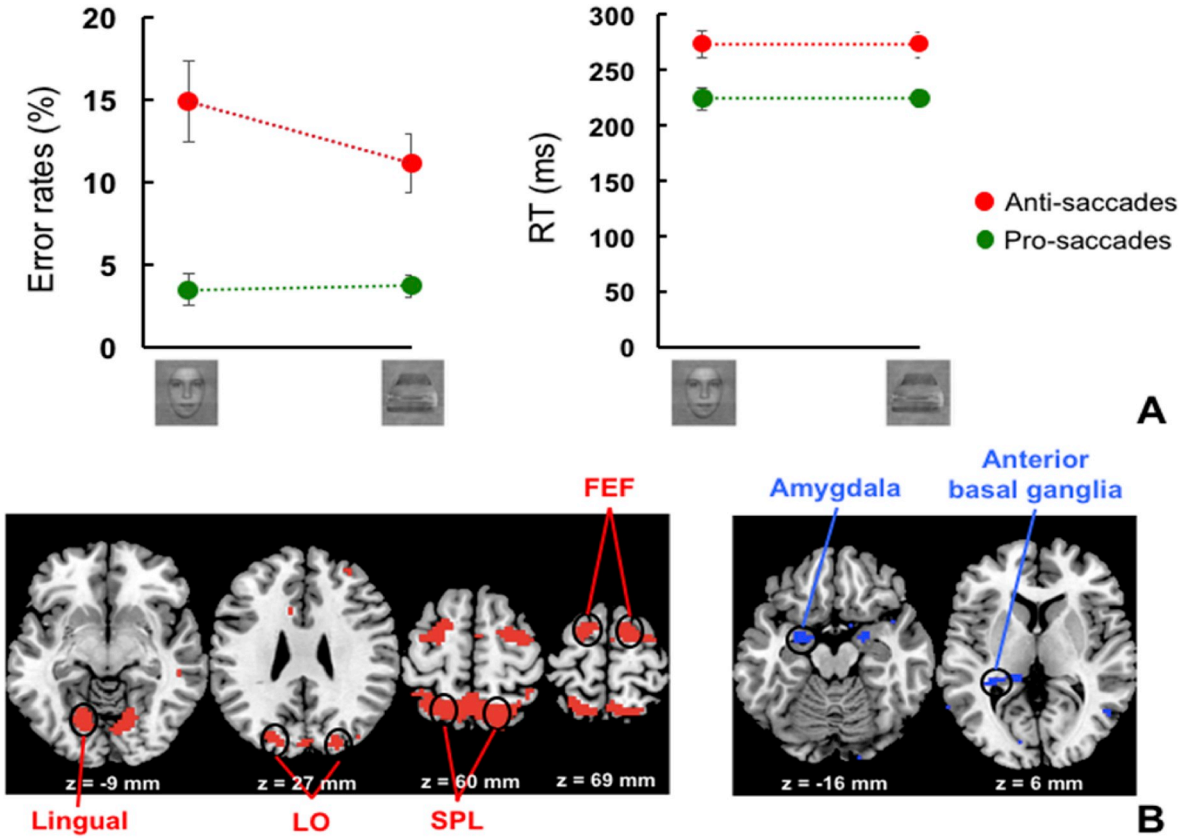



**Fig. 2.** A. **Behavioural results**. Mean error rate (left panel) and median latencies (right panel) for correct saccades across 13 participants, presented for faces and cars, for the pro-saccade (green circles) and anti-saccade (red circles) condition. B. **Results of fMRI group-level GLM analysis.** Brain activations related to anti-saccades (on the left) and stimulus processing (on the right) (i.e. social vs. non-social). Full-group activation maps for anti > pro-saccades (on the left) and faces > cars (on the right) contrasts are rendered on a standard T1 template. Maps are thresholded at $p < .001$ uncorrected ($t > 3.3$). Clusters of activity ($n \geq 5$ contiguous voxels) are indicated with arrows. LO: lateral occipital cortex, SPL: superior parietal lobule, FEF: frontal eye-field. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
**Anti-vs. pro-saccades peaks location**. t-values refer to significant activation peaks at $p < .001$ (uncorrected for multiple comparisons). All reported clusters were significantly active at $p < .05$ (FWE correction). SPL: superior parietal lobule, FEF: frontal eye-field, LO: lateral occipital cortex; R: right hemisphere; L: left hemisphere.

| Contrast | Region | Side | x | y | z | t-value | Cluster extent ($mm^3$) |
|---|---|---|---|---|---|---|---|
| **Anti > Pro** | SPL | R | 12 | −63 | 60 | 7.24 | $16.10^3$ |
| | | L | −30 | −57 | 63 | 7.12 | |
| | | L | −15 | −63 | 60 | 6.40 | |
| | Lingual gyrus | L | −18 | −66 | −9 | 6.44 | 5157 |
| | | L | −12 | −81 | 3 | 5.41 | 1647 |
| | | R | 9 | −72 | −6 | 4.89 | |
| | Dorsal precentral gyrus (FEF) | L | −15 | 3 | 69 | 5.62 | 4887 |
| | | L | −24 | −6 | 48 | 5.13 | |
| | | R | 15 | −3 | 69 | 5.45 | 5805 |
| | | R | 33 | −6 | 57 | 5.28 | |
| | LO (superior part) | L | −21 | −81 | 27 | 5.37 | 6561 |
| | | R | 24 | −87 | 30 | 5.23 | 1647 |
| **Pro > Anti** | Posterior Occipital cortex | L | −30 | −90 | −6 | 9.95 | $20\ 10^3$ |
| | | L | −33 | −90 | 6 | 7.68 | |
| | | L | −21 | −99 | 0 | 7.64 | |
| | Posterior Occipital cortex | R | 27 | −90 | −12 | 9.78 | $21\ 10^3$ |
| | | R | 36 | −93 | −6 | 9.34 | |
| | | R | 30 | −93 | 6 | 9.09 | |

