# Mapping the self in the brain's default mode network

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## ABSTRACT

The brain's default mode network (DMN) has become closely associated with self-referential mental activity, particularly in the resting-state. While the DMN is important for such processes, it has functions other than self-reference, and self-referential processes are supported by regions outside of the DMN. In our study of 88 participants, we examined self-referential and resting-state processes to clarify the extent to which DMN activity was common and distinct between the conditions. Within areas commonly activated by self-reference and rest we sought to identify those that showed additional functional specialization for self-referential processes: these being not only activated by self-reference and rest but also showing increased activity in self-reference versus rest. We examined the neural network properties of the identified 'core-self' DMN regions—in medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), and inferior parietal lobule—using dynamic causal modeling. The optimal model identified was one in which self-related processes were driven via PCC activity and moderated by the regulatory influences of MPFC. We thus confirm the significance of these regions for self-related processes and extend our understanding of their functionally specialized roles.

The brain's default mode network (DMN) has become almost synonymous with self-referential mental activity. The DMN – composed primarily of posterior cingulate cortex (PCC), medial prefrontal cortex (MPFC), and the inferior parietal lobule (IPL) – was first identified by an analysis of nuclear imaging studies that showed that these brain regions consistently displayed higher levels of activity during passive task conditions than during conditions that required goal-directed task performance (Shulman et al., 1997; Raichle et al., 2001). When initially described it was hypothesized that the DMN might support a range of self-related mental processes, including unconstrained self-referential thought, but also broader self-related processes such as 'monitoring of the external environment, body, and emotional state' (Shulman et al., 1997). Since then, the link between self-referential thought and DMN has received particular empirical attention, likely because of the intuitive appeal of the idea that a dedicated brain system might support the human sense of self. This view of the DMN has been reinforced by functional magnetic resonance imaging (fMRI) studies of self-referential cognitive tasks that have reported brain activation patterns resembling resting-state characterizations of the DMN (Harrison et al., 2008). Similarly, imaging studies that have examined

subjective reports of mind-wandering have noted substantial overlap with DMN regions (McKiernan et al., 2006; Mason et al., 2007).

While it is generally accepted that self-related mental processes are prominent at rest, disentangling the processes is not straightforward. It has been complicated by the convention of using the resting-state as an imaging baseline state, which has impeded the examination of rest as a condition in its own right (Callard et al., 2012). As such, many important questions remain unanswered. Within the DMN, for instance, which components are truly common between resting and self-referential mental states? The few studies that have compared the states suggest that the degree of anatomical overlap between them might be relatively discrete in relation to the diffuse pattern of brain activity that characterizes the DMN at rest (D'Argembeau et al., 2005; Harrison et al., 2008; Whitfield-Gabrieli et al., 2011).

Studies that have directly compared rest and self-referential conditions, within the same experiment, have identified overlapping activation in a region of mid-MPFC, intermediate between ventral and dorsal MPFC (D'Argembeau et al., 2005; Whitfield-Gabrieli et al., 2011). Self-referential tasks often activate the PCC (Harrison et al., 2008; Whitfield-Gabrieli et al., 2011), but generally not over-and-above the region's high level of resting-state activity (D'Argembeau et al., 2005; Whitfield-Gabrieli et al., 2011). The PCC has among the highest levels of metabolic activity and connectivity of all brain regions, and as such has been argued to be the core node of the DMN (Hagmann et al., 2008; Tomasi and Volkow, 2011; Leech and Sharp, 2014). It is

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unclear, however, to what extent it makes specific contributions to self-referential activity beyond its broader role as one of the brain's key network hubs.

The aims of our study were three-fold. First, by employing a single experimental task design comprising resting-state, self-referential, and non-self-referential conditions, we sought to clarify the extent to which brain activity was both common and distinct between rest and self-reference—relying on classical fMRI subtraction and conjunction tests. Second, within the common areas evoked by rest and self-reference, we sought to identify regions that showed evidence of additional functional specialization for self-reference, defined by their showing greater activation during self-referential task performance versus rest. Finally, we aimed to examine the neural network properties of the core-self-related regions using deterministic dynamic causal modeling (DCM). In particular, we sought to establish the relative influences of MPFC versus PCC—to determine whether self-related processes were best considered as being driven via MPFC or PCC and to determine how self-reference modulated efferent connectivity from these core-self nodes.

## Materials and methods

### Participants

Ninety-six adolescents and young adults, 15–25 years of age, were recruited for the study and completed the full imaging protocol. Participants were considered eligible if they were (i) without current or past diagnosis of mental illness (Structured Clinical Interview for DSM-IV; First et al., 1997), (ii) competent English speakers, (iii) not taking psychoactive medication, (iv) not pregnant, and (v) had no further contraindications to MRI. Participants (and their parents if they were under 18 years of age) provided their informed consent to participate in the study, which was approved by the Melbourne Health Human Research and Ethics Committee. Of the 96 participants who completed the paradigm, 3 were subsequently excluded due to excessive head movement during scanning, and 5 due to poor performance on the external attention control task (defined as less than 85% accuracy). The final composition of the sample was 88 participants (46 female) with a mean age of 20.1 years (S.D. 2.9 years).

