

Isolated from input: Transmodal cortex in the default mode network supports  
perceptually-decoupled and conceptually-guided cognition

Abbreviated Title – Distant memories

Charlotte Murphy<sup>1</sup>, Elizabeth Jefferies<sup>1</sup>, Shirley-Ann Rueschemeyer<sup>1</sup>, Mladen Sormaz<sup>1</sup>, Hao-ting Wang<sup>1</sup>, Daniel S. Margulies<sup>2</sup> and Jonathan Smallwood<sup>1</sup>

<sup>1</sup>Department of Psychology / York Neuroimaging Centre, University of York.

<sup>2</sup> Max Planck Research Group for Neuroanatomy & Connectivity, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig.

Address for correspondence:

Charlotte Murphy

Department of Psychology / York Neuroimaging Centre, University of York.

Email: [charlotte.murphy@york.ac.uk](mailto:charlotte.murphy@york.ac.uk)

Tel +44 (0)1904 323190

## Abstract

The default mode network supports a variety of mental operations such as semantic processing, episodic memory retrieval, mental time travel and mind-wandering, yet the commonalities between these functions remains unclear. One possibility is that the default mode network supports cognition that is independent of the immediate environment; alternatively or additionally, it might support higher-order conceptual representations that draw together multiple features. We tested these accounts using a novel paradigm that contrasted decisions based on perceptual and conceptual features, while separately manipulating whether these decisions were driven by features in the environment or recovered from memory. Task-based fMRI identified regions that responded when stimulus independence and semantic retrieval were combined: these included left and right angular gyri and left middle temporal gyrus. Although these sites were within the default mode network, they showed a stronger response to demanding memory judgements than to an easier perceptual task, contrary to the view that they support automatic aspects of cognition. In a subsequent analysis, we showed that these regions were located at the extreme end of a macroscale gradient, which describes gradual transitions from sensorimotor to transmodal cortex. This shift in the focus of neural activity towards transmodal default mode regions might reflect isolation from specific sensory inputs, both when decisions are guided by conceptual as opposed to perceptual features and when cognitive states are generated in the absence of input.

Key words: transmodal cortex, default mode network, semantic, conceptual processing, stimulus independence.

## 45    Highlights

- 46        • Brain regions supporting meaning overlap with stimulus independence.
- 47        • Bilateral angular gyri and left MTG respond strongly to both features of
- 48           cognition.
- 49        • These patterns reflect a shift in activity towards regions of transmodal cortex.
- 50        • Complex memory representations may emerge in cortical areas distant from
- 51           input.

## 1. Introduction

Although early studies characterized the default-mode network (DMN) as “task negative”, this network actively supports aspects of cognition (Spreng, 2012), including semantic processing (Binder, Desai, Graves, & Conant, 2009; Krieger-Redwood et al., 2016), episodic recollection (Rugg & Vilberg, 2013), working memory (Konishi, McLaren, Engen, & Smallwood, 2015; Spreng et al., 2014; Vatansever, Menon, Manktelow, Sahakian, & Stamatakis, 2015), autobiographical planning (Spreng, Gerlach, Turner, & Schacter, 2015; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010), self-generation of emotion (Engen, Kanske, & Singer, 2017) and imagining the future or the past (Schacter & Addis, 2007). Although we lack an overarching account of a core function for the DMN, many of these situations involve memory retrieval – i.e., a requirement to focus cognition on previously-encoded knowledge, as opposed to information in the external environment. In line with this account, many regions within or allied to the DMN are considered to be heteromodal ‘hubs’ for memory-related processes, including the posterior cingulate cortex (Leech, Braga, & Sharp, 2012; Leech & Sharp, 2014), angular gyrus (Binder & Desai, 2011; Bonnici, Richter, Yazar, & Simons, 2016; Seghier, 2013), hippocampus (Moscovitch, Cabeza, Winocur, & Nadel, 2016) and anterior temporal lobes (Lambon Ralph, Jefferies, Patterson & Rogers, 2017; Patterson, Nestor & Rogers, 2007; Visser, Jefferies, & Lambon Ralph, 2010). In addition, cognitive states that activate the DMN tend to involve meaningful content that has personal relevance.

The current study was motivated by the hypothesis that there might be common neurocognitive processes underpinning perceptually-decoupled and conceptually-guided cognition in the DMN. During states of episodic recollection, we recreate past experiences that involve places, objects and people not currently present in the environment. Consequently, memory retrieval might necessitate a process of decoupling from sensory-motor systems, allowing cognition to be generated internally in a way that diverges from what is going on around us. These perceptually-decoupled states might recruit brain regions whose neural computations are functionally independent, or distant, from systems important for perceiving and acting. This is consistent with the observation that the distributed regions of the DMN are maximally distant from primary visual and motor cortex,



both in terms of their pattern of functional connectivity and in their geodesic distance across the cortical surface (Margulies et al., 2016).

In addition, DMN regions might support higher-order representations with predictive value across multiple situations and modalities, which integrate features from diverse sensory-motor regions. Contemporary accounts of semantic representation envisage an interaction between unimodal brain regions that support knowledge about specific features (e.g., knowledge that BANANAS are YELLOW and CURVED in visual cortex) and heteromodal regions within or allied to the DMN, which extract deeper similarity structures across these domains (i.e., allow us to understand that BANANA and KIWI are conceptually related, despite salient differences in colour, shape etc.). This view is also consistent with the observation that DMN lies at the extreme end of a gradient from heteromodal to unimodal cortex (Margulies et al., 2016), since increasingly abstract and complex representations might be formed at greater distances along the gradient, as the influence of specific features and modalities is reduced (Buckner & Krienen, 2013; Margulies et al., 2016; Mesulam, 1998). Within the DMN, angular gyrus (Binder & Desai, 2011; Bonner et al., 2013) and anterior temporal cortex (Lambon Ralph et al., 2017; Patterson et al., 2007) are both implicated in heteromodal semantic processing. However, their roles remain controversial since other regions such as left inferior frontal gyrus and posterior aspects of the temporal lobe frequently show stronger task-induced activation in fMRI. Angular gyrus, in particular, typically shows a pattern of task-induced deactivation, which is greater for harder judgements in both semantic and non-semantic tasks (Humphreys et al., 2015; Humphreys & Lambon Ralph, 2015). In addition, despite commonalities in the intrinsic connectivity of these regions, differences in semantic content have been proposed although not broadly accepted (Jackson, Hoffman, Pobric & Lambon Ralph, 2016): the anterior temporal lobes might support object identification, while angular gyrus is potentially more sensitive to thematic associations (Davey et al., 2015; Schwartz et al., 2011).

