In search of the functional neuroanatomy of sociality: MRI subdivisions of orbital frontal cortex and social cognition

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We examined social cognition in a sample of healthy participants who had prior magnetic resonance imaging (MRI) gray matter volume studies of the orbital frontal cortex (OFC) that was parcellated into three regions: gyrus rectus, middle orbital gyrus and lateral orbital gyrus. These subjects also completed a self-report measure of Machiavelli personality traits, along with psychometric tests of social comprehension and declarative episodic memory, all of which we used as proxy measures to examine various features of social cognition. The data pointed to distinct functional-anatomical relationships highlighted by strong correlations of left lateral orbital gyrus and Machiavellian scores and right middle orbital gyrus with social comprehension and declarative episodic memory. In addition, hierarchical regression analyses revealed statistical evidence of a double dissociation between Machiavellian scores and left lateral orbital gyrus on one hand, and social comprehension with right middle orbital gyrus, on the other hand. To our knowledge, these findings are the first to show evidence linking normal variation in OFC subregions and different aspects of social cognition.

**Keywords:** orbital frontal cortex; social cognition

**INTRODUCTION**

In 1846 in Cavendish Vermont, a railroad foreman named Phineas Gage had been laying track when a sharp-pointed 3-cm-thick, 109-cm-long tamping iron rod exploded through his left cheekbone, slicing behind his left eyeball and impaling his frontal lobes. Miraculously, Gage, described as only momentarily stunned, regained consciousness immediately and with the help of his fellow railroad workers walked away from the accident. But his personality and social comportment would never be the same, and the once conscientious and capable foreman was now seen as crass and unpredictable, and as his friends and acquaintances attested ‘Gage was no longer Gage’ (Harlow, 1868 cited in Damasio et al., 1994) (p. 1102).

Fast forward over a century later, Damasio et al. (1994), using measurements from Gage’s skull and modern techniques of computerized neuroimaging, reconstituted the entry facial and exit skull wounds suffered by Gage. Their computerized modeling of Gage’s brain revealed damage confined to prefrontal cortices, particularly for the left hemisphere, the anterior half of the orbital frontal cortex (OFC), the anterior and mesial frontal cortices and for the right hemisphere, an-
as well as lamination and formation of cytoarchitecture (Rakic, 1988; Armstrong et al., 1995).

In light of such structural and functional diversity, researchers have focused on dividing the OFC into distinct subregions. Duvernoy (1999), for example, used the major orbital sulci to divide the OFC into five subregions of gyrus rectus, and medial, anterior, posterior and lateral orbital gyri. More recently, Nakamura et al. (2008), in an effort to mitigate differences arising from variability of OFC sulcogyriform morphology, particularly the H-shaped sulcus (Chiavaras and Petrides, 2000), used a 3D MRI region-of-interest approach to develop a reliable parcellation of the OFC into three subdivisions. Focusing on two of the most stable and reliably imaged sulci as anatomical boundaries—olfactory sulcus and lateral orbital sulcus—Nakamura et al. (2008) divided the OFC into three regions of interest: gyrus rectus, middle orbital gyrus and lateral orbital gyrus, and examined each region in relation to gray matter volume and neuropsychological performance in schizophrenia and age-matched control subjects. Their results lent validity to these OFC subdivisions, pointing to a bilateral reduction in middle orbital gyrus in schizophrenia, with smaller volumes in this subregion correlating with disease-related difficulties in social communication as reflected by increased severity of thought disturbance (Nakamura et al., 2008). Moreover, for healthy participants who served as control comparisons for the schizophrenia sample, social decision making, as assessed by the Iowa Gambling Task, correlated with increased gray matter volume of the right middle orbital gyrus (Nakamura et al., 2008).

Other studies have compared the functional roles of lateral and medial OFC subregions in sociality in non-clinical samples. For example, functional magnetic resonance imaging (fMRI) findings suggest that abstract rewards and punishments, as measured monetarily, may lead to differential engagement of lateral and medial OFC sectors (O’Doherty et al., 2001; Kringelbach, 2005). These data pointed to heightened activation of the lateral but not medial area of the OFC following a punishing outcome, whereas a rewarding outcome elicited increased activation of the medial but not lateral area of the OFC (O’Doherty et al. 2001). Spitzer et al. (2007) extended these findings by examining the relationship of individual differences in Machiavellian personality characteristics and fMRI brain activation recorded while pairs of research participants played a social norm compliance game involving an economic exchange. They reported that Machiavelli scores correlated strongly with both heightened lateral OFC activation, especially of the left hemisphere, and norm compliance under the threat of social punishment. Spitzer and colleagues concluded that left lateral OFC may represent an important neural network for social norm compliance, providing neurobiological substrata for judging and evaluating social opportunities and threats—abilities that are central to the development of Machiavellianism.