### Paradigm design

Participants completed an fMRI task composed of three experimental conditions: self-reference, non-self-referential external attention, and rest-fixation. In the self-referential condition, participants were presented with a trait adjective and asked whether or not the word described them, similarly to previously published paradigms (Kelley et al., 2002; Heatherton et al., 2006; Moran et al., 2006; Whitfield-Gabrieli et al., 2011). Words were drawn from a frequently used list of trait adjectives (Anderson, 1968)—we selected 96 words distributed around the median rating for 'likeableness' reported in the original dataset, from the subset of words rated as most 'meaningful' (see Supplementary Table 1). The words were selected so as not to be extremely favorable or unfavorable, with the intention of heightening self-reflection (trait adjectives included words such as 'skeptical,' 'perfectionistic,' and 'lucky'). Participants viewed 8 blocks of 6 words, presented for 5 s each, and responded to the question, 'Does this word describe you?', by pressing the left or right button on the button-box. In the external attention condition, participants viewed 8 blocks of 6 words, also presented for 5 s each, and responded to the question, 'Does this word have 4 or more vowels?'. This condition was designed to require a high level of attention; the intent being to minimize the likelihood of task-independent thoughts during its performance, which are known to correlate with increased DMN activity (McKiernan et al., 2003; Mason et al., 2007). The 2 lists of 48 words that formed the self-referential and external attention conditions,
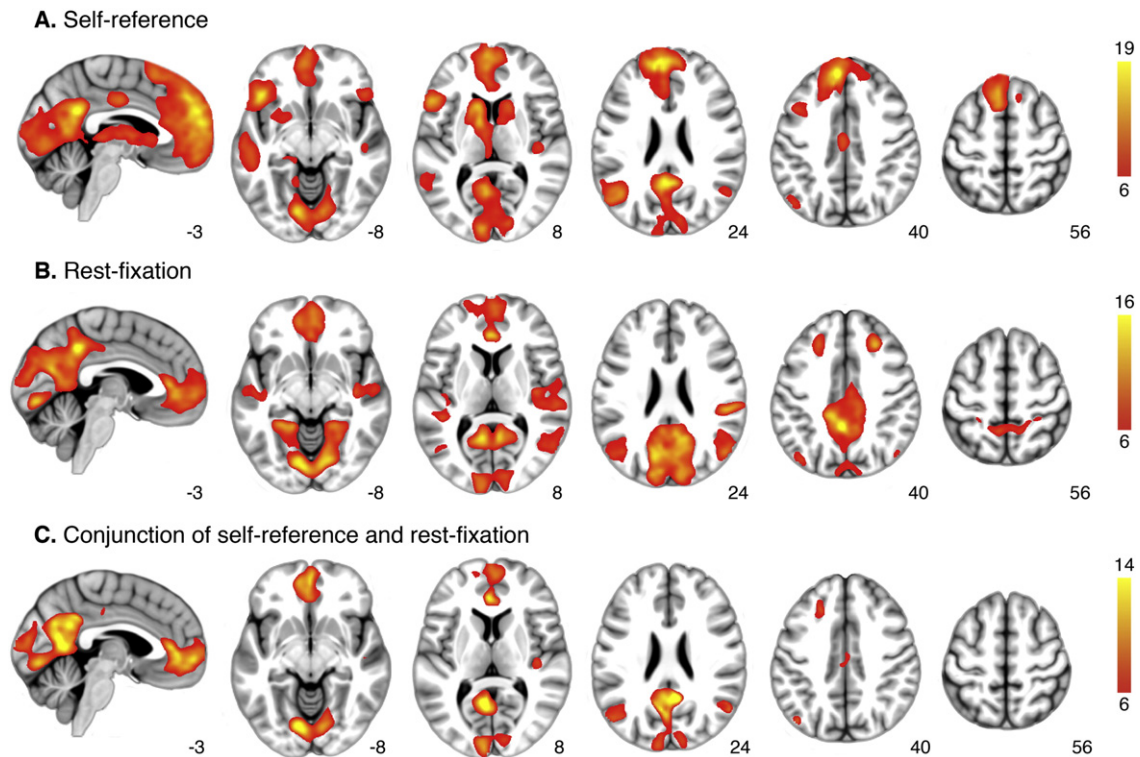