In this study, we contrasted situations designed to maximise two potential aspects of DMN function – i.e., sensory-motor decoupling and/or the need to focus cognition on conceptual identity as opposed to simple perceptual features. Our experiment builds on prior work by Konishi and colleagues (2015), who showed DMN

activation when participants recalled the location of simple shapes (triangles, squares and circles), rather than performing a perceptual match. Since the recall task was more demanding, these results contradict the view that DMN only supports easy or automatic aspects of cognition. The current study extended this paradigm by varying the information to be encoded and retrieved. Participants made match-to-sample judgements based on a perceptual feature (colour) or conceptual categories. We also manipulated whether these decisions were made when the relevant information was on the screen (0-back) or when information had to be retrieved from memory (1-back; see Figure 1).

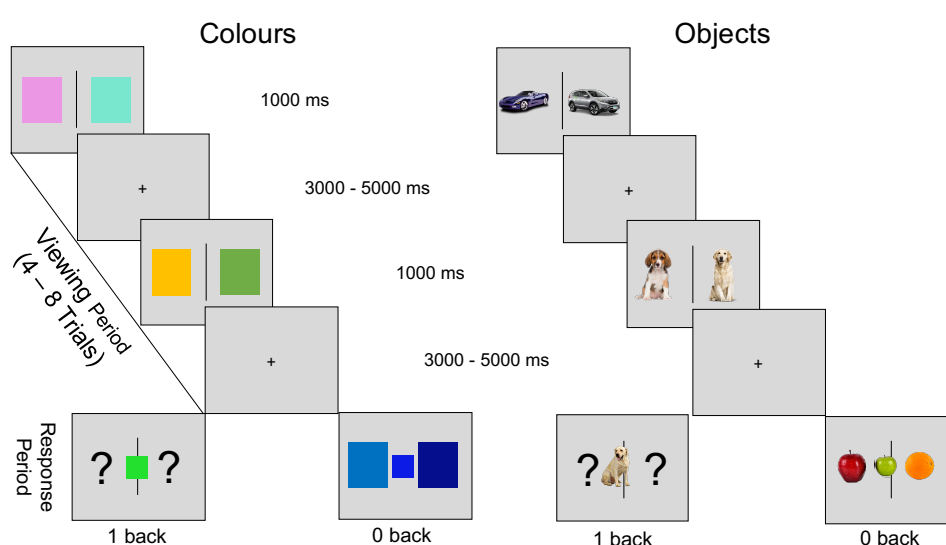


Figure 1

Our aim was to establish whether regions sensitive to perceptual decoupling and conceptual retrieval lay within the DMN, and whether these effects were located in overlapping or distinct regions. We also characterized the whole-brain maps from these manipulations in terms of their position on the macro-scale gradient from unimodal to heteromodal cortex described by Margulies et al. (2016). This allowed us to test the hypothesis that isolation from input is a critical feature shared by cognitive states activating the DMN.

## 2. Material and Methods

### 2.1 Participants

Thirty right-handed native British-speaking participants with normal or corrected-to-normal vision were recruited from the University of York (16 female; mean age 22.68, range 18-34 years). One participant's data was excluded due to excessive motion artifacts, leaving twenty-nine subjects in the final analysis for (15 female; mean age 22.57, range 18-24 years). In a subsequent analysis we used a set of 60 participants resting state data from the same pool of individuals (34 female; mean age 20.32, range 18-29 years). Both studies were approved by the York Neuroimaging Centre (YNIC) Ethics Committee. Participant's provided informed consent prior to the start of the experimental session.

## 2.2 Stimuli

The task paradigm had four conditions: (A) Object 0-back, (B) Object 1-back, (C) Colour 0-back and (D) Colour 1-back using a block design. In all conditions, pairs of items were presented separated by a central line. In the colour conditions, these were different coloured squares, while in the object conditions, these were familiar and meaningful objects, taken from the same semantic category (i.e., different types of cars, fruit, dogs; see Figure 1). Items were presented once with no repetition. The contrast between object and colour conditions allowed us to investigate regions that are important for the retrieval of conceptual information. The colour patches only varied on one feature (their colour), while the objects were meaningful multi-featural concepts. In addition, the contrast of 0-back and 1-back conditions allowed us to investigate the effect of stimulus-independent processing (1 back > 0 back).

## 2.3 Procedure

In the scanner, participants completed a total of four functional runs (average run time 8 min 32 s). Within each run, there were two blocks related to each of the 4 conditions (Object 1-back; Object 0-back; Colour 1-back; Colour 0-back). Each block began with written instructions stating the task type (0-back or 1-back). Blocks consisted of observing pairs of items (1000 ms); each pair was separated by a jittered inter-stimulus interval (ISI; 3000-5000 ms) in which a fixation cross was presented. At random intervals (4-8 trials), a third item was presented in the centre of the screen and participants were asked to indicate the location of one of the pair (left or right)

171 that was most similar to this probe (see Figure 1). This paradigm also required  
 172 participants to match items that were present and compared this with items in  
 173 memory. In the 0-back catch-trials participants had to decide which stimulus (left or  
 174 right of the screen) was most similar to this centrally-presented probe (i.e., all items  
 175 were present on the screen). In the 1-back catch-trials, participants had to decide  
 176 which stimulus (left or right of the screen) had been most similar to this centrally-  
 177 presented probe on the previous trial (i.e., the critical stimulus was absent). Blocks  
 178 consisted of 5 probes in total and lasted on average 64 s.