**Table 2**
**Faces vs. cars peaks location**. t-values refer to significant activation peaks at $p < .001$ (uncorrected for multiple comparisons). All reported clusters were significantly active at $p < .05$ (FWE correction). R: right hemisphere; L: left hemisphere.

| Contrast | Region | Side | x | y | z | t-value | Cluster extent ($mm^3$) |
|---|---|---|---|---|---|---|---|
| Faces > Cars | Amygdala | L | −21 | 0 | −18 | 6.88 | 1107 |
| | Caudate n. (tail) | L | −30 | −36 | 6 | 4.38 | 1161 |
| | Putamen | | −15 | −36 | 6 | 3.88 | |
| Cars > Faces | No above threshold cluster | | | | | | |
| **Pro Face > Pro Car** | Post STS/ MTG | R | 51 | −66 | 9 | 5.83 | 1782 |
| | Cuneus | R | 3 | −81 | 18 | 5.04 | 2430 |
| | Amygdala | R | 21 | −3 | −21 | 5.59 | 2133 |
| | | | 12 | −6 | −18 | 5.05 | |
| | Cerebellum | R | 12 | −45 | −12 | 5.10 | 1377 |
| **Pro Car > Pro Face** | No above threshold cluster | | | | | | |
| **Anti Face > Anti Car** | No above threshold cluster | | | | | | |
| **Anti Car > Anti Face** | No above threshold cluster | | | | | | |

right amygdala, posterior lateral part of the superior temporal sulcus, cuneus and cerebellum, while activity in the left hemisphere remained sub-threshold. For the anti-saccade condition, even if a focus of activity was observed in the left amygdala (peak T = 5.26, 16 voxels, p < .040), it was not significant when considering the whole set of clusters.

#### 3.2.3. Interactions

We observed a positive interaction between task and stimulus in a region within the right superior frontal sulcus (see Table 3 & Fig. 3A). This region displayed higher activity for anti-saccades than pro-saccades when the stimulus was a face but not when the stimulus was a car. In addition, results revealed a negative interaction, that is a greater difference between anti- and pro-saccades in the car than in the face condition, within the posterior superior temporal sulcus, adjacent to the middle temporal gyrus, the occipital fusiform gyrus, the cuneus, the amygdala, and the cerebellar vermis (lobule IV), all in the right hemisphere (see Table 3 & Fig. 3B).

#### 3.2.4. Additional exploratory analyses

To characterize the observed brain activity further, we explored to what extent, at the group level, it was related to behavioural performance measured *via* error rates and latencies. For the regions more active during anti-compared to pro-saccades, we correlated the peaks of parameter estimates of the individual analyses to the individual behavioural measures (error rates, median latencies, differences in error rates or latencies for faces and cars). We observed that the increased activity during anti-saccades (anti > pro contrast of parameter estimates) was negatively correlated with the anti-saccade direction error rates in the frontal eye field (left FEF: Kendal rho = −0.75, p < .0004, Benjamin-Hochberg correction at 0.05; right FEF: rho = −0.58, p = .04). That is, participants who showed more activity in the FEF during correct anti-saccades compared to pro-saccades, were those who made the fewest errors. The parietal and occipital regions also showed similar trends, but this was not statistically significant. There were no correlation with measures of latencies.

### 3.3. Psycho-physiologic interaction (PPI) analysis

The PPI analysis with the right FEF as seed revealed a significant interaction between FEF connectivity and the stimulus condition in the left caudate nucleus only (see Table 4). That is the functional coupling was strengthened when the stimulus was a face. For the left FEF, the analysis revealed stimulus-dependant functional connectivity in the ipsilateral posterior parietal cortex and in the ventral premotor cortex (see Table 4). Lowering the voxel threshold to p < .005 revealed, in addition, the pulvinar, the occipital pole, the precuneus and the frontal pole, for the left FEF. For the right FEF, at lower threshold, we could identify regions in the posterior occipital cortex, the cerebellar vermis and the claustrum. Analyses of the other seeds (i.e., parietal, STS, fusiform and amygdala) did not reveal any significant result.

**Table 3**
**Peaks location for both positive and negative interactions**. t-values refer to significant activation peaks at p < .05 (corrected for multiple comparisons within a search volume characterized by activity during any conditions). SFS: superior frontal sulcus; STS: superior temporal sulcus; MTG: middle temporal gyrus, IOG inferior occipital gyrus; R: right hemisphere; L: left hemisphere.

| Contrast | Region | Side | x | y | z | t-value | Extent ($mm^3$) |
|---|---|---|---|---|---|---|---|
| **Positive interaction (Anti Face – Pro Face)> (Anti Car – Pro Car)** | SFS | R | 30 | 12 | 42 | 4.74 | 378 |
| **Negative interaction (Anti Car– Pro Car)> (Anti Face – Pro Face)** | Post STS/ MTG | R | 51 | −66 | 9 | 5.48 | 702 |
| | Amygdala | R | 9 | −6 | −18 | 4.58 | 648 |
| | Cerebellum lobule IV | R | 12 | −45 | −12 | 4.49 | 405 |
| | Cuneus | R | 0 | −78 | 21 | 4.78 | 2970 |
| | IOG (occipital fusiform) | R | 27 | −72 | −12 | 4.37 (ns) | 486 |

## 4. Discussion

We investigated how a social or non-social stimulus influences the activity and connectivity in brain networks involved in oculomotor programming and visual processing differentially. Using a mixed pro- and anti-saccade paradigm, we replicate the finding that faces interfere with oculomotor inhibition to a greater extent than non-social stimuli such as cars, thereby inducing more anti-saccade direction errors. With regard to brain activity, we also replicate previous findings of greater activity in fronto-parietal and occipital regions during anti-saccade tasks. Furthermore, we observed three types of interaction between task and stimulus: (i) a region within the superior frontal sulcus, just anterior to the frontal eye field, that was more active when participants performed anti-saccades away from faces compared to all the other conditions, (ii) regions in the amygdala, cerebellum and inferior occipital gyrus showing more activity for pro-saccades than for anti-saccades for faces, but the reverse for cars, and (iii) regions in the middle temporal gyrus and cuneus exhibiting significant contrast for anti-/pro-saccades for cars, but no task related modulation for faces. In addition, we showed that the functional connectivity between the FEFs and other regions involved in oculomotor control, namely the inferior FEF, the posterior parietal cortex and the basal ganglia, was strengthened when the stimulus was a face. We discuss these results in relation to the increased demand induced by orienting away from faces as compared to other objects.