**Fig. 1.** Activation maps for the self-referential and rest-fixation tasks. Activations to self-reference (A) and rest-fixation (B), relative to external attention baseline, are illustrated, along with a conjunction map for self-reference and rest-fixation (C). All activations are thresholded at $P_{FWE} < 0.001$. Left = left.
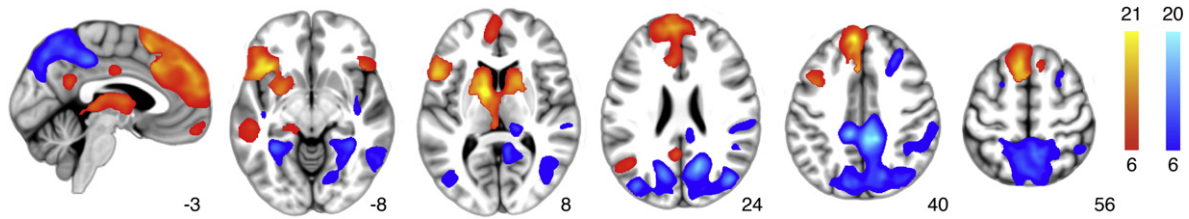
**Fig. 2.** Comparison of the self-reference and rest-fixation conditions. Activations for self-reference *minus* rest-fixation are shown in orange, and rest-fixation *minus* self-reference in blue. All activations are thresholded at $P_{FWE} < 0.001$. Left = left.

which were matched on valence and number of vowels, were counterbalanced across participants. Each 32 s block (2 s instruction followed by 6 words presented for 5 s each) was interspersed with a 10 s rest-fixation block in which participants were asked to fixate on a centrally presented cross-hair. Behavioral data (accuracy and response-times) were analyzed with Stata 13.1 (StataCorp, College Station, USA).

*Image acquisition*

A 3 T General Electric Signa Excite system equipped with an 8-channel phased-array head coil was used in combination with ASSET parallel imaging. The functional sequence consisted of a single-shot gradient-recalled EPI sequence in the steady state (repetition time, 2 s; echo time, 35 ms; and pulse angle, 90°) in a 23-cm field-of-view, with a 64 × 64-pixel matrix and a slice thickness of 3.5 mm (no gap). Thirty-six interleaved slices were acquired parallel to the anterior–posterior commissure line with a 20° anterior tilt to better cover ventral prefrontal cortical brain regions. The total sequence time was 11 min 22 s, corresponding to 341 whole-brain echo-planar imaging volumes. The first four volumes from each run were automatically discarded to allow for T1 equilibration effects. A T1-weighted high-resolution anatomical image was acquired for each participant to assist with functional time-series co-registration (140 contiguous slices; repetition time, 7.9 s; echo time, 3 s; flip angle, 13°; in a 25.6-cm field-of-view, with a 256 × 256 pixel matrix and a slice thickness of 1 mm). To assist with noise reduction and head immobility, all participants used earplugs and had their heads supported with foam-padding inserts.

*Image preprocessing*

Imaging data were transferred and processed on an Apple Macintosh platform running MATLAB version 8.2 (The MathWorks Inc., Natick, USA). Preprocessing was performed with Statistical Parametric Mapping software (SPM12; Wellcome Trust Centre for Neuroimaging, UK). Motion correction was performed by aligning each participant's time-series to the first image using least-squares minimization and a six-parameter rigid-body spatial transformation. Participants' data were excluded if movement in the translational or rotational planes exceeded 2 mm or 2°, respectively. These realigned functional images were then co-registered to each participant's respective T1 anatomical scan, which were segmented and spatially normalized to the International Consortium for Brain Mapping template using the unified segmentation approach. The functional images were transformed to 2 mm isotropic resolution and were smoothed with a 5–mm full-width-at-half-maximum Gaussian filter.

*General linear modeling*

For our GLM analysis, we used SPM 12 to examine and compare the self-referential and rest-fixation conditions, with the external attention condition acting as the implicit baseline. The external attention condition was as an appropriate baseline condition for our interests, being matched with self-reference on stimulus features, but requiring specific attentional demands, and designed to suppress the likelihood of task-

independent activity. For each participant primary regressors for the self-referential and rest-fixation conditions were created by specifying the onset and duration of each block, followed by convolution with a canonical hemodynamic response function, and use of a high-pass filter set at 128 s to remove low-frequency drifts. Parameter estimates were calculated at each voxel using the general linear model (GLM) and local autocorrelation correction. Second-level analysis identified voxels that were activated in the self-referential and rest-fixation blocks, and that showed greater activation in the self-referential compared to the rest-fixation blocks and vice versa. The self-referential greater than rest-fixation contrast was masked by the self-referential contrast (equivalent to self-reference *minus* external attention) to exclude motor and attentional processes common to the self-referential and external attention tasks. We used conjunction-null tests to examine conjunctions between rest-fixation and self-reference and to examine conjunction between rest-fixation and self-reference *minus* rest-fixation. For all GLM analyses, highly stringent whole-brain, family-wise error (FWE) corrected statistical thresholds were applied ($P_{FWE} < 0.001$).