179

## 180 2.4 MRI Acquisition

181 Data for both experiments were acquired using a GE 3 T HD Excite MRI  
182 scanner at the YNIC. A Magnex head-dedicated gradient insert coil was used in  
183 conjunction with a birdcage, radio-frequency insert coil tuned to 127.4 MHz. A  
184 gradient-echo EPI sequence was used to collect data from 38 bottom-up axial slices  
185 aligned with the temporal lobe (TR = 2s, TE = 18ms, FOV = 192x192mm, matrix size =  
186 64x64, slice thickness = 3mm, slice-gap = 1mm, flip-angle = 90°). Voxel size was  
187 3x3x3mm. Functional images were co-registered onto a T1-weighted anatomical  
188 image from each participant (TR = 7.8s, TE = 3ms, FOV = 290x290mm, matrix size =  
189 256x256mm, voxel size = 1.13x1.13x1mm) using linear registration.

190

## 191 2.5 Pre-processing

192 All imaging data were pre-processed using a standard pipeline and analysed  
193 via FMRIB Software Library (FSL Version 6.0). Images were skull-stripped using a  
194 brain extraction tool [BET, (Smith, 2002)]. The first five volumes (10s) of each scan  
195 were removed to minimize the effects of magnetic saturation, and slice-timing  
196 correction with Fourier space time-series phase-shifting was applied. Motion  
197 correction (MCFLIRT, (Jenkinson, Bannister, Brady, & Smith, 2002)) was followed by  
198 temporal high-pass filtering (cut-off = 0.01Hz). Individual participant data was  
199 registered to their high-resolution T1-anatomical image, and then into a standard  
200 space (Montreal Neurological Institute); this process included tri-linear interpolation  
201 of voxel sizes to 2x2x2 mm.

202 The resting state functional data used were pre-processed and analysed using  
203 the FMRI Expert Analysis Tool (FEAT). The individual subject analysis involved:  
204 motion correction using MCFLIRT; slice-timing correction using Fourier space time-  
205 series phase-shifting; spatial smoothing using a Gaussian kernel of FWHM 6mm;  
206 grand-mean intensity normalisation of the entire 4D dataset by a single  
207 multiplicative factor; high-pass temporal filtering (Gaussian-weighted least-squares  
208 straight line fitting, with sigma = 100 s); Gaussian low-pass temporal filtering, with  
209 sigma = 2.8s

210

## 211 2.6 Task based fMRI

212 For our task-based analysis, the time points of interest were the probe trials  
213 where participants had to make a decision about something present (0-back) or  
214 absent (1-back) from the screen. We therefore used a box-car regressor to model (i)  
215 the probe trial for each condition and (ii) the entire block. Modelling the entire block  
216 ensured any effect detected from our analysis can be attributed to the probe itself  
217 and not the general effect of the block. Box-car regressors for each probe/block, for  
218 each condition, for each run, were convolved with a double gamma hemodynamic  
219 response function. Regressors of no interest were included to account for head  
220 motion. We computed four contrasts: (1) 0-back > 1-back, (2) 1-back > 0-back, (3)  
221 Object > Colour and (4) Colour > Object. A fixed effect design (FLAME,  
222 <http://www.fmrib.ox.ac.uk/fsl>) was conducted to average the four runs, within each  
223 individual. Individual participant data were then entered into a higher-level group  
224 analysis using a mixed effects design (FLAME, <http://www.fmrib.ox.ac.uk/fsl>) whole-  
225 brain analysis. Finally, our analysis focused on a conjunction of 1-back > 0-back and  
226 Object > Colour to identify regions engaged in both stimulus independent processing  
227 and conceptually abstract representations.

228

## 229 2.7 Resting-state fMRI

230 We extracted the time series from regions identified by univariate analysis  
231 and used these as explanatory variables in a connectivity analyses at the single  
232 subject level. In each analysis, we entered 11 nuisance regressors; the top five  
233 principal components extracted from white matter (WM) and cerebrospinal fluid  
234 (CSF) masks based on the CompCor method (Behzadi, Restom, Liao, & Liu, 2007), six  
235 head motion parameters and spatial smoothing (Gaussian) was applied at 6mm  
236 (FWHM). WM and CSF masks were generated from each individual's structural image  
237 (Zhang, Brady, & Smith, 2001). No global signal regression was performed, following  
238 the method implemented in Murphy, Birn, Handwerker, Jones, & Bandettini (2009).

239 Whole brain analyses were cluster corrected using a z-statistic threshold of  
240 3.1 to define contiguous clusters. Multiple comparisons were controlled using  
241 Gaussian Random Field Theory at a threshold of  $p < .05$  [34]. All statistical maps

produced in these analyses are freely available at Neurosynth at the following URL:  
<http://neurovault.org/collections/2296/>.

### 3. Results

Table 1 presents behavioural performance, in the form of response efficiency (RT/ACC), for each of the four conditions of our task. These data were compared using a 2 (task; 0-back vs. 1-back) by 2 (condition; object vs. colour) repeated-measures analysis of variance (ANOVA). There was no significant differences between stimulus type ( $F(1,28) = 2.55$ ,  $p = .116$ ) but a significant main effect of task ( $F(1,28) = 15.38$ ,  $p < .001$ ). There was no significant interaction ( $p > .05$ ). These analyses demonstrate that performance on the 1-back task was less efficient than for the 0-back task but that object and colour conditions were well matched in terms of overall task difficulty.

Table 1. Behavioural results.

Condition	Response Efficiency	
	Mean	SE
Colour 1-back	1028	206
Colour 0-back	829	287
Object 1-back	1041	229
Object 0-back	841	295

Footnote: SE = standard error. Response efficiency = reaction time in milliseconds / percent accuracy.

We next generated statistical maps for describing patterns of neural activity at the moments when participants responded in each of our four conditions. These maps were compared at the group level using a GLM (see Methods). The contrast of 0-back > 1-back decisions captures perceptually-guided decision-making, revealing increased activity in the bilateral ventral visual stream, from occipital pole through to posterior fusiform cortex (see Figure 2). These regions have a well-documented role in online visual processing. The contrast of 1-back > 0-back reflects stimulus independence in decision-making. This comparison revealed greater activation in bilateral angular gyrus and anterior temporal lobes, as well as medial structures in the posterior cingulate cortex and medial prefrontal cortex. Many of these regions

267 fall within the DMN (58.44% of voxels fell within the DMN as defined by Yeo et al.,  
 268 2011) and are spatially similar to the ‘general recollection network’ proposed by  
 269 Rugg and Vilburg (2013). The comparison of Objects > Colours identifies brain areas  
 270 that support the processing of multi-featural conceptual representations. This  
 271 contrast revealed a similar set of regions to the stimulus independence contrast (left  
 272 and right angular gyrus and anterior temporal lobe) with the addition of the right  
 273 dorsolateral cortex (52.49 % of voxels fell within the DMN as defined by Yeo et al.,  
 274 2011). The contrast of Colours > Objects yielded no significant whole-brain corrected  
 275 results. To allow comparison with previous research, the spatial maps for the  
 276 contrast of 1-back > 0-back from Konishi and colleagues are also displayed:  
 277 similarities can be seen in posterior cingulate cortex, medial prefrontal cortex, right  
 278 angular gyrus and dorsolateral cortex.