### 4.1. Anti-saccades network

When comparing anti- and pro-saccades, we found the expected activation pattern including the superior parietal cortex and the dorsal precentral cortex corresponding to the frontal eye-field and extending towards more frontal territories. This provides important verification that our event-related anti-saccade paradigm, using both social (i.e. faces) and non-social (i.e. cars) stimuli, recruits similar brain areas previously found to be activated in anti-saccades tasks using more basic meaningless stimuli (Brown et al., 2006; Kimmig et al., 2001; Ford et al., 2005; Grosbras et al., 2005; Jamadar et al., 2013). Moreover we observe that activity in the FEF correlates negatively with error rate, that is with the ability to suppress the reflexive response successfully. This further emphasize that the multiple roles of this region (Grosbras et al., 2005). Other regions often associated with anti-saccades, namely the supplementary eye-field, the caudate nucleus and the anterior cingulate cortex were only mildly activated and, at the whole brain level, below our statistical threshold. This is in line with the literature available on anti-saccades for which these regions are identified less consistently (cf. meta-analyses by Grosbras et al., 2005; Jamadar et al., 2013). With regards to the dorso-lateral prefrontal cortex (DLPFC), which is often associated with anti-saccades (Pierrot-Deseilligny et al., 2003), several studies have shown that this area is involved specifically in the phase prior to target appearance (when participants prepare to perform an anti-saccade, compared to when they prepare to perform a pro-saccade), and not so much during execution, contrary to the FEF and parietal regions that are more active for anti-than pro-saccades in both preparation and response phases (Brown et al., 2007; DeSouza et al., 2003; Ford et al., 2005). This might explain why this prefrontal region does not appear in our analysis, which is time-locked to target onset and thus does not reflect so much task-set preparation but rather takes into account activity related to inhibition, saccade programming and visual processing.