*Dynamic causal modeling*

We used DCM to determine how self-related processes drove and modulated a network comprised of the regions determined by the last of the above analyses: regions that showed significant conjunction between activation to rest-fixation and activation to self-referential *minus* rest-fixation (i.e, that were not only activated by self-reference and rest-fixation, but showed additional activation to self-reference over-and-above rest-fixation). We defined the VOIs according to their activation by what we have termed 'broad self'—equivalent to the main effect of self-reference and rest-fixation. We examined how a network composed of these VOIs was driven by broad self, and how it was modulated by the self-referential condition. The group coordinates for the VOIs were the maxima for the main effect of self-reference and rest-fixation in MPFC ($x = -4$, $y = 58$, $z = 16$), PCC ($x = -4$, $y = -50$, $z = 26$), and left IPL ($x = -48$, $y = -68$, $z = 28$). For each
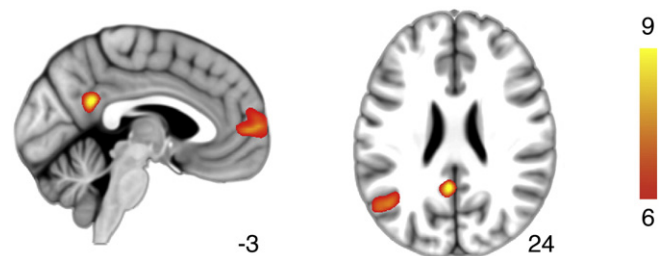


**Fig. 3.** Conjunction analysis of the rest-fixation and self-reference *minus* rest-fixation contrasts. The conjunction test identified regions that were not only active in rest-fixation (compared to the external attention task), but that also showed greater activation to self-reference relative to rest-fixation. Such activity was demonstrated in MPFC, ventral PCC, and left IPL. Activations are thresholded at $P_{FWE} < 0.001$. Left = left.
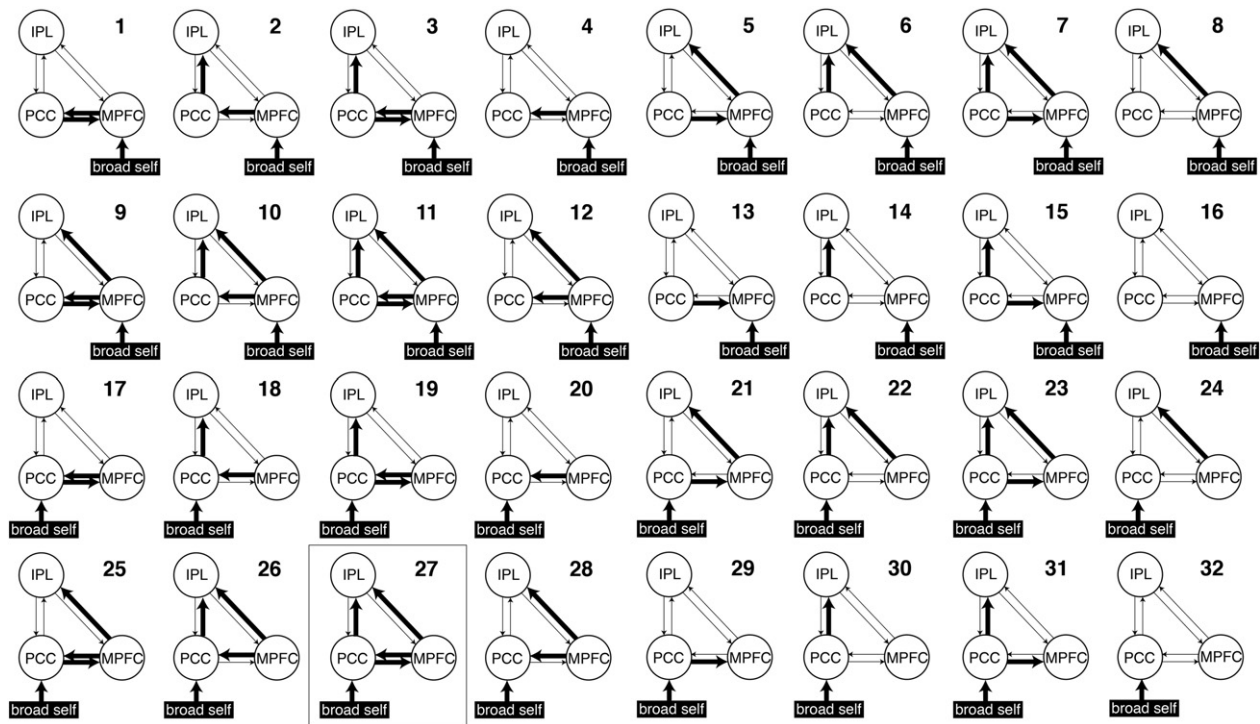
**Fig. 4.** The DCM candidate model-space. Network connections between the core-self regions were elaborated in 32 models, which varied according to whether broad self (rest-fixation and self-reference) drove network activity via MPFC or PCC, and whether self-reference modulated efferent connections from MPFC to PCC, IPL, both, or neither, and connections from PCC to MPFC, IPL, both, or neither (i.e., a 2 × 4 × 4 = 32 candidate model-space). Bayesian model selection favored model 27 (see Fig. 5).

participant, we extracted regional time-series, summarized as the first eigenvariate of voxels that showed significant activation to self-reference and rest-fixation ($P < 0.01$) within 5 mm of the subject-specific maxima, which were themselves no more than 10 mm from the group maxima. By this process we extracted time-series for all VOIs from 82 of the 88 participants.