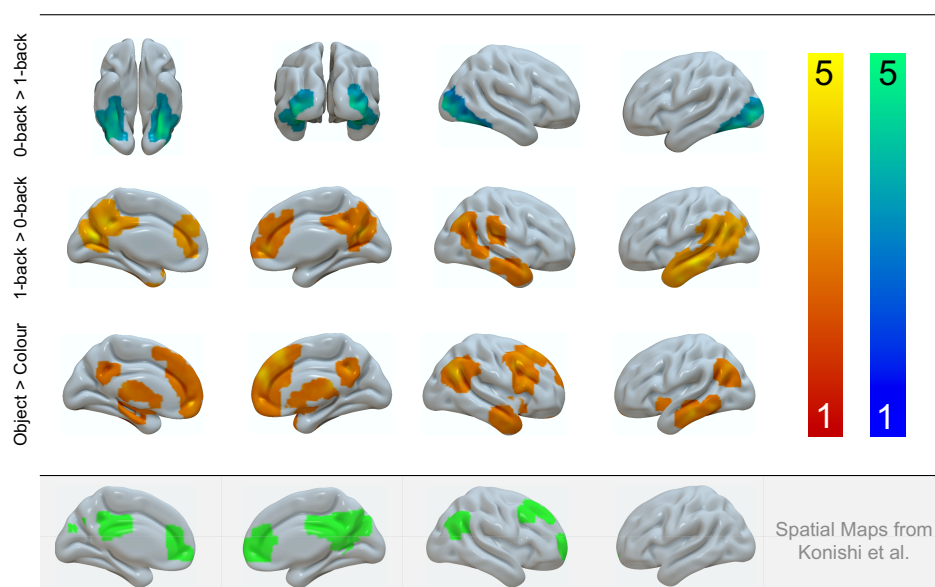


Figure 2

281 Our next analysis formally identifies regions that show a response to both  
 282 stimulus independence and memory complexity. Figure 3 shows the results of a  
 283 formal conjunction of the contrasts of Object > Colour and 1-back > 0-back, revealing  
 284 three regions – bilateral angular gyrus and lateral medial temporal gyrus in the left  
 285 hemisphere. The left hand panel of Figure 3 summarizes the parameter estimates  
 286 from each of these regions in each condition of our task. In every case the strongest  
 287 response was when decisions were made in the Object 1-back condition.  
 288 Importantly, although these regions fell within the DMN (88.07% of voxels within the



289 conjunction mask fell within the DMN as defined by Yeo et al., 2011), their response  
 290 profile indicated greater responding during a demanding condition (i.e. Object 1-  
 291 back) ruling out a task-negative interpretation of these results.

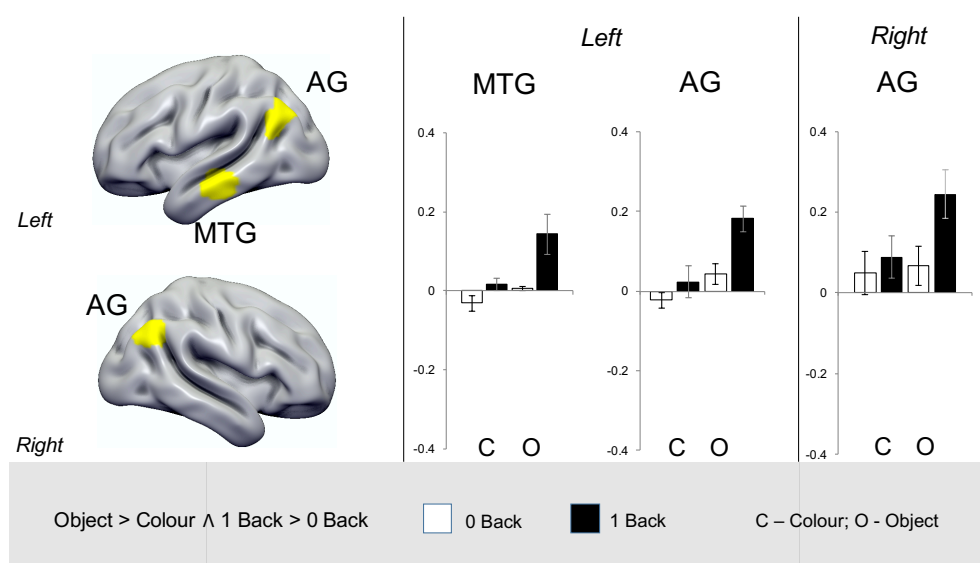
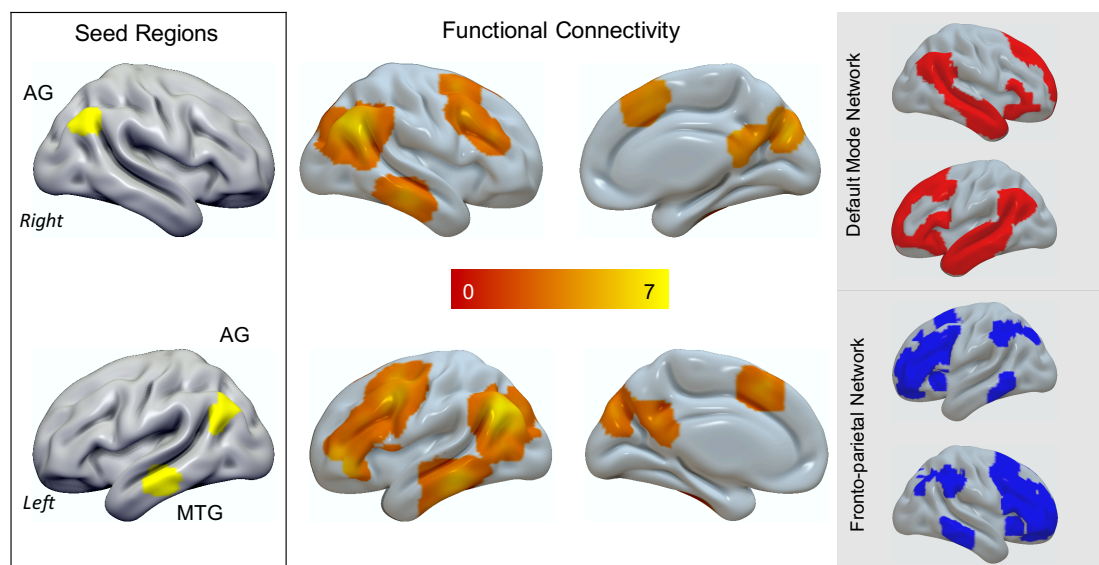