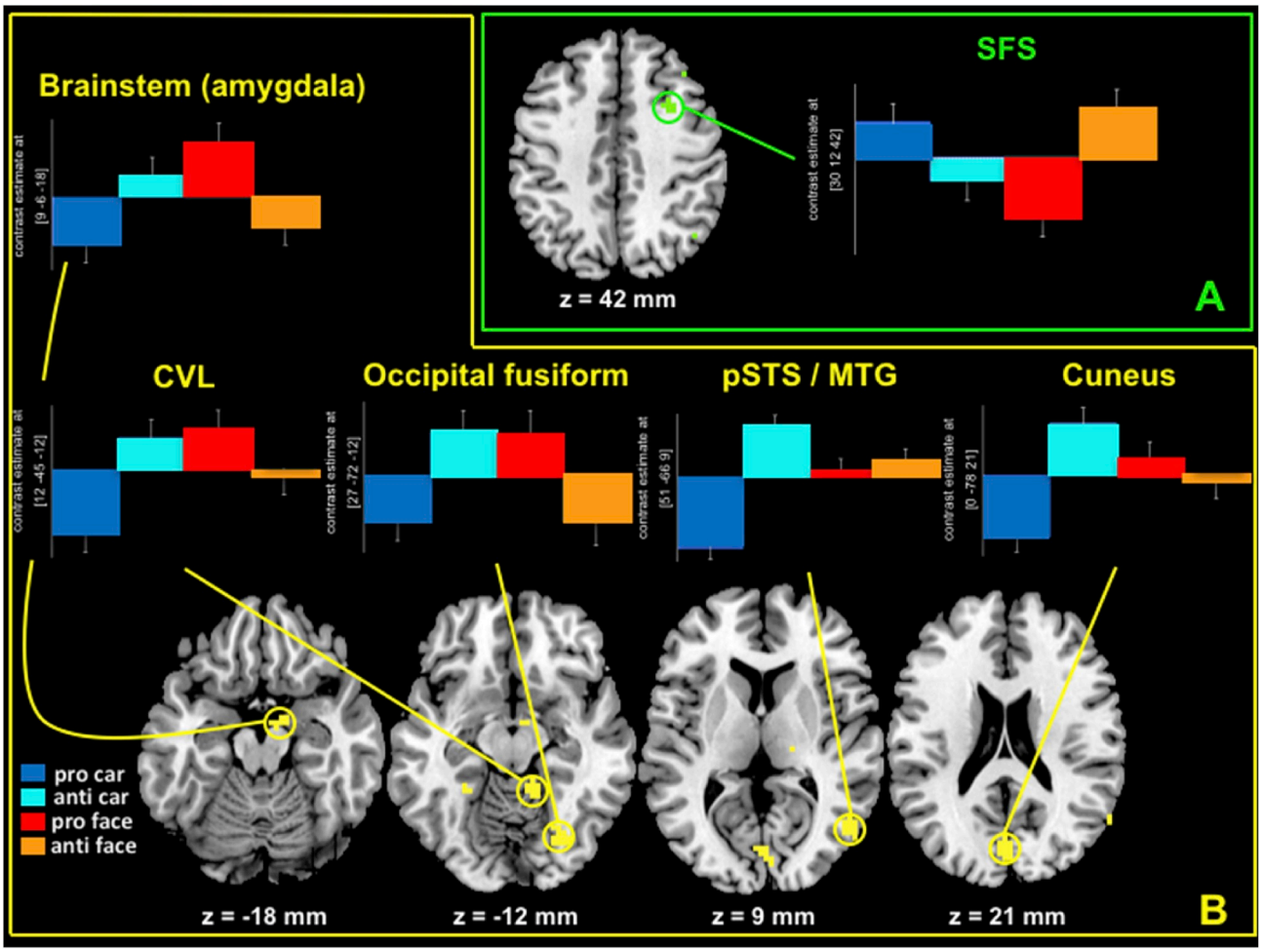



**Fig. 3. Statistical maps of interaction between task and stimulus.** Group activation results for (A) positive and (B) negative interactions rendered on a standard T1 template. Maps are thresholded at $p < .001$ uncorrected ($t > 3.3$). Circles indicate clusters of activity encompassing at least 4 contiguous voxels. For these regions showing significant interactions, plots represent the pattern of activity at the activation peak (model parameter estimates converted to arbitrary units). The dark blue bar, the light blue bar, the red bar and the orange bar represent the pattern of activity for the pro car (PC), anti car (AC), pro face (PF) and anti face (AF) conditions, respectively. Positive interaction (A) reveals that the differences between anti- and pro-saccades are larger for faces than for cars. Negative interactions (B) reveal, on the contrary, greater differences between anti- and pro-saccades for cars than for faces and/or greater brain activities for anti car, pro face and anti face compared to pro car. SFS: superior frontal sulcus, CVL: cerebellum vermis lobe, pSTS: posterior part of the superior temporal sulcus, MTG: middle temporal gyrus. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

**Table 4**
**PPI analysis –** functional connectivity between seed regions (R/L FEF) and all other brain areas modulated by the presentation of different stimuli (i.e., connectivity strengthened while viewing faces rather than cars). Seed coordinates are those revealed in the univariate analysis: R FEF: [15–3 69]; L FEF: [-15 3 69].

| Contrast | Region | Side | x | Y (mm) | z | t-value | Extent ($mm^3$) |
|---|---|---|---|---|---|---|---|
| **PPI Left FEF** | Posterior Parietal | L | −39 | −75 | 33 | 5.27 | 567 |
| | Ventral Premotor | L | −33 | 0 | 30 | 4.64 | 459 |
| **PPI right FEF** | Caudate | L | −21 | 21 | 15 | 5.59 | 459 |

For the reverse contrast we observed higher activity for pro-than anti-saccades in visual occipital regions. This is unsurprising since, in the second phase of the trials, visual processing differed between pro- and anti-saccades, as participants looked either directly at the target or kept the target in peripheral vision.

### 4.2. Stimulus effect on saccade programming in oculomotor regions

As many studies have shown that stimuli with a social content can modulate the oculomotor programming (Meermeier et al., 2016; Crouzet et al., 2010), we expected the core oculomotor regions to be influenced by the stimulus category. Yet, contrary to our expectation, face and car stimuli did not activate the oculomotor network differently. Thus, in this context at least, it seems that the FEF, the SEF and the parietal oculomotor regions are not sensitive to whether the stimulus is a face or a car.

### 4.3. Stimulus effect on saccade programming in face-related regions

With regards to the regions classically involved in face perception, we observed that faces induced significantly greater activity than cars in the amygdala only (when contrasting face and car trials independently of saccade condition). This is consistent with numerous fMRI studies reporting amygdala activity when observers are presented with faces compared to other stimulus categories (e.g., Ishai et al., 2005; Fusar-Poli et al., 2009; Rossion et al., 2012), and consistent with the view that the amygdala acts as a detector of socially relevant information (Sander

et al., 2003; Adolphs et al., 1998) and is important for guiding gaze when looking at a face (Adolphs et al., 2005). Faces also induced higher activity than cars in the basal ganglia, which could perhaps be related to the increased saliency faces have in goal directed behaviours.

Regarding other regions of the face network, such as the fusiform face area and the occipital face area (Haxby et al., 2000; Yovel and Kanwisher, 2004, Rossion et al., 2012), we found that the level of activity was weak. Indeed, no statistical significance emerged when correcting for multiple comparisons in the whole brain and pooling data from both anti- and pro-saccades. A posterior part of the fusiform gyrus was significantly active, in the face > car contrast, when we considered the pro-saccades only, that is the trials during which the faces were foveated. A possibility is that normalizing the amplitude spectra of the stimuli, as we did, resulted in a weakened response of face sensitive cortices. In addition, in contrast to our design, most brain imaging studies that characterize the brain network subserving face perception present stimuli in the center. When displayed in the periphery, faces have been reported to yield lower cortical visual activity compared to foveal presentation (Levy et al., 2001; rev. In Malach et al., 2002; Schwarzlose et al., 2008; Hamamé et al., 2014), similarly to what is reported for neurons in face-sensitive regions in the monkey temporal cortex (Desimone et al., 1984; rev. In Barraclough; Perrett, 2011).

These findings are supported further by our observation that occipito-temporal regions showed a significant interaction between stimulus and saccade task, reflecting reduced activity in the anti-saccade compared to the pro-saccade condition, for faces but not for cars. In particular, such an interaction was present in a locus close to the occipital fusiform gyrus, likely corresponding to the OFA (see Rossion et al., 2012; Ishai et al., 2005). As expected, this region was more active during pro-saccades to faces than pro-saccades to cars, yet showed the reverse pattern in the anti-saccades condition. This may be due to a contextual change of specialisation as a function of top-down mechanisms, which could, when inhibition of reflexive responses is recommended, inhibit responses to the preferred category and release activation to the non-preferred stimulus. This modulation of activity as a function of the saccadic context is reminiscent of experiments in animals showing positive (enhancement) or negative (inhibition) top-down modulation of extra-striate activity depending on task and stimulus significance (rev. In Knight et al., 1999). Using TMS and lesion data, Miller et al. (2011) demonstrated that disruption of the prefrontal cortex, presumably supporting top-down control of perception, modulated not only the magnitude, but also the category selectivity of the BOLD response of extra-striate cortex to faces and scenes. Changes in the response of face-sensitive extra-striate cortex to cars have also been demonstrated when the experimental context, such as inhibitory set, is changed, while changes to other specialized cortical areas were not as striking (e.g., Summerfield et al., 2006). It might thus be possible that the inhibitory set induced by the anti-saccade condition, results in increased activity in the lateral occipital gyrus for all kinds of visual stimuli, not just faces. This is also consistent with recent models based on causal functional connectivity approaches proposing that the more lateral part of the lateral occipital cortex (LO), which is associated with object-processing, has a modulatory influence on the OFA (Nagy et al., 2012).