A three-region deterministic DCM was specified for each participant with bidirectional endogenous connections between MPFC, PCC, and IPL. We developed a 32 candidate model-space composed of models where broad self (self-reference and rest-fixation) drove either MPFC or PCC, and where self-reference modulated efferent connections from MPFC to PCC, IPL, both, or neither, and connections from PCC to MPFC, IPL, both, or neither (i.e., a 2 × 4 × 4 = 32 candidate model-space— see Fig. 4).

The models were compared using random-effects Bayesian model selection (BMS) in DCM12. We computed posterior probabilities and protected exceedance probabilities at the group level (Stephan et al., 2009; Rigoux et al., 2014). The protected exceedance probability, which represents the probability that a given model is more frequent than the others (above and beyond chance), was our primary measure for model selection (Rigoux et al., 2014). The strength of effective connectivity and modulatory effects were summarized using random-effects Bayesian model averaging (BMA). The model space was partitioned according to whether broad self drove MPFC or PCC, and average connectivity estimates (weighted by their posterior model probabilities) were obtained from models in the winning family (Penny et al., 2010).

## Results

Mean accuracy on the external attention condition was 97.0% (S.D. 3.1%). Mean reaction time for the external attention condition was 1.92 s (range of participant means 1.08–3.09 s), which was, as expected,

longer than the mean reaction for the self-referential condition (1.68 s; range 1.08–2.87 s; paired t-test: $t_{174} = 4.3$, $P < 0.001$).

### Mapping common and distinct brain activations to rest and self-reference

Conventional general linear model (GLM) time-series analyses and group-level subtraction and conjunction tests were used to identify those brain regions whose activity was either common or distinct between the self-referential and rest-fixation conditions. As shown in Fig. 1A and B, both the self-referential and rest-fixation conditions (relative to external attention baseline) were associated with widespread and broadly similar patterns of activation encompassing the characteristic anatomical features of the human DMN: namely, the anterior medial wall cortex (ventral to mid-MPFC), posteromedial cortex (incorporating the PCC and precuneus), and IPL (see Supplementary Table 2). A conjunction analysis was used to determine which regions demonstrated consistently significant effects across both comparisons: that is, self-referential and rest-fixation versus external attention baseline. This test confirmed a highly robust pattern of common activation between the self-referential and rest-fixation conditions, with the most pronounced effects being isolated to the ventral PCC and ventral MPFC, but also extending to the retrosplenial PCC, rostral anterior and mid-cingulate cortex, IPL, dorsal posterior insular cortex, and dorsal and ventral cuneus (Fig. 1C).

Direct comparison of the self-referential and rest-fixation conditions – via classical subtraction tests – identified brain regions that showed significant differences in activation between the conditions (Fig. 2, Supplementary Table 3). Regions that demonstrated greater relative activation in the self-referential condition encompassed primarily left-hemisphere-dominant effects, including large expanses of the dorsal MPFC and lateral prefrontal cortex (including frontal operculum), left IPL, left superior temporal sulcus, dorsal caudate nucleus, left (primarily

midline) thalamus, hippocampus, medial orbitofrontal cortex, and a well-circumscribed area of ventral PCC.

In comparison, regions that demonstrated greater relative activation in the rest-fixation condition encompassed primarily right-hemisphere-dominant effects, including most of the posterior medial wall cortex (precuneus and dorsal PCC), with the exception of the ventral PCC. Additional significant differences included the intra- and superior parietal cortex, right somatosensory cortex, ventral posterior insular cortex, mid superior temporal cortex, posterior parahippocampal cortex, right posterolateral thalamus, and a small area of dorsal (superior) prefrontal cortex.

To more specifically address the notion of functionally specialized DMN activity during self-reference, we determined which of the brain regions commonly activated during rest-fixation and self-reference also demonstrated greater relative activation during self-reference by performing a two-way conjunction analysis of the rest-fixation (versus external attention baseline) and the self-reference *minus* rest-fixation contrasts. Results from this conjunction test identified three significant 'core-self' regions ($P_{FWE} < 0.001$): mid-MPFC (peak coordinate, $x = 2$, $y = 60$, $z = 10$; cluster size = 269; peak t-value = 8.1), ventral PCC (peak coordinate, $x = -4$, $y = -50$, $z = 26$; cluster size = 106; peak t-value = 9.1), and left IPL (peak coordinate, $x = -50$, $y = -66$, $z = 26$; cluster size = 96; peak t-value = 7.3)—see Fig. 3. Note that while right IPL was activated by both rest-fixation and self-reference, it did not show relatively greater activation to self-reference versus rest-fixation.