Figure 3

292  
 293 We also explored the intrinsic architecture of conjunction regions responding  
 294 to Object > Colour and 1-back > 0-back in an independent resting-state data set (see  
 295 Methods). The results of this analysis are presented in Figure 4 and reveal coupling  
 296 beyond the seed regions to the posterior cingulate cortex, dorsolateral prefrontal  
 297 cortex and pre-supplementary motor area bilaterally. Some of these regions fall  
 298 outside the DMN, as defined by Yeo and colleagues, and instead are members of the  
 299 frontoparietal network linked with cognitive control (40.15% of voxels within the  
 300 DMN mask and 17.81% fell within the frontoparietal network, as defined by Yeo et  
 301 al., 2011). These findings are consistent with previous work showing functional  
 302 integration between the DMN and the executive network in demanding memory  
 303 tasks, and at odds with the view that angular gyrus and lateral anterior temporal  
 304 cortex only contribute to automatic aspects of retrieval or to task-negative states.

306 We also conducted a supplementary analysis contrasting Object and Colour  
 307 decisions separately in the 1-back and 0-back conditions to confirm regions  
 308 important for stimulus-independent semantic decisions (see Supplementary Figure  
 309 1). This analysis showed that 1-back trials involving meaningful objects activated  
 310 regions including angular gyrus, middle temporal gyrus and right dorsolateral

311 prefrontal regions more than colours. In contrast, the comparison of Objects >  
 312 Colours in the 0-back condition only revealed greater activity in fusiform cortex.



313  
 314 Figure 4

315 Together these analyses highlight a network of regions that are important  
 316 when decisions are made in the absence of external sensory support, and when they  
 317 involve multi-feature concepts (Figure 5). Common regions responding to the two  
 318 task contrasts (1-back > 0-back; Object > Colour), and showing high intrinsic  
 319 connectivity with conjunction regions in the left hemisphere, include angular gyrus  
 320 and middle temporal gyrus. In the right hemisphere, all three maps include angular  
 321 gyrus and two also include dorsolateral cortex. Both of these right hemisphere  
 322 regions responded to a similar 1-back > 0-back contrast involving abstract shapes  
 323 (circle, triangle, square) in the study by Konishi and colleagues (2015). The current  
 324 study therefore provides a replication of the key conclusion that these regions of the  
 325 DMN show activation when retrieving categorical information from memory, even  
 326 when the task is relatively hard.

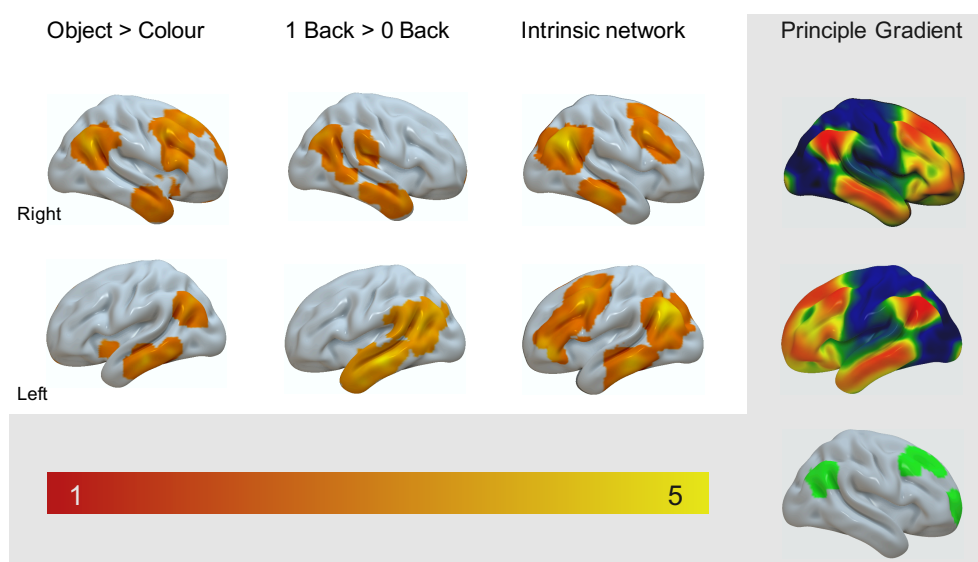


Figure 5

In Figure 5, these spatial maps are presented alongside the principal gradient from Margulies and colleagues (2016), which describes a functional spectrum of intrinsic connectivity across the cortical surface, extending from primary sensory motor systems to regions of the DMN at the other extreme. More similar colours on this gradient reflect greater similarity in connectivity. It can be seen that common regions implicated in stimulus-independent and conceptual processing are localized towards the transmodal end of the principal gradient.