### 4.4. Interactions between task and stimulus: regions engaged in anti-saccades away from faces

Our main question of interest was whether the stimulus effect would be different for anti-vs. pro-saccades. We identified a region within the right superior frontal sulcus that showed a greater difference between anti- and pro-saccades for faces than for cars. This region, just anterior to the FEF, most likely corresponds to the region named pre-FEF (Connolly et al., 2000), which is part of the spatial orienting network (Grosbras et al., 2005; Courtney et al., 1998; Corbetta et al., 2008). It is more active for anti-than pro-saccades and also for anti-pointing (Connolly et al., 2002) suggesting a more general role in visuo-spatial control. Other studies have shown its implication in both inhibition of return and covert reorienting (Lepsien and Pollmann, 2002) as well as in tasks requiring the updating of a plan of action (e.g., Kobayashi and Hsu, 2017), including anti-saccades and no-go paradigms (Brown et al., 2006). We propose that the increased activity for anti-saccades to faces reflects the fact that the social context might impose higher demand on these process, including inhibition of the automatic response and selective reorienting (see for instance Mostofsky and Simmonds, 2008 or Mäki-Marttunen and Espeseth, 2019 for similar account). Yet, we cannot rule out the possibility that the differential activity for faces and cars in this region relates to perceptual aspects of the task. In particular, although we took great care to equate the stimuli for low-level visual features. It is still possible that any effect we observe may be due to differential processing of second order visual features that would induce, for some reason to be determined, differential visual activity specifically when stimuli are presented in the periphery.

#### 4.4.1. Interactions between task and stimulus: regions showing increased activity for anti-saccades away from cars

We observed the opposite interaction in other regions: the right occipital fusiform gyrus, the right cerebellar vermis and the right amygdala (with activity also extending to the brainstem). All of these regions showed greater activity for faces in the pro-saccade condition compared to the anti-saccade condition, but greater activity for cars in the anti-saccade condition. Although this should be interpreted with caution as the contrasts between the pro car and anti car conditions as well as between the anti car and anti face conditions were not significant in these regions, this pattern might be linked to processes of mutual inhibition between face- and car-specific networks, involving the amygdala and cerebellum in addition to the occipital fusiform cortex (see discussion above).

Lastly, part of the cuneus and the right middle temporal gyrus/pSTS showed specific activity in the anti-saccade car vs pro-saccade car contrast, with no change for the face condition as a function of task. Or to put it differently, they showed a difference between faces and cars only in the pro-saccade condition, with a deactivation for pro-saccades to cars, but not in the anti-saccades conditions. As these regions are not reported in previous studies of anti-saccades with meaningless stimuli (i.e., dots or gabors), we speculate that this pattern of activity might be related to different categorical processing when foveating a stimulus, as discussed above. Given the sensitivity of the surrounding cortex (MTG/pSTS) for motion it could be that in the context of our task, where we presented faces and objects that can potentially move such as cars, activity in this cortex, sensitive to faces, is suppressed when a car is presented in pro-saccades trials and enhanced when inhibiting the response to non-face stimuli. Yet the mechanism and meaning of this, as well as the potential influence of second-order visual properties would require further investigation. In particular, also in view of the functional specialisation of the visual cortex, we suspect that this effect is not car specific but could occur for other objects particularly those that can engage this part of cortex sensitive to motion and implied motion.

### 4.5. Functional connectivity strengthened while viewing faces compared to cars

Contrary to our prediction, we did not find any modulation of functional connectivity, due to stimulus category, between the regions showing the highest oculomotor activity, namely the frontal eye fields, and the temporo-occipital regions typically involved in face processing, like the OFA and FFA. In contrast, when the stimulus was a face, we observed an increased coupling between the FEF and other regions involved in oculomotor control, including the caudate nucleus, the intraparietal sulcus, and the ventral premotor cortex corresponding to the lateral or inferior FEF (Lobel, 2001; Grosbras et al., 2005). Furthermore, at a lower threshold there was some indication of

strengthened functional connection with regions of the early visual cortex, which may be related to an increased top-down inhibition of visual processing, yet unspecific of the visual category. Thus, our data do not support a modulation of *inter*-cortical network functional organization as a function of the stimulus category, but rather points towards a change *within* the oculomotor network, possibly due to the increased task demand when the stimulus is a face (as reflected in the higher error rate). Nonetheless, further studies using tasks and stimuli that elicit stronger responses in the face network will be necessary to fully explore whether oculomotor brain activity could be influenced by faces (Coy and Hutton, 2012).

### 4.6. Limitations and future direction

Here we replicated the finding that faces induce more errors than cars in an anti-saccade task. As in previous studies, the effect is small but significant and consistent across subjects. Yet, we did not observe any latency differences between the face and the car stimuli, which is at odds with studies reporting a very fast processing of faces compared to other visual stimuli (Crouzet et al., 2010; Hershler and Hochstein, 2005; Honey et al., 2008). It has to be noted however that some of these studies suggest that the rapid orienting response to faces is partly driven by low-level visual features (VanRullen, 2006; Crouzet and Thorpe, 2011). The normalization of the amplitude spectrum of the stimuli may thus have weakened the differential response to faces. It is also possible that, in the context of a mixed pro/anti-saccades task, the effect of stimulus category on saccades latencies is more complex and less robust. In our original study, using the same paradigm and stimuli (Morand et al., 2010), we did not find any significant latency differences, nor did Gilchrist and Proske (2006). Yet in a more recent study, using the same design, we observed significantly shorter latencies for pro-saccades to faces compared to cars. This effect was relatively variable, however, and, interestingly, it correlated with the amplitude of face-specific parieto-occipital electroencephalography components (Morand et al., 2014). In the present study the contrasts of brain activity between conditions did not correlate with latencies, nor with stimulus- or task-related differences in latencies. It thus seems that how and in exactly which context faces influence saccadic reaction times should be investigated further. However, since we did show an effect on performance and were more interested in the effect of stimulus type on inhibitory control than in the facilitation of pro-saccades as such, we do not think that this compromises the interpretation of our results.