Elliot et al. (2000), in their review of fMRI studies, also revealed evidence of dissociation between the medial and lateral OFC. They noted medial orbital frontal involvement in a variety of cognitive tasks, including delayed match to sample, guessing, as well as language tests of sentence completion and story comprehension. They suggested that although these tasks impose different cognitive demands, all require for effective performance monitoring, and holding in mind prior reward values in order that current contingencies can be abstracted and future outcomes can be predicted. Elliot et al. (2000) noted that while these mental processes and computations depend on prefrontal lobe circuitry, in general, it is the specific demands that these diverse tasks impose on the monitoring of reward values that account for the differential role of medial orbital frontal activation, with studies suggesting right medial orbital frontal to be especially important in social decision making (Zald and Rauch, 2006; Nakamura et al., 2008).

Taken together, these functional and structural neural imaging studies suggest that medial and lateral OFC regions can be dissociated, both functionally and anatomically. That is, as Elliot et al. (2000) findings suggested, the engagement of the medial OFC in reward learning may have an important role in a diversity of learning tasks of higher order abilities ranging from those that may be described primarily as cognitive to those that extend to social domains related to understanding personal interactions. Moreover, the medial OFC has its strongest connections to the hippocampus and associated areas of the cingulate, retrosplenial and entorhinal cortices and anterior thalamus (Mesulam et al., 1985; Vogt et al., 1987; Morecraft et al., 1992), which would also be consistent with its involvement in higher order cognition, especially declarative episodic memory. On the other hand, while the lateral OFC also has strong connections to brain regions critical for higher order cognition, its links to the inferior parietal lobe and dorsolateral prefrontal cortex (Goldman-Rakic, 1987; Fuster, 1997), may suggest a special role in Machiavellian personality traits related to detecting and evaluating social threats to self-interest (Spitzer et al., 2007).

Based on these fMRI studies, the current study tested for a double dissociation between anatomy, as measured by lateral and middle orbital gyrus gray matter, and function, as assessed by a self-report measure of Machiavelli personality traits and psychometric tests of cognition, which include measures of social reasoning and judgment. A pencil-and-paper measure of Machiavellianism, psychometric tests of declarative memory, intellectual abilities, including social reasoning as well OFC gray matter volumes were all acquired from a sample of healthy participants who had served as control subjects in several of our other studies of schizophrenia (Nakamura et al., 2008; Nestor et al., 2010). Based on prior research, we hypothesize a double dissociation of function and anatomy: to wit, variance in self-report Machiavelli personality traits but not in psychometric intellect and memory will be significantly accounted for by gray matter volumes of left lateral orbital gyrus but not right middle orbital gyrus, whereas variance in intellect and memory but not Machiavelli personality traits will be significantly accounted for by gray matter volumes in right middle orbital gyrus but not left lateral orbital gyrus.

**METHODS**

**Participants**

Twenty-five healthy right-handed, participants (19 males/6 females) who served as normal comparison subjects for prior MRI studies of veterans with schizophrenia (Nakamura et al., 2008) participated. All participants met Structured Clinical Interview for DSM-IV Axis I Disorders-Non-patient Edition (SCID-NP) criteria of no past or current Axis I and/or Axis II disorder (First et al., 1997, 2002). Participants had a mean age (s.d.) of 41.08 (9.10) years and a mean education (s.d.) of 15 (1.98) years. All participants gave informed consent. The self-report and psychometric tests were administered at the Boston VA Medical Center (Brockton, MA Division) and the MRI studies were conducted at the Brigham and Women’s Hospital in Boston, MA, USA. MRI studies and neuropsychological testing were completed over the course of ~3 months. The research protocol was approved by the Institutional Review Board of the Boston VA Medical Center and Harvard Medical School.