Our final analysis characterizes the similarity between the neural patterns captured by our task and the spatial distribution of the principle gradient from Margulies et al., (2016) in a more formal manner. Following Margulies et al., we divided the principle gradient into 20 equally sized bins. Next for each participant we calculated the average signal in each bin for each condition of our task. The left hand panel in Figure 6 presents these data plotted across the principle gradient separately for each condition; the shaded bars represent the 95% confidence intervals. It can be seen that the conditions are most distinct towards the transmodal end, with the highest values when participants made judgments about objects from memory. To quantify these patterns, we compared their distribution using a 2 (stimulus independence) X (stimulus complexity) X 20 (Gradient Bin) ANOVA. This revealed a significant 3-way interaction [ $F(19, 532) = 5.136, p < .001$ ]. To follow up this interaction, we performed a principle components analysis (PCA) on the condition level data, describing the dynamics captured in the left hand panel of Figure 6. The

results revealed two components with eigenvalues greater than 1 accounting for over 86% of the variance (component 1 = 70.49%; component 2 = 15.73%) across the principal gradient bins. The first two components are presented in the right hand panel of Figure 6. The second component describes a gradual transition showing increasing levels of BOLD activity from the unimodal end of the gradient towards the transmodal end. Projecting the values from component 2 back onto the task conditions, and averaging them at the group-level, revealed that this pattern of variance loaded almost exclusively on the 'object' 1-back condition. There was a significant positive fit between the spatial map of the principle gradient and recruitment in the Object 1-Back task, but not other conditions.

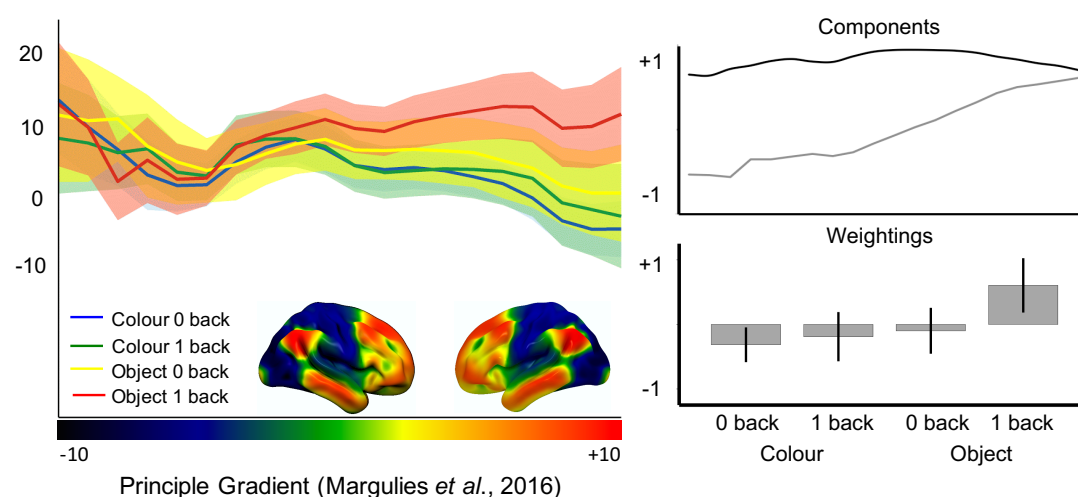


Figure 6

#### 4. Discussion

Our experiment establishes that overlapping regions in the DMN are sensitive to both perceptual decoupling (i.e., the requirement to make decisions based on memory, as opposed to the immediate environment) and conceptual processing (i.e., decisions based on semantic rather than perceptual information). We also showed that these regions fell at the extreme end of a gradient from unimodal to heteromodal cortex (Margulies et al., 2016). Therefore, isolation from input appears to be a critical feature shared by at least two manipulations that activate the DMN. Distance from sensory-motor cortex might be necessary to form heteromodal conceptual representations, which are thought to be abstracted from individual

features and modalities. Also, when cognition is driven by internal rather than external representations, brain regions that have intrinsically weak connectivity with unimodal input regions might play an important role, since memory retrieval can create mental simulations that differ markedly from the external environment. These findings have broad implications for the role of DMN in cognition, and also contribute to our understanding of specific DMN regions, particularly angular gyrus and lateral temporal lobe. We first consider the results in terms of their implications for functional accounts of these regions. Secondly, we consider the macroscale organisation of the cortex, focusing on approaches which can explain the functional similarity of these distributed clusters and their relative position on the cortical surface.

Functional implications for the angular gyri: There were stronger responses in left and right angular gyri, as well as in left middle temporal gyrus, when conceptual decisions were based on information that was no longer present in the environment. These findings are inconsistent with several existing accounts of the contribution of angular gyrus to memory and semantic cognition. First, they do not easily align with the proposal that specific aspects of meaning are represented in angular gyrus – namely thematic associations, but not item identity (Davey et al., 2015; Schwartz et al., 2011). Our conceptual task involved matching items on the basis of their identity, yet it still robustly activated this region. Secondly, the findings are at odds with the proposal that the angular gyri only activate during contrasts of easier versus harder tasks, and for “automatic” and not “controlled” patterns of retrieval (Humphreys et al., 2015; Humphreys & Lambon Ralph, 2017). The 1-back condition was harder than the 0-back condition and still elicited a greater response.

Our findings are potentially more consistent with suggestions that the angular gyri contribute to semantic and episodic retrieval tasks via processes that allocate attention in a bottom-up fashion, i.e., to strongly-activated memory representations. The angular gyri show a stronger response to a range of memory retrieval situations in which the retrieved representations are detailed, specific or precise (Binder et al., 2005; Price, et al., 2015; Bonnici et al., 2016; Davey et al., 2015). The 1-back trials required attention to be focused on conceptual information represented internally, consistent with the purported role of inferior parietal cortex

in reflexive attention to memory (Cabeza et al., 2011). We did not obtain the same findings for the colour condition, which required more similar colours to be matched (e.g., two bright greens compared with a darker green), perhaps because these stimuli did not activate pre-existing representations in memory.

Functional implications for temporal cortex: Angular gyrus shows strong intrinsic connectivity with ventral anterior temporal cortex (Davey et al., 2016; Jackson et al., 2016), which is proposed to support the integration of multiple features and modalities to capture ‘deep’ conceptual similarities between items with diverse ‘surface’ features (e.g., items such as PINEAPPLE and KIWI that have different colours, sizes, shapes, phonology etc.; for a review see Lambon Ralph et al., 2017). Semantic dementia patients with atrophy focussed on this region show highly consistent degradation of conceptual knowledge across tasks (Bozeat et al., 2000; Jefferies & Lambon Ralph, 2006), while neuroimaging studies of healthy participants localise the response during heteromodal conceptual processing to ventral anterior temporal lobes and anterior middle temporal gyrus (Murphy et al., 2017; Visser et al., 2011). Word meaning can be decoded within anterior middle and inferior temporal gyri, while patterns of activation in superior temporal gyrus instead reflect the presentation format (Murphy et al., 2017).