*Dynamic causal modeling analysis*

The three regions identified in our conjunction analysis were included in a neural network and subjected to examination using DCM to determine the network's structure. DCM uses Bayesian procedures to infer effective connectivity between brain regions – distinguishing between endogenous and context-specific connectivity – and to determine the optimal model from a set of candidate models (Friston et al., 2003; Penny et al., 2004). Our primary rationale for implementing this approach was to determine how MPFC and PCC contributed to the core-self network: whether the network was driven via MPFC or PCC, and how self-reference modulated efferent connectivity primarily from MPFC and PCC. BMS showed that model 27 (Fig. 4) outperformed the other models, with a posterior expected probability of 0.17, and a

protected exceedance probability of 0.90 (Fig. 5). This model contained a driving influence of 'broad self' (self-referential and rest-fixation) on PCC, with self-reference modulating both of the efferent connections from PCC and MPFC.

Parameter estimates were calculated using BMA over a model-space partitioned according to whether broad self drove PCC or MPFC. We found clear evidence to support broad self driving PCC, with this family of models having an expected probability of 0.79 and exceedance probability of 1. (Note that when model selection was restricted to the winning family, the optimal model remained the same, with an expected probability of 0.24 and posterior exceedance probability of 0.88.) BMA over the 16 candidate models in the winning family demonstrated significant positive endogenous influences from PCC to MPFC – both directly and indirectly via IPL – and significant negative endogenous influences from MPFC to PCC. The modulatory effects of self-reference were such that PCC had a greater positive influence on MPFC and IPL, and MPFC had a greater negative influence on PCC (Fig. 6, Table 1).

## Discussion

We have demonstrated both commonality and functional specialization within a core set of DMN regions during rest and self-referential thought, using a carefully tailored experimental design in a large participant sample. Specifically, we identified a discrete set of regions – PCC, MPFC, and left IPL – whose activity was common to these two conditions, but also increased when thinking explicitly about the self. Further, neural network modeling indicated that the activity of this tripartite 'core-self' system was driven primarily via activity of the ventral PCC, whose activity had a positive influence on activity in the MPFC and IPL. We demonstrated that the MPFC had a specific moderating functional influence on the ventral PCC, acting to regulate its activity across the resting and self-referential conditions, and to an even greater extent during self-reference.

*Common signatures of DMN function during rest and self-reference*

The self-referential and rest-fixation conditions evoked overlapping activity across the DMN, encompassing large expanses of anterior and posterior medial wall cortex, and inferior parietal areas, consistent with the results of prior studies (D'Argembeau et al., 2005; Whitfield-Gabrieli et al., 2011). The results are also similar to those reported by
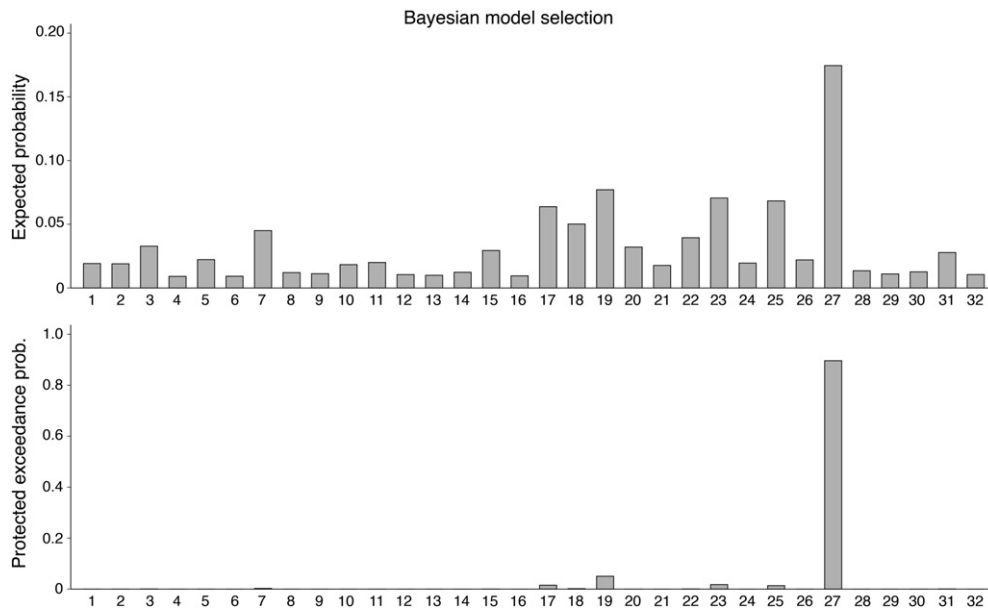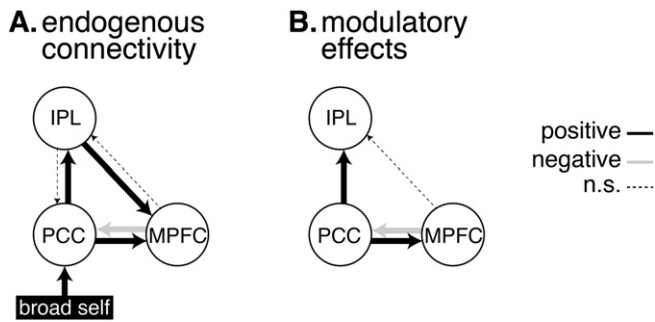


**Fig. 5.** Bayesian model selection. BMS clearly favored model 27 (see Fig. 4 for models), which had an expected probability of 0.17, and a protected exceedance probability of 0.90.