**Measures**

The Mach IV, a measure of Machiavelli personality traits, consists of 20 statements that participants rate on a 7-point Likert scale (1 = strongly disagree, 4 = no opinion and 7 = strongly agree). This ordinal scale, with a constant arbitrary base of 20 points, generates scores ranging from 40 to 160. A total score of 100 is set to represent the mean.
voxel dimensions throughout the brain (TE double-echo (proton-density- and T2-weighted) slices, with 54 levels, Next, a double-echo spin-echo yielded 108 contiguous axial scanner (GE Medical Systems, Milwaukee) at the Brigham and Extra-hippocampal regions in Comprehension and Picture Arrangement scores (i) validated two empirically derived subtypes of emotionally disordered murderers, a psychotic subtype, diagnosed primarily with schizophrenia and a non-psychotic subtype defined primarily by high levels of psychopathy (Nestor et al, 2002) and (ii) predicted mentally ill, incompetent-to-stand trial defendants (Nestor et al, 1999).

The Wechsler Memory Scale-Third Edition (WMS-III) (Wechsler, 1997b) provides a highly reliable and valid standardized test of declarative episodic memory. Among the WMS-III indexes are immediate memory and delayed memory, each divided into both auditory and visual domains. The Doors and People Test (DPT) was administered as an additional measure of declarative episodic memory (Baddeley et al, 1994). It consists of four subtests: verbal recall (People Test); visual recall (Shapes Test); verbal recognition (Names Test); and visual recognition (Doors Test). The DPT has been used to demonstrate involvement of hippocampus and extra-hippocampal regions in memory impairment in idiopathic lesion case studies (Reed and Squire, 1997; Vargha-Khadem et al, 1997; Manns and Squire, 1999; Baddeley et al, 2001) as well as patients with chronic schizophrenia (Nestor et al, 2007).

MRI processing
The MRI processing is described in detail in Nakamura et al. (2008). In brief, MR images were acquired with a 1.5-Tesla General Electric scanner (GE Medical Systems, Milwaukee) at the Brigham and Women’s Hospital in Boston. A 3D Fourier transformed spoiled gradient-recalled (SPGR) acquisition sequence yielded a coronal series of contiguous 1.5 mm images (TE = 5 ms, TR = 35 ms, repetition = 1, nutation angle = 45°, field of view = 24 cm, acquisition matrix = 256 x 256 x 124, voxel dimension = 0.9375 x 0.9375 x 1.5 mm). Next, a double-echo spin-echo yielded 108 contiguous axis double-echo (proton-density- and T2-weighted) slices, with 54 levels, throughout the brain (TE = 30 and 80 ms, TR = 3000 ms, field of view = 24 cm, an interleaved series with 3-mm slice thickness, voxel dimensions = 0.9375 x 0.9375 x 3.0 mm). The T2 information from the double-echo spin-echo axial slices was registered to the SPGR images. An expectation-maximization (EM) segmentation technique (Bouix et al, 2007; Pohl et al, 2007) was used to segment the images into three major tissue classes: gray matter; white matter; and CSF, using both SPGR and T2-weighted MR information as well as spatial priors. This technique was used to obtain Intra-Cranial Contents (ICC) volume. Manual tracing of OFC ROI was performed on non-segmented images to avoid segmentation errors due to susceptibility artifacts which are common in the OFC region. Images were realigned using the line between the anterior and posterior commissures and the sagittal sulcus to correct head tilt, and resampled into isotropic voxels (0.9375 mm³). This realignment procedure was essential for precise and consistent ROI delineation. 3D information was used to provide reliable delineation of the OFC ROI with a software package for medical image analysis [3D slicer, http://www.slicer.org] on a workstation. Definition and details of the method of region of interest for the OFC are provided in Nakamura et al. (2008). The relative volume is calculated as: absolute volume/intracranial contents (ICC) * 100 (%). Figure 1 depicts image of the OFC divided into three subregions: gyrus rectus, middle orbital gyrus and lateral orbital gyrus.

Statistical analyses
Pearson Product Moment correlations tested for associations between scores on Mach IV and psychometric measures of social comprehension and declarative episodic memory with OFC subregion gray matter volumes. We next employed partial correlations as a test for the specificity of the relationship of Mach IV and OFC volume, covarying for scores on psychometric tests. Likewise, we tested for the relationship of social comprehension and OFC volume, covarying for Mach IV scores. Parametric, hierarchical regression analyses were then used to partition the total variance of the dependent variable, test score, among the independent variables, MRI measures of OFC subregions volumes.