The ventral anterior temporal lobes are thought to provide a “graded hub” in which different unimodal features are gradually integrated to form heteromodal concepts, with visual information reaching this region along the ventral visual pathway (fusiform cortex), auditory and motor information arriving from superior temporal gyrus and frontal cortex, and social/emotional information merging from the temporal pole (Lambon Ralph et al., 2017). Nevertheless, the peak response in the anterior temporal lobes in the current study was in lateral MTG, and not in the site of the putative hub in ventral anterior temporal cortex (Murphy et al., 2017). Visser et al. (2012) observed evidence compatible with two gradients of information convergence in the temporal lobes: first, there is a posterior-to-anterior axis, since posterior temporal lobe regions proximal to visual and auditory cortex show largely unimodal responses, while more anterior regions integrate across these types of input to support heteromodal conceptual processing. Secondly, there may be integration from superior and inferior regions, implicated in auditory and visual

processing respectively, towards middle temporal gyrus, which shows a more heteromodal response along the length of the temporal cortex. The site we observed in the conjunction of semantic and perceptually-decoupled decisions in the current study appears to correspond with the extreme heteromodal end of *both* of these temporal lobe gradients.

Implications for the default mode network: We replicated prior demonstrations that transmodal regions in the DMN are engaged when participants make decisions that rely on information from memory rather than input from perception, even though the 1-back task was more difficult than the 0-back task (Konishi et al., 2015). This pattern of task-positive behaviour adds to a growing body of evidence that the DMN contributes in an active manner to demanding external cognitive tasks (Konishi et al., 2015; Krieger-Redwood et al., 2016; Spreng et al., 2014; Spreng et al., 2015; Spreng et al., 2010; Vatansever et al., 2015). The contribution of DMN to controlled cognitive states appears to reflect situations in which DMN regions work in tandem with the frontoparietal network. Prior work has established the combination of these networks is important for tasks including controlled semantic retrieval (Krieger-Redwood et al., 2016), working memory (Vatansever et al., 2015), autobiographical planning (Spreng et al., 2014; Spreng et al., 2015), retrieving memories of close personal friends (de Caso et al., 2017) and the control of spontaneous thoughts in a deliberate manner (Golchert et al., 2017). Our study shows that right angular gyrus, within the DMN, and right dorsolateral prefrontal cortex, a member of the frontoparietal network, activate together when participants make judgments about meaningful objects from memory rather than colours (see Supplementary Figure 1). Our functional connectivity analysis demonstrates that these regions are correlated at rest. The right dorsolateral cluster replicates the spatial distribution observed from the prior study by Konishi et al. (2015) and overlaps with a region of greater grey matter associated with more deliberate mind-wandering (Golchert et al., 2017). Both 1-back retrieval in our paradigm, and more deliberate spontaneous thought, require memory retrieval to be shaped in a goal-directed fashion. It is possible that a range of states requiring the goal-directed control of memory depend on co-operation between these two large-scale networks.



At the most general level, our study supports the idea that similar responses across disparate brain regions (e.g., lateral middle temporal gyrus and angular gyrus) and across apparently different cognitive manipulations (semantic vs. non-semantic processing; decisions based on memory or perception) can be explained in terms of the topographical organisation of the cortex. Prior work highlighted that regions of transmodal cortex, such as the DMN, show the greatest distance from unimodal sensorimotor cortex in both functional and structural space (Margulies et al., 2016). Our findings build on this observation by showing that this dimension of connectivity is related to the combined requirement to match items on the basis of conceptual as opposed to sensory features and the need to retrieve relevant information from memory as opposed to the ongoing visual presentation of this information. Using both standard and novel methods of analysis, we demonstrated that the neural activity associated with this type of activity is prevalent in transmodal regions (Figure 5) and can be represented as a whole brain shift in the balance of neural activity, away from sensorimotor regions and towards the transmodal end of the gradient (Figure 6). This topographical shift in the distribution of neural processing is consistent with theoretical accounts that assume that more abstract cortical functions are facilitated through functional isolation from incoming input (Buckner & Krienen, 2013; Margulies et al., 2016; Mesulam, 1998; Smallwood, 2013). Both angular gyrus and middle temporal gyrus respond to heteromodal aspects of meaning, in line with their position at the heteromodal end of the principal gradient (Binder & Desai, 2011; Bonner et al., 2013; Humphreys & Lambon Ralph, 2015; Simanova et al., 2014). Moreover, the two task contrasts – highlighting perceptual decoupling and semantic decisions – might emphasise processes that utilise heteromodal cortex, explaining their common recruitment. In line with this, a recent study found that strong connectivity between subnetworks of the DMN predicted poor performance on tasks that required encoding and retention of recently presented information, but not poor retrieval of previously-encoded knowledge, consistent with a failure to engage with the external world (Poerio et al., 2017).

There are a number of limitations that should be borne in mind when considering the results of this study. First, our comparison of semantic and colour decisions allowed us to demonstrate a neural pattern associating conceptual



processing with stimulus independency. This comparison is too crude a manipulation to determine which aspects of the semantic judgements gave rise to this response in the DMN; for example, is it the richness of concepts such as Labrador or apple, their heteromodal nature, the fact that they are acquired over a lifetime, and/or their broad predictive value in the real world, which dissociates them from colours? Future studies could probe different features of retrieval, such as whether the target is a concrete or abstract concept, whether it has to be identified at a specific or superordinate level, and whether there are differences according to the modality of the representation being probed. Second, the nature of our design precludes the ability to separate different aspects of memory retrieval engaged during 1-back decisions. In our paradigm, these decisions require both the integration of appropriate information from memory, as well as the inhibition of the non-probed item representation. Interestingly, studies have implicated dorsolateral prefrontal cortex in the suppression of memories (Anderson et al., 2004) whereas both the angular gyrus has been linked to the integration of appropriate semantic features (Wagner et al., 2015) and the retrieval of specific information (Davey et al., 2015). It is possible that the angular gyrus and dorsolateral prefrontal cortex are performing distinct roles in the integration of relevant associations and the suppression of irrelevant information during retrieval. Future work could address this question by manipulating the featural overlap between the target and distractor in this paradigm. Finally, although we showed that two aspects of cognition recruit common regions in the DMN, and that this pattern can be recovered in a whole-brain gradient analysis, we did not recover a conjunction across the entire DMN, and other tasks that activate DMN might elicit a peak response in other nodes of this network. Our findings are consistent with the view that the DMN supports aspects of cognition that require integration of, and isolation from, unimodal systems, yet since each node of the DMN receives a different balance of local inputs, these regions might differ to some extent in their relevance for any given task.