Although our results should be taken with caution due to the low sample size, and thus relatively liberal statistical threshold, for the first time, these data highlight specific neural bases for the increased demand induced by faces on the orienting system. Future research should investigate the effect of other social signals of varying behavioural relevance (e.g. emotional faces). In addition, our design, which had a fixed and short cue-target interval, does not allow us to tease apart which specific processes differentiating anti- and pro-saccades explain the greater activity for antisaccades away from faces. While the literature we cite suggests that the SFS is involved in both inhibition and reprogramming, future studies need to be designed to separate the effect of faces on these two phases of the task. Likewise, as the activity we analyse reflects also visual processing, we cannot rule out that the interaction observed in the SFS might be driven by the visual perception part of the task. This could be investigated in greater depth by adapting the timing of the task to isolate activity linked to these different cognitive, motor and/or perceptual components, ideally by testing the same participants with tasks that tap specifically into these different components.

## 5. Summary and conclusion

In the present study, we establish that performing the anti-saccade task in the context of face or car stimuli results in differential modulation of brain activity in visual as well as oculomotor regions. In particular, we identify a region of the superior frontal sulcus, known to be involved in spatial attention, as specifically involved in anti-saccades away from faces, whereas part of the middle temporal gyrus and the cuneus are involved in anti-saccades away from cars, but not from face stimuli.

Furthermore, we show that the functional connectivity patterns of key regions for anti-saccade programming are exaggerated when the stimulus is a face. This modulation is characterized by an increased integration between the right FEF and the basal ganglia, and the left FEF and the ipsilateral ventral premotor and the parietal cortex, likely to reflect the increased attentional demand imposed by programming anti-saccades away from faces as compared to other stimuli.

## CRediT authorship contribution statement

**E. Salvia:** Formal analysis, Writing - original draft, Data curation. **M. Harvey:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **B. Nazarian:** Methodology, Resources. **M.H. Grosbras:** Conceptualization, Methodology, Formal analysis, Funding acquisition, Project administration, Writing - original draft, Writing - review & editing.

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## References

Adolphs, R., Tranel, D., Damasio, A.R., 1998. The human amygdala in social judgment. Nature 393, 470–474.
Adolphs, R., Gosselin, F., Buchanan, T.W., Tranel, D., Schyns, P., Damasio, A.R., 2005. A mechanism for impaired fear recognition after amygdala damage. Nature 433, 68–72.
Alkan, Y., Biswal, B.B., Alvarez, T.L., 2011. Differentiation between vergence and saccadic functional activity within the human Frontal Eye Fields and midbrain revealed through fMRI. PloS One 6, e25866.
Awasthi, B., Friedman, J., Williams, M.A., 2011. Faster, stronger, lateralized: low spatial frequency information supports face processing. Neuropsychologia 49 (13), 3583–3590.
Barraclough, N.E., Perrett, D.I., 2011. From single cells to social perception. Philos. Trans. R. Soc. Lond. B Biol. Sci. 366, 1739–1752.
Bindemann, M., Burton, A.M., Hooge, I.T.C., Jenkins, R., DeHann, E.H.F., 2005. Faces retain attention. Psychon. Bull. Rev. 12, 1048–1053.
Bressler, S.L., Tang, W., Sylvester, C.M., Shulman, G.L., Corbetta, M., 2008. Top-down control of human visual cortex by frontal and parietal cortex in anticipatory visual spatial attention. J. Neurosci. 28, 10056–10061.
Brown, M.R.G., Goltz, H.C., Vilis, T., Ford, K.A., Everling, S., 2006. Inhibition and generation of saccades: rapid event-related fMRI of prosaccades, antisaccades, and nogo trials. Neuroimage 33, 644–659.
Cerf, M., Harel, J., Enhäuser, W., Koch, C., 2007. Predicting human gaze using low-level saliency combined with face detection. Neural Info. Process. Syst. 20, 241–248.
Brown, M.R., Vilis, T., Everling, S., 2007. Frontoparietal activation with preparation for antisaccades. J. Neurophysiol. 98 (17), 51–62.
Cerf, M., Frady, E.P., Koch, C., 2009. Faces and text attract gaze independent of the task: experimental data and computer model. J. Vis. 9 (12), 10, 1.
Connolly, J.D., Goodale, M.A., Desouza, J.F., Menon, R.S., Villis, T., 2000. A comparison of frontoparietal fMRI activation during anti-saccades and anti-pointing. J. Neurophysiol. 84, 1645–1655.
Corbetta, M., Patel, G., Shulman, G.L., 2008. The reorienting system of the human brain: from environment to theory of mind. Neuron 58, 306–324.
Courtney, S.M., Petit, L., Maisog, J.M., Ungerleider, L.G., Haxby, J.V., 1998. An area specialized for spatial working memory in human frontal cortex. Science 279, 1347–1351.
Coy, A.L., Hutton, S.B., 2012. The influence of extrafoveal emotional faces on prosaccade latencies. Vis. Cognit. 20 (8), 883–901.
Crouzet, S.M., Kirchner, H., Thorpe, S.J., 2010. Fast saccades toward faces: face detection in just 100 ms. J. Vis. 10 (16), 1–17.
Crouzet, S.M., Thorpe, S.J., 2011. Low-level cues and ultra-fast face detection. Front. Psychol. 2, 342.