To examine the unique contribution of MRI measures to test scores, partial (rp) and semi-partial (rSp) correlations were computed in a series of hierarchical regression analyses, which permitted the evaluation of significant univariate relationships by partitioning total variance of the dependent variable (test score) among independent variables (MRI OFC subregion volumes) (Cohen and Cohen, 1975). The partial correlation squared (rp²) is the proportion of variance of a particular test score (e.g. Mach IV) shared by a specific OFC subregion (e.g. left lateral orbital gyrus), after the effects of the other OFC subregions (e.g. right lateral orbital gyrus) have been removed from both the test score and MRI gray matter volumes (Cohen and Cohen, 1975). This statistic answers the question, ‘What proportion of the remaining test score variance (i.e., that which is not estimated by the other IVs in the equation) is uniquely estimated by this gray matter volume?’ By comparison, the square of the semi-partial correlation (rSp²) estimates the amount of test score variance that is uniquely shared with a particular gray matter subregion volume measure after the effects of all other subregions on that particular brain area have been removed (Cohen and Cohen, 1975). It is semi-partial because the effects of the other independent variables have been removed from the independent variable but not from the dependent variable. In conjunction with other linear regression statistics, partial and semi-partial correlations provide a comprehensive picture of how subregion gray matter volumes of the OFC relate to scores on particular measures of social cognition when collinearity is controlled.

In addition, based on prior fMRI studies, we hypothesized a double dissociation with Mach IV but not social comprehension scores corresponding to gray matter volume of left lateral orbital gyrus but not right middle orbital gyrus gray matter volume, in comparison to social comprehension but not Mach IV scores corresponding to gray matter volume of right middle orbital gyrus but not left lateral orbital gyrus. We test for this hypothesized double dissociation using a pair of hierarchical regression model: for Mach IV as the dependent variable, left lateral orbital gyrus gray matter, entered first as an independent variable, followed by right middle orbital gyrus gray matter. For social comprehension as the dependent variable, right middle orbital gyrus
gray matter, entered first as an independent variable, followed by left lateral orbital gray matter. For all regression analyses, the $F$-to-enter probability was 0.05 and the $F$-to-exclude probability was 0.1. Significance levels are two tailed.

**RESULTS**

Table 1 presents the mean scores for the Mach IV, WAIS-III, DPT and WMS-III. Participants showed nearly identical Mach IV ($M$ (s.d.) = 101.58 (13.76)) and WAIS-III Full Scale IQ ($M$ (s.d.) = 101.21 (8.92)) scores, $F < 1$. Participants had similar scores across WAIS-III indexes of verbal comprehension ($M$ (s.d.) = 103.13 (14.48)), perceptual organization ($M$ (s.d.) = 107.48 (17.56)), working memory ($M$ (s.d.) = 105.74 (15.68)) and processing speed ($M$ (s.d.) = 101.87 (14.48)) and social comprehension ($M$ (s.d.) = 105.57 (11.96)). Likewise, participants had similar scores for WMS-III indexes of immediate ($M$ (s.d.) = 102.86 (17.20)) and delayed ($M$ (s.d.) = 105.48 (14.65)) memory. For the DPT, participants had similar scores across measures of verbal recall for the People Test ($M$ (s.d.) = 9.95 (3.39)), visual recall for the Shapes Test ($M$ (s.d.) = 10.15 (3.92)) and visual recognition for the Doors Test ($M$ (s.d.) = 10.25 (3.11)), with higher scores for verbal recognition for the Names Test ($M$ (s.d.) = 13.25 (3.34)).

Table 2 presents relative volumes for the orbital frontal subregions. A repeated measures analysis of variance (ANOVA) with two within-subject factors of side (left/right) and subregion (gyrus rectus, middle orbital gyrus and lateral orbital gyrus) revealed significant effects for subregion: $F(2,48) = 1427.03, P < 0.001, \eta^2 = 0.983$ and the interaction of side x subregion: $F(2,48) = 8.68, P = 0.001, \eta^2 = 0.266$. Paired t-tests indicated a significantly greater right than left gray matter volume for gyrus rectus, $t(24) = 3.90, P = 0.001$, but greater left than right gray matter volume for middle orbital gyrus, $t(24) = 2.50, P = 0.02$ in contrast to similar gray matter volume for right and left lateral orbital gyrus, $t(24) = 1.38, P = 0.181$.