**Fig. 6.** Parameter estimates for the winning model. BMA over the family of models in which broad self drove PCC showed endogenous connectivity comprised PCC having positive influence on MPFC – both directly and indirectly via its influence on IPL – and MPFC having negative influence on PCC (A). These effects were enhanced by the modulatory effects of self-reference: PCC had a greater positive influence on MPFC and IPL, and MPFC had a greater negative influence on PCC (B).

our team (Harrison et al., 2008), where the same areas were mapped as part of a common DMN response across conditions of continuous rest, rest-fixation versus goal-directed cognitive performance, and self-referential activity invoked by moral decision-making. The anatomical consistency of such findings provides strong support for the notion that ventral PCC and MPFC represent generalizable neural correlates of resting-state and self-referential mental activity, and their representation in the DMN likely reflects a true neural correlate of unconstrained self-referential thought: as frequently hypothesized, but rarely directly demonstrated.

Other brain regions are often associated with the DMN; their presence depending on whether the DMN was mapped under continuous resting-state conditions or as signal changes relative to goal-directed task conditions (i.e., 'deactivations'), and on the analytic approach employed (Harrison et al., 2008). Such DMN-associated regions include the retrosplenial–temporal cortical system, which supports episodic memory, and areas of the mid and anterior cingulate cortex (Buckner et al., 2008; Harrison et al., 2008; Harrison et al., 2011). The additional regions we have mapped by conjunction of the self-referential and rest-fixation conditions correspond to this broader characterization of the DMN, with the exception of the common effects we observed within the primary visual system and posterior insular cortex. In the former instance, it is likely that the common activation in visual cortex represents an idiosyncratic feature of our task: the visual search feature of external attention appears to have suppressed activity in the primary visual cortex relative to self-reference and rest-fixation. The posterior insular cortex, as a zone of convergence for interoceptive information, has complex functions (Craig, 2002). In representing the internal somatic state, it has a role in detecting salience (Liberati et al., 2016); and the salience network has been demonstrated to operate independently of the DMN (Sridharan et al., 2008; Menon and Uddin, 2010). Co-activation of the posterior insular cortex with the DMN has, however, been observed in experiments that have compared rest-fixation

**Table 1**
DCM parameter estimates of endogenous and modulatory connections.

| Connection type | Mean | S.D. | 95% C.I. | t-value | p-value |
|---|---|---|---|---|---|
| Endogenous parameters | | | | | |
| MPFC → PCC | −0.18 | 0.23 | −0.23 to −0.13 | −7.11 | <0.0001 |
| MPFC → IPL | −0.04 | 0.22 | −0.09 to 0.01 | −1.52 | 0.13 |
| PCC → MPFC | 0.20 | 0.20 | 0.16 to 0.25 | 9.26 | <0.0001 |
| PCC → IPL | 0.33 | 0.22 | 0.28 to 0.38 | 13.59 | <0.0001 |
| IPL → MPFC | 0.11 | 0.22 | 0.06 to 0.15 | 4.46 | <0.0001 |
| IPL → PCC | 0.01 | 0.33 | −0.06 to 0.08 | 0.24 | 0.81 |
| Modulatory parameters | | | | | |
| MPFC → PCC | −0.53 | 0.92 | −0.73 to −0.32 | −5.14 | <0.0001 |
| MPFC → IPL | −0.07 | 0.51 | −0.18 to 0.04 | −1.20 | 0.23 |
| PCC → MPFC | 0.62 | 0.90 | 0.42 to 0.82 | 6.24 | <0.0001 |
| PCC → IPL | 0.56 | 1.09 | 0.32 to 0.80 | 4.67 | <0.0001 |

with attentionally demanding cognitive tasks, with high levels of goal-directed attention argued to suppress somatic self-awareness (Harrison et al., 2011). Consistent with this view, increased activity during rest-fixation and self-reference in the posterior insular suggests that broader aspects of the self were being drawn upon during the self-referential condition, beyond purely cognitive self-representations.

### Distinct signatures of DMN function during rest and self-reference

Comparison of activations to self-reference versus rest-fixation confirmed greater involvement of ventral PCC, left IPL, and a large area extending from mid to dorsal MPFC. We also identified regions outside of the conventional DMN that contributed to self-referential processing as evoked by the specific demands of our task. These regions included the left dorsolateral and ventrolateral prefrontal cortex, left superior temporal sulcus, left thalamus, and bilateral caudate nucleus. While we accounted for task-related effects common to the self-referential and external attention tasks, these non-DMN activation differences, predominantly in the left hemisphere, likely resulted because the self-referential task invoked abstract language-based concepts of self. Participants were asked to make explicitly semantic judgments about themselves, processes that in imaging experiments evoke lateralized activation of dorsolateral prefrontal and temporo-parietal cortical systems (Binder et al., 1997).