Curtis, C.E., D'Esposito, M., 2003. Success and failure suppressing reflexive behavior. J. Cognit. Neurosci. 15, 409–418.
Dale, A.M., 1999. Optimal experimental design for event-related fMRI. Hum. Brain Mapp. 8, 109–114.
Devue, C., Brédart, S., 2008. Attention to self-referential stimuli: can I ignore my own face? Acta Psychol. 128, 290–297.
DeSouza, J.F., Menon, R.S., Everling, S., 2003. Preparatory set associated with pro-saccades and anti-saccades in humans investigated with event-related FMRI. J. Neurophysiol. 89 (10), 16–23.
Devue, C., Belopolsky, A.V., Theeuwes, J., 2012. Oculomotor guidance and capture by irrelevant faces. PloS One 7 (4), e34598. https://doi.org/10.1371/journal.pone.0034598.
Desimone, R., Albright, T.D., Gross, C.G., Bruce, C., 1984. Stimulus-selective properties of inferior temporal neurons in the macaque. J. Neurosci. 8, 2051–2062.
Everling, S., Munoz, D.P., 2000. Neuronal correlates for preparatory set associated with pro-saccades and anti-saccades in the primate frontal eye field. J. Neurosci. 20, 387–400.
Ford, K.A., Goltz, H.C., Brown, M.R.G., Everling, S., 2005. Neural Processes associated with antisaccade task performance investigated with event-related fMRI. J. Neurophysiol. 94, 429–440.
Forman, S.D., Cohen, J.D., Fitzgerald, M., Eddy, W.F., Mintun, M.A., Noll, D.C., 1995. Improved assessment of significant activation in functional magnetic resonance imaging (fMRI): use of a cluster-size threshold. Magn. Reson. Med. 33, 636–647.
Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.P., Frith, C.D., Frackowiak, R.S.J., 1995. Statistical parametric maps in functional imaging: a general linear approach. Hum. Brain Mapp. 2, 189–210.
Fusar-Poli, P., Placentino, A., Carletti, F., Landi, P., Allen, P., Surguladze, S., Benedetti, F., Abbamonte, M., Gasparotti, R., Barale, F., Perez, J., McGuire, P., Politi, P., 2009. Functional atlas of emotional faces processing: a voxel-based meta-analysis of 105 functional magnetic resonance imaging studies. J. Psychiatry Neurosci. 34, 418–432.
Gilchrist, I.D., Proske, H., 2006. Anti-saccades away from faces: evidence for a influence of high-level visual processes on saccade programming. Exp. Brain Res. 173, 708–712.
Gitelman, D.R., Parrish, T.B., Friston, K.J., Mesulman, M.-M., 2002. Functional anatomy of visual search: regional segregations within the frontal eye fields and effective connectivity of the superior colliculus. Neuroimage 15, 970–982.
Grill-Spector, K., Knouf, N., Kanwisher, N., 2004. The fusiform face area subserves face perception, not generic within-category identification. Nat. Neurosci. 7, 555–562.
Grosbras, M.-H., Laird, A.R., Paus, T., 2005. Cortical regions involved in eye movements, shifts of attention, and gaze perception. Hum. Brain Mapp. 25, 140–154.
Hagberg, G.E., Zito, G., Patria, F., Sanes, J.N., 2001. Improved detection of event-related functional MRI signals using probability functions. Neuroimage 14, 1193–1205.
Hallett, P.E., 1978. Primary and secondary saccades to goals defined by instructions. Vision Res. 18, 1279–1296.
Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2000. The distributed human neural system for face perception. Trends Cognit. Sci. 4, 223–233.
Hamamé, C.M., Vidal, J.R., Perrone-Bertolotti, M., Ossandón, T., Jerbi, K., Kahane, P., Bertrand, O., Lachaux, J.P., 2014. Functional selectivity in the human occipitotemporal cortex during natural vision: evidence from combined intracranial EEG and eye-tracking. Neuroimage 95 (2), 76–86.
Honey, C., Kirchner, H., VanRullen, R., 2008. Faces in the cloud: fourier power spectrum biases ultrarapid face detection. J. Vis. 8 (9), 1–13.
Hutton, S.B., 2008. Cognitive control of saccadic eye movements. Brain Cognit. 68, 327–340.
Hwang, K., Velanova, K., Luna, B., 2010. Strengthening of top-down frontal cognitive control networks underlying the development of inhibitory control: a functional magnetic resonance imaging effective connectivity study. J. Neurosci. 30, 15535–15545.
Hershler, O., Hochstein, S., 2005. At first sight: a high- level pop out effect for faces. Vision Res. 45 (13), 1707–1724.
Ishai, A., Schmidt, C.F., Boesiger, P., 2005. Face perception is mediated by a distributed cortical network. Brain Res. Bull. 67, 87–93.
Jamadar, S.D., Fielding, J., Egan, G.F., 2013. Quantitative meta-analysis of fMRI and PET studies reveals consistent activation in fronto-striatal-parietal regions and cerebellum during antisaccades and prosaccades. Front. Psychol. 4, 749.
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.
Kimmig, H., Greenlee, M.W., Gondan, M., Schira, M., Kassubek, J., Mergner, T., 2001. Relationship between saccadic eye movements and cortical activity as measured by fMRI: quantitative and qualitative aspects. Exp. Brain Res. 141, 184–194.
Knight, R.T., Staines, W.R., Swick, D., Chao, L.L., 1999. Prefrontal cortex regulates inhibition and excitation in distributed neural networks. Acta Psychol. 101, 159–178.
Kobayashi, K., Hsu, M., 2017. Neural mechanisms of updating under reducible and irreducible uncertainty. J. Neurosci. 37 (29), 6972–6982.
Koval, M.J., Hutchison, R.M., Lomber, S.G., Everling, S., 2014. Effects of unilateral deactivations of dorsolateral prefrontal cortex and anterior cingulate cortex on saccadic eye movements. J. Neurophysiol. 111, 787–803.