Table 3 shows higher Mach IV scores correlated significantly with increased gray matter volume of the left lateral orbital frontal gyrus ($r = 0.492, P = 0.028$). This correlation remained significant when controlling for WAIS-III Full Scale IQ (partial $r = 0.549, P = 0.018$). As shown in Table 3, for the WAIS-III, higher social comprehension correlated significantly with increased volume of left ($r = 0.538, P = 0.008$) and right ($r = 0.553, P = 0.006$) middle orbital gyrus as well as with left ($r = 0.428, P = 0.041$) and right ($r = 0.494, P = 0.017$) total OFC volume. Higher WAIS-III social comprehension remained significantly correlated with increased gray matter volume of the left middle orbital gyrus when controlling for WAIS-III indexes of working memory (partial $r = 0.521, P = 0.013$), processing speed (partial $r = 0.471, P = 0.027$) and perceptual organization (partial $r = 0.453, P = 0.034$). Likewise, WAIS-III social comprehension remained significantly correlated with right middle orbital gyrus when controlling for WAIS-III indexes of working memory (partial $r = 0.484, P = 0.002$) and processing speed (partial $r = 0.449, P = 0.03$) but not for perceptual organization or verbal comprehension. These partial correlations indicated that the relationship of greater left middle orbital gray matter volume and higher WAIS-III social comprehension was independent of scores on WAIS-III index of verbal comprehension, working memory, and processing speed.

**Fig. 1** Orbital frontal cortex subregions of the lateral orbital gyrus (LOG; left: purple, right: light green), middle orbital gyrus (MiOG; left: brown, right: red) and gyrus rectus (GR; left: blue, right: green) along with scatter plots of left lateral orbital frontal gyrus and Machiavellianism, and right middle orbital frontal gyrus and social comprehension.
Table 1  Self-report and neuropsychological test scores for research participants

| Measures                      | M (±s.d.)   |
|-------------------------------|-------------|
| Demographics                  |             |
| Age                           | 41.08 (±9.10)|
| Education                     | 15.00 (±1.98)|
| SES                           | 2.42 (±1.06)|
| Mach IV                       |             |
| Duplicious                    | 38.50 (±5.56)|
| Human nature views            | 31.10 (±5.62)|
| Mortality                     | 11.40 (±2.64)|
| Total                         | 101.00 (±8.74)|
| WAIS-III                      |             |
| Verbal comprehension          | 103.13 (±14.48)|
| Perceptual organization       | 107.48 (±17.56)|
| Working memory                | 105.74 (±15.68)|
| Processing speed              | 101.87 (±14.48)|
| Social comprehension          | 104.56 (±23.93)|
| Full-scale IQ                 | 105.22 (±16.25)|
| WMS-III                       |             |
| Auditory immediate            | 104.32 (±17.56)|
| Visual immediate              | 101.05 (±15.22)|
| Auditory delayed              | 105.76 (±14.82)|
| Visual delayed                | 101.43 (±15.28)|
| Immediate memory              | 103.82 (±17.38)|
| Delayed memory                | 105.48 (±14.65)|
| Delayed recognition           | 105.71 (±14.26)|
| Doors and people               |             |
| People                        | 9.95 (±3.39) |
| Shapes                        | 10.15 (±3.92) |
| Names                         | 13.25 (±3.34) |
| Doors                         | 10.25 (±3.11) |

*Standard scores [M (s.d.) = 100 (15)].

*Age-scaled scores [M (s.d.) = 10 (3)].

Note. Values are means ± s.d.’s. Mach IV = Machiavellianism; WAIS-III = Wechsler Adult Intelligence Scale—Third Edition; WMS-III = Wechsler Memory Scale—Third Edition.

Table 2  Relative volumes for orbital frontal cortex subregions

| OFC subregion                  | M (±s.d.)   |
|-------------------------------|-------------|
| Gyrus rectus                  |             |
| Left                          | 0.161 (±0.026)|
| Right                         | 0.174 (±0.026)|
| Middle orbital gyrus          |             |
| Left                          | 0.520 (±0.056)|
| Right                         | 0.495 (±0.056)|
| Lateral orbital gyrus         |             |
| Left                          | 0.00 (±0.014)|
| Right                         | 0.054 (±0.012)|

Note. Values are means ± s.d.’s.

measures of working memory, processing speed and perceptual organization but not for WAIS-III verbal comprehension. By comparison, the right middle orbital gyrus volume and WAIS-III social comprehension correlated positively, independently of WAIS-III indexes of working memory and processing speed, but not for WAIS-III indexes of perceptual reasoning or verbal comprehension.