In comparison, rest-fixation produced greater activation than self-reference in a broad area of posteromedial cortex (including dorsal PCC and most of precuneus), in superior parietal areas (including right-sided secondary somatosensory cortex), and in ventral posterior insular cortex. In the domain of self-related processes, these regions might support broader aspects of self-awareness that are suppressed during the self-referential task. This likely includes broad low-level monitoring of the environment ('surveillance' or 'watchfulness'), which has been hypothesized to represent an important function of the DMN (Gilbert et al., 2007; Buckner et al., 2008), and which previous studies have shown is supported by dorsal midline parietal areas (Hahn et al., 2007; Andrews-Hanna et al., 2010). In addition, increased regional activity in rest-fixation versus self-reference might also be associated with spatial and somatic body-awareness processes, a contention that is supported by the right-sided involvement of superior parietal regions. These broader resting-state functions are consistent with the original contention of Shulman and colleagues that the DMN not only supports 'unconstrained verbally mediated thoughts' but also 'monitoring of the external environment, body, and emotional state' (Shulman et al., 1997).

### A tripartite core-self system within the DMN

We have confirmed that MPFC, PCC, and left IPL have important roles in self-related processes by demonstrating their increased activity in rest-fixation (relative to external attention), but even greater activity in self-reference. DCM illuminated specific relationships between the regions, endorsing a model in which self-related processes were driven via PCC, which had a positive influence on activity in MPFC and IPL, and in which MPFC had a moderating influence on PCC. These influences were apparent in broad self-related processes (across rest-fixation and self-reference) and were further enhanced by explicit self-reference.

One of the hypothesized roles of PCC is the coordination of mental representations (Cavanna and Trimble, 2006); a function that the PCC, as one of the most anatomically and functionally connected regions of the brain – particularly with sensory association areas – is well placed to perform (Hagmann et al., 2008; Tomasi and Volkow, 2011; Leech and Sharp, 2014). Such internal representations stream through consciousness when we are at rest and come into sharper focus when we attend to particular representations, as in self-reference (Damasio, 2010). Left-sided IPL has a role in retrieving and integrating complex semantic information (Binder et al., 2009; Jouen et al., 2015), and its

involvement in the network suggests that such processes make an important contribution to the sense of self.

Our results also suggest that selective attention to sensory and semantic self-representations is regulated by activity in the MPFC, in a region confined to the medial aspect of Brodmann Area 10, or medial frontopolar cortex. MPFC has been argued to have a role in directing ongoing thought processes (Moran et al., 2013), and its frontopolar aspect, in particular, has been proposed to perform a 'gateway' function (Burgess et al., 2007a). It is said to be active when a person must choose to attend to one among competing sensory representations – from internal and external sources – and particularly in unstructured settings where the correct response is not readily known (Burgess et al., 2007a; Burgess et al., 2007b). Its transitional location between ventral MPFC, which regulates processes in the homeostatic-motivational domain, and dorsal MPFC, which represents higher cognitive 'reflective' thinking about oneself in relation to others (Moran et al., 2006; Northoff et al., 2006), suggests it integrates these information sources in performing this gateway role.

We suggest that this tripartite core-self system is responsible for engendering conscious self-awareness—providing a sense of oneself as a subjective agent in space and time. The system can be hypothesized to function as a network in which complex phenomena, such as self-representations, are dynamically accessible via PCC and IPL activity, and which are gated into conscious awareness by activity in the MPFC, as influenced by changing internal and external demands. The PCC, which has a unique anatomical position as a brain-wide connectivity hub (Hagmann et al., 2008; Tomasi and Volkow, 2011; Leech and Sharp, 2014), likely acts as the central conduit through which temporal and parietal cortical representations of self are made accessible to prefrontal cortical reflective systems; with a unitary notion of self defined by the large-scale integration of the network's activity (Carhart-Harris et al., 2014). Intriguingly, the ingestion of psychedelic drugs has been reported to reduce connectivity within the DMN (Carhart-Harris et al., 2012) and to reduce PCC-mediated network synchronization, the extent of which was reported to be correlated with a sense of dissolution of the self (Muthukumaraswamy et al., 2013). Further studies with careful design – including experimental disruption of the sense of self – will be needed to disambiguate the specific roles of PCC, MPFC, and IPL in structuring the self and its integration within the brain's default mode network. The implications of this ongoing research are likely to be profound with regards to 'big questions' in cognitive and clinical neuroscience about the construction of human self-consciousness.

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## Conflicts of interest

None of the authors have competing interests to declare.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.neuroimage.2016.02.022.

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