Laidlaw, K.E.W., Badiudeen, T.A., Zhu, M.J.H., Kingston, A., 2015. A fresh look at saccadic trajectories and task irrelevant stimuli: social relevance matters. Vision Res. 111, 82–90.
Langton, S.R.H., Law, A.S., Burton, A.M., Schweinberger, S.R., 2008. Attention capture by faces. Cognition 107, 330–342.
Lepsien, J., Pollmann, S., 2002. Covert reorienting and inhibition of return: an event-related fMRI study. J. Cognit. Neurosci. 14 (2), 127–144.
Levy, L., Hasson, U., Avidan, G., Hendler, T., Malach, R., 2001. Center-periphery organization of human object areas. Nat. Neurosci. 4, 533–539.
Lieberman, M.D., Cunningham, W.A., 2009. Type I and Type II error concerns in fMRI research: re-balancing the scale. Soc. Cognit. Affect Neurosci. 4 (4), 423–428.
Malach, R., Levy, I., Hasson, U., 2002. The topography of high-order human object areas. Trends Cognit. Sci. 6, 176–184.
Mäki-Marttunen, V Hagen T., Espeseth, T., 2019. Task context load induces reactive cognitive control: an fMRI study on cortical and brain stem activity. Cognit. Affect Behav. Neurosci. 19 (4), 945–965. https://doi.org/10.3758/s13415-019-00691-6.
McDowell, J.E., Dyckman, K.A., Austin, B.J., Clementz, B.A., 2008. Neurophysiology and neuroanatomy of reflexive and volitional saccades: evidence from studies of humans. Brain Cognit. 68, 255–270.
Meermeier, A., Gremmler, S., Lappe, M., 2016. The influence of image content on oculomotor plasticity. J. Vis. 16 (8) https://doi.org/10.1167/16.8.17, 17-17.
Miller, B.T., Vytlacil, J., Fegen, D., Pradhan, S., D'Esposito, M., 2011. The prefrontal cortex modulates category selectivity in human extrastriate cortex. J. Cognit. Neurosci. 23, 1–10.
Morand, S.M., Grosbras, M.H., Caldara, R., Harvey, M., 2010. Looking away from faces: influence of high-level visual processes on saccade programming. J. Vis. 10, 1–10.
Morand, S.M., Harvey, M., Grosbras, M.H., 2014. Parieto-occipital cortex shows early target selection to faces in a reflexive orienting task. Cerebr. Cortex 24, 898–907.
Mostofsky, S.H., Simmonds, D.J., 2008. Response inhibition and response selection: two sides of the same coin. J. Cognit. Neurosci. 20 (5), 751–761. https://doi.org/10.1162/jocn.2008.20500.
Munoz, D.P., Everling, S., 2004. Look away: the anti-saccade task and the voluntary control of eye movement. Nat. Rev. Neurosci. 5, 218–228.
Nagy, K., Greenlee, M.W., Kovács, G., 2012. The lateral occipital cortex in the face percep- tion network: an effective connectivity study. Front. Psychol. 3, 141. https://doi.org/10.3389/fpsyg.2012.00141.
Pa, J., Dutt, S., Mirsky, J.B., Heuer, H.W., Keselman, P., Kong, E., Trujillo, A., Gazzaley, A., Kramer, J.H., Seeley, W.W., Miller, B.L., Boxer, A.L., 2014. The functional oculomotor network and saccadic cognitive control in healthy elders. Neuroimage 95, 61–68.
Pierrot-Deseilligny, C., Müri, R.M., Ploner, C.J., Gaymard, B., Demeret, S., Rivaud-Pechoux, S., 2003. Decisional role of the dorsolateral prefrontal cortex in ocular motor behaviour. Brain 126, 1460–1473.
Rossion, B., Caldara, R., Seghier, M., Schuller, A.-M., Lazeyras, F., Mayer, E., 2003. A network of occipito-temporal face-sensitive areas besides the right middle fusiform gyrus is necessary for normal face processing. Brain 126, 2381–2395.
Rossion, B., Hanseeuw, B., Dricot, L., 2012. Defining face perception areas in the human brain: a large-scale factorial fMRI face localizer analysis. Brain Cognit. 79, 138–157.
Sander, D., Grafman, J., Zalla, T., 2003. The human amygdala: an evolved system for relevance detection. Rev. Neurosci. 14, 303–316.
Schwarzlose, R.F., Swisher, J.D., Dang, S., Kanwisher, N., 2008. The distribution of category and location information across object-selective regions in human visual cortex. Proc. Natl. Acad. Sci. 105 (44), 47–52.
Schweinberger, S.R., Kaufmann, J.M., Moratti, S., Keil, A., Burton, A.M., 2007. Brain responses to repetitions of human and animal faces, inverted faces, and objects - an MEG study. Brain Res. 1184, 226–233.
Simpson, E.A., Husband, H.L., Yee, C., Fullerton, A., Jakobsen, K.V., 2015. Visual search efficiency is greater for human faces compared to animal faces. Exp. Psychol. 61, 439–456.
Summerfield, C., Egner, T., Mangels, J., Hirsch, J., 2006. Mistaking a house for a face: neural correlates of misperception in healthy humans. Cerebr. Cortex 16, 500–508.
Tu, P., Buckner, R.L., Zollei, L., Dyckman, K.A., Goff, D.C., Manoach, D.S., 2010. Reduced functional connectivity in a right-hemisphere network for volitional ocular motor control in schizophrenia. Brain 133, 625–637.
VanRullen, R., 2006. On second glance: still no high-level pop-out effect for faces. Vision Res. 46 (18), 3017–3027. https://doi.org/10.1016/j.visres.2005.07.009.
Vossel, S., Mathys, C., Stephan, K.E., Friston, K.J., 2015. Cortical coupling reflects bayesian belief updating in the deployment of spatial attention. J. Neurosci. 35, 11532–11542.
Xu, J., Jiang, M., Wang, S., Kankanhalli, M.S., Zhao, Q., 2014. Predicting human gaze beyond pixels. J. Vis. 14 1, 20.
Xu-Wilson, M., Zee, D., Shadmehr, R., 2009. The intrinsic value of visual information affects saccade velocities. Exp. Brain Res. 196, 475–481.
Yovel, G., Kanwisher, N., 2004. Face perception: domain specific, not process specific. Neuron 44, 889–898.