The WMS-III, higher scores for immediate memory correlated with increased gray matter volume for right middle orbital gyrus (r = 0.562, P = 0.007) and total right OFC volume (r = 0.582, P = 0.005). WMS-III delayed memory correlated with right middle orbital gyrus (r = 0.445, P = 0.043) and total right OFC volume (r = 0.448, P = 0.042). Higher scores on WMS-III auditory delayed recognition correlated with increased gray matter volume in left (r = 0.445, P = 0.043) and right (r = 0.481, P = 0.027) middle orbital gyrus.

When controlling for WAIS-III social comprehension, immediate memory but not delayed memory remained significantly correlated with right middle orbital gyrus (partial r = 0.469, P = 0.03) and total right OFC volume (partial r = 0.506, P = 0.019). By contrast, auditory recognition memory no longer correlated with gray matter for either left or right middle orbital gyrus after controlling for WAIS-III social comprehension. Yet when controlling for Mach IV scores, immediate memory remained significantly correlated with right middle orbital frontal gyrus (partial r = 0.563, P = 0.015) and total right OFC volume (partial r = 0.574, P = 0.013). Delayed memory also remained significantly correlated with gray matter volume of right middle orbital frontal gyrus when controlling for Mach IV scores (partial r = 0.482, P = 0.05) as did delayed auditory recognition with left (partial r = 0.550, P = 0.022) and right (partial r = 0.589, P = 0.013) middle orbital gyrus.

For the DPT, left middle orbital gyrus volume correlated with higher scores on recall of people (r = 0.499, P = 0.025) and recognition of names (r = 0.455, P = 0.044), as did right middle orbital gyrus volume correlate with recall of people (r = 0.540, P = 0.014) and shapes (r = 0.477, P = 0.033) and recognition of names (r = 0.443, P = 0.051). Age-scaled scores for recall of people also correlated with total gray matter volume for both left (r = 0.558, P = 0.011) and right (r = 0.591, P = 0.006) OFC and remained significant when controlling for WAIS-III social comprehension for total gray matter volume for both left (partial r = 0.452, P = 0.052) and right (partial r = 0.472, P = 0.041) OFC. Also when controlling for WAIS-III social comprehension, a strong relationship emerged between recall scores for people and left gyrus rectus volume (partial r = 0.616, P = 0.005). When controlling for Mach IV, recall for people remained significantly correlated with left (partial r = 0.644, P = 0.007) and right (partial r = 0.526, P = 0.036) middle orbital gyrus, and for total gray matter volume for both (partial r = 0.729, P = 0.001) and right (partial r = 0.588, P = 0.017) OFC. In addition, when controlling for Mach IV, significant partial correlations emerged for shape recall and right middle orbital gyrus (partial r = 0.503, P = 0.047) and for recognition of doors and left middle orbital gyrus (partial r = 0.554, P = 0.026) as well as for recognition of names for left (partial r = 0.558, P = 0.025) and right (partial r = 0.547, P = 0.028) middle orbital gyrus, and for left total gray matter OFC volume (partial r = 0.520, P = 0.039).

We next used hierarchical multiple regression to compare the contributions of orbital frontal subregion volumes to the behavioral measures. For the dependent variable Mach IV scores, we entered the subregion volumes in the following order: left lateral orbital gyrus, left middle orbital gyrus, right lateral orbital gyrus and right middle orbital gyrus. The regression indicated that gray matter volume for the left lateral orbital gyrus produced an R = 0.492, R² change = 0.242, F(1,18) = 5.74, P = 0.028 and adding the other subregion volumes did not significantly increase the variance explained. However, both left lateral orbital gyrus (standardized B = 0.709, t = 3.06, P = 0.008) and left middle orbital gyrus (standardized B = 0.776, t = 2.13, P = 0.05) contributed significantly to Mach IV scores, with left lateral orbital gyrus yielding a partial correlation of 0.620 and a semi-partial correlation of 0.588, and left middle orbital gyrus a partial correlation of 0.482 and semi-partial correlation of 0.409. These values indicated that the left lateral orbital gyrus uniquely accounted for ~38.44 and 34.57% and left middle orbital gyrus, 23.23 and 16.73% of the variance in Mach IV scores.

For the dependent variable, WAIS-IV social comprehension, hierarchical multiple regression analyses with right middle orbital gyrus entered first, followed by left middle orbital gyrus, right lateral orbital gyrus and left lateral orbital gyrus revealed the following: Gray matter volume for only the right middle orbital gyrus produced an R = 0.553, R² change = 0.306, F(1,21) = 9.27, P = 0.006, with a partial correlation...
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Table 3 Pearson correlations of orbital frontal cortex subregions and social cognitive and memory measures.

| Measures        | Left GR | Left MOG | Left LOG | Right GR | Right MOG | Right LOG |
|-----------------|---------|----------|----------|----------|-----------|-----------|
| Mach IV         | -0.307  | 0.313    | 0.492*   | -0.394  | 0.169     | 0.118     |
| WAIS-III SC     | -0.120  | 0.538**  | 0.054    | 0.025   | 0.553**   | 0.141     |
| WMS-III         |         |          |          |          |           |           |
| Immediate       | 0.348   | 0.237    | -0.043   | 0.297   | 0.562**   | -0.187    |
| Delayed         | 0.294   | 0.318    | -0.147   | 0.176   | 0.445**   | -0.170    |
| Recognition     | 0.152   | 0.445*   | -0.252   | 0.048   | 0.481*    | -0.355    |
| Doors and people|        |          |          |          |           |           |
| People          | 0.343   | 0.499*   | -0.002   | 0.297   | 0.540*    | 0.063     |
| Shapes          | 0.030   | 0.369    | -0.053   | -0.063  | 0.477*    | -0.074    |
| Names           | 0.077   | 0.465*   | -0.103   | 0.091   | 0.443*    | -0.102    |
| Doors           | -0.053  | 0.371    | -0.204   | 0.297   | 0.381     | 0.271     |

*P < 0.05; **P < 0.01
Note: GR = gyrus rectus; MOG = lateral orbital gyrus; Mach IV = Machiavellianism; MOG = m middle orbital gyrus; WAIS-III SC = Wechsler Intelligence Scale—Third Edition Social Comprehension; WMS-III = Wechsler Memory Scale—Third Edition.

of 0.353 and semi-partial correlation of 0.297. These correlation values indicated that the right middle orbital gyrus uniquely accounted for \( \sim 12.46 \) and 8.8% of the variance in WAIS-III social comprehension scores.

For the dependent variable, WMS-III immediate memory, with independent variables, right middle orbital gyrus entered first, followed by left middle orbital gyrus, right lateral orbital gyrus and left lateral orbital gyrus, hierarchical regression revealed the following: grey matter volume for only the right middle orbital gyrus produced an \( R = 0.562, R^2 \text{change} = 0.315, F(1,20) = 9.22, P = 0.007 \), with a partial correlation of 0.516 and semi-partial correlation of 0.485. These correlation values indicated that the right middle orbital gyrus uniquely accounted for 30.25 and 28.52% of the variance in WMS-III immediate memory scores.

Last, we employed hierarchical regression to examine the question of a double dissociation between OFC anatomy and sociality: that is, whether grey matter volume of two distinct regions (left lateral orbital gyrus, right middle orbital gyrus) differentially predicted scores on two tasks (Mach IV, WAIS-III social comprehension). For Mach IV, left lateral orbital gyrus grey matter predicted first as an independent variable, predicted Mach IV scores (standardized \( B = 0.499, t = 2.42, P = 0.027 \)) whereas right middle orbital gyrus grey matter did not (\( P > 0.35 \)). For social comprehension, right middle orbital gyrus grey matter, entered first as an independent variable, predicted WAIS-III social comprehension (standardized \( B = 0.552, t = 2.97, P = 0.008 \)), whereas left lateral orbital grey matter did not (\( P > 0.50 \)). These hierarchical regression results pointed to a double dissociation of anatomy and function, whereby grey matter of left lateral but not right middle orbital gyrus predicted Mach IV but not WAIS-III social comprehension scores, in stark contrast to the right middle but not left lateral orbital grey matter which predicted WAIS-III social comprehension but not Mach IV scores.

**DISCUSSION**

The principal question addressed in the current study centered on whether Machiavellian personality traits, on one hand and social comprehension on the other hand, may each reflect dissociable functions of the lateral and middle orbital gyr, respectively. In fact, the current study employed hierarchical regression as a specific test for a double dissociation between grey matter volumes of the left lateral orbital gyrus and the right middle orbital gyr grey matter with Machiavellian personality traits and psychometric tests of cognition, particularly intelligence tests of social reasoning and judgment. The results lent support for a double dissociation: on one hand, increased grey matter volume of the left lateral orbital gyrus but not the right middle orbital gyrus predicted higher levels of Machiavellianism but not social comprehension. On the other hand, increased grey matter volume of the right middle orbital gyrus but not the left lateral orbital gyrus predicted higher levels of social comprehension but not Machiavellian personality characteristics.

Prior MRI studies have also examined the question of dissociated functions in the lateral and medial OFC. For example, Spitzer et al. (2007) found that higher levels of Machiavellian traits predicted heightened left lateral OFC activation in subjects’ performance on a norm compliance task under the threat of social punishment. These results complement the current finding linking increased left lateral orbital gyrus grey matter volume and higher levels of Machiavellian personality traits. Likewise, O’Doherty and colleagues reported heightened activation of the lateral but not medial area of the OFC following a punishing outcome, whereas a rewarding outcome elicited increased activation of the medial but not lateral area of the OFC (O’Doherty et al., 2001). Elliot and colleagues (2000) in their literature review proposed differential fMRI engagement of medial OFC in a diversity of higher order cognitive tasks, and such a relationship comports well with the current finding linking increased middle orbital grey matter volume with better performance on psychometric tests of social comprehension and declarative episodic memory.

These findings suggested individual differences in OFC grey matter may be linked to performance on behavioral measures of various aspects of social cognition. For the Mach IV, the data showed a rather specific relationship of higher Machiavelli personality traits and larger grey matter volume for left lateral orbital gyrus, and to a lesser extent, though statistically insignificant, for left middle orbital gyrus. In fact, hierarchical regression analyses indicated \( \sim 34.57–38.44\% \) of the variance in Mach IV scores could be specifically explained by grey matter volume of left lateral orbital gyrus, with another \( \sim 16.73–23.23\% \) variance in the measurement of Machiavelli personality characteristics uniquely accounted for by left middle orbital gyrus grey matter volume. These values indicate that 51.3–61.67% of the variance in Mach IV scores could be uniquely accounted for by individual differences in grey matter volumes in left lateral and middle orbital gyr.
Against this backdrop, the current findings, which point to a double dissociation functions in lateral and medial orbital frontal gyri, suggest that each of these brain regions may make specific contributions to different aspects of social cognition. For example, Machiavelli personality traits tap a broad set of social attitudes and strategies that may be described as reflecting a mixture of selfishness and opportunism. For the Mach IV questionnaire, respondents rate their degree of agreement with 20 statements, such as ‘It’s hard to get ahead without cutting corners here and there’. ‘The best way to deal with people is tell them what they want to hear.’ Here the current results suggested the left lateral orbital gyrus as a uniquely important source of the OFC contribution to variation in Machiavelli personality traits. Indeed, the results provided evidence of a rather strong and specific relationship of left lateral orbital gyrus and Machiavelli characteristics, with neither the gyrus rectus nor the middle orbital gyrus gray matter volumes contributing to Mach IV scores. By comparison, for the psychometric measures of social comprehension and declarative memory, respondents perform various mental exercises that call for judgment and reasoning about social dilemmas, as assessed by the WAIS-III Picture Arrangement and Comprehension subtests, or learning and remembering new information such as stories, word pairs, names and faces of people, as measured by the WMS-III and the DPT. And here the current results suggested that gray matter volume in right middle orbital gyrus but not left lateral orbital gyrus accounted for a unique portion of the variance in social comprehension and declarative memory, as assessed psychometrically.

Thus, taken together, these findings help to parse social cognition into distinct but related domains of attitudes, preferences and personality traits, on one hand and information processing abilities, on the other, with each domain influenced by a specific OFC subregion. The pattern emerging from the current findings, then, is one in which individual differences in left lateral orbital gyrus volume influenced social attitudes embodied in Machiavelli personality traits, and variation in right middle orbital gyrus volume corresponded to information processing abilities related to learning and memory in general as well as reasoning and judgment particularly about social matters. The neural processes underlying this division of OFC anatomy and social and cognitive functions are, however, unknown. Researchers have emphasized the OFC as a key site, among other regions, in support of reward learning and instrumental conditioning that includes both non-social and social content (e.g. Behrens et al., 2009). This may reflect that cognitive and social processes are tightly linked, coevolving to favor a host of vital specialized functional adaptations that advanced fitness by promoting effective human transactions (Duchaine et al., 2006). Meeting of minds: the medial frontal cortex and social cognition. Nature Reviews Neuroscience, 7, 268–77.

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