530     Funding:

531     The research was supported by BBSRC grant BB/J006963/1. EJ was supported by a  
532     grant from the European Research Council (SEMBIND - 283530). JS was supported by  
533     a grant from the European Research Council (Wandering Minds – 303701).

## References

- Anderson, M. C., Ochsner, K. N., Kuhl, B., Cooper, J., Robertson, E., Gabrieli, S. W., . . . Gabrieli, J. D. (2004). Neural systems underlying the suppression of unwanted memories. *Science*, 303(5655), 232-235. doi:10.1126/science.1089504
- Behzadi, Y., Restom, K., Liau, J., & Liu, T. T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage*, 37(1), 90-101. doi:10.1016/j.neuroimage.2007.04.042
- Binder, J. R., & Desai, R. H. (2011). The neurobiology of semantic memory. *Trends in cognitive sciences*, 15(11), 527-536.
- Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cereb Cortex*, 19(12), 2767-2796. doi:10.1093/cercor/bhp055
- Binder, J. R., Westbury, C. F., McKiernan, K. A., Possing, E. T., & Medler, D. A. (2005). Distinct brain systems for processing concrete and abstract concepts. *Journal of cognitive neuroscience*, 17(6), 905-917.
- Bonner, M. F., Peelle, J. E., Cook, P. A., & Grossman, M. (2013). Heteromodal conceptual processing in the angular gyrus. *Neuroimage*, 71, 175-186.
- Bonnici, H. M., Richter, F. R., Yazar, Y., & Simons, J. S. (2016). Multimodal Feature Integration in the Angular Gyrus during Episodic and Semantic Retrieval. *J Neurosci*, 36(20), 5462-5471. doi:10.1523/JNEUROSCI.4310-15.2016
- Bozeat, S., Ralph, M. A. L., Patterson, K., Garrard, P., & Hodges, J. R. (2000). Non-verbal semantic impairment in semantic dementia. *Neuropsychologia*, 38(9), 1207-1215.
- Buckner, R. L., & Krienen, F. M. (2013). The evolution of distributed association networks in the human brain. *Trends Cogn Sci*, 17(12), 648-665. doi:10.1016/j.tics.2013.09.017
- Cabeza, R., Mazuz, Y. S., Stokes, J., Kragel, J. E., Woldorff, M. G., Ciaramelli, E., . . . Moscovitch, M. (2011). Overlapping parietal activity in memory and perception: evidence for the attention to memory model. *J Cogn Neurosci*, 23(11), 3209-3217. doi:10.1162/jocn\_a\_00065

565 Davey, J., Cornelissen, P. L., Thompson, H. E., Sonkusare, S., Hallam, G., Smallwood,  
566 J., & Jefferies, E. (2015). Automatic and Controlled Semantic Retrieval: TMS  
567 Reveals Distinct Contributions of Posterior Middle Temporal Gyrus and  
568 Angular Gyrus. *J Neurosci*, 35(46), 15230-15239.  
569 doi:10.1523/JNEUROSCI.4705-14.2015

570 Davey, J., Thompson, H. E., Hallam, G., Karapanagiotidis, T., Murphy, C., De Caso, I.,  
571 ... & Jefferies, E. (2016). Exploring the role of the posterior middle temporal  
572 gyrus in semantic cognition: Integration of anterior temporal lobe with  
573 executive processes. *NeuroImage*, 137, 165-177.

574 de Caso, I., Karapanagiotidis, T., Aggus-Vella, E., Konishi, M., Margulies, D. S.,  
575 Jefferies, E., & Smallwood, J. (2017). Knowing me, knowing you: Resting-state  
576 functional connectivity of ventromedial prefrontal cortex dissociates memory  
577 related to self from a familiar other. *Brain Cogn*, 113, 65-75.  
578 doi:10.1016/j.bandc.2017.01.004

579 Engen, H. G., Kanske, P., & Singer, T. (2017). The neural component-process  
580 architecture of endogenously generated emotion. *Soc Cogn Affect Neurosci*,  
581 12(2), 197-211. doi:10.1093/scan/nsw108

582 Golchert, J., Smallwood, J., Jefferies, E., Seli, P., Huntenburg, J. M., Liem, F., . . .  
583 Margulies, D. S. (2017). Individual variation in intentionality in the mind-  
584 wandering state is reflected in the integration of the default-mode, fronto-  
585 parietal, and limbic networks. *Neuroimage*, 146, 226-235.  
586 doi:10.1016/j.neuroimage.2016.11.025

587 Humphreys, G. F., Hoffman, P., Visser, M., Binney, R. J., & Ralph, M. A. L. (2015).  
588 Establishing task-and modality-dependent dissociations between the  
589 semantic and default mode networks. *Proceedings of the National Academy*  
590 *of Sciences*, 112(25), 7857-7862.

591 Humphreys, G. F., & Ralph, M. A. L. (2015). Fusion and fission of cognitive functions  
592 in the human parietal cortex. *Cerebral Cortex*, 25(10), 3547-3560.

593 Jackson, R. L., Hoffman, P., Pobric, G., & Ralph, M. A. L. (2016). The semantic  
594 network at work and rest: Differential connectivity of anterior temporal lobe  
595 subregions. *Journal of Neuroscience*, 36(5), 1490-1501.

596 Jefferies, E., & Ralph, M. A. L. (2006). Semantic impairment in stroke aphasia versus  
 597 semantic dementia: a case-series comparison. *Brain*, 129(8), 2132-2147.  
 598 Chicago

599 Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for  
 600 the robust and accurate linear registration and motion correction of brain  
 601 images. *Neuroimage*, 17(2), 825-841.

602 Konishi, M., McLaren, D. G., Engen, H., & Smallwood, J. (2015). Shaped by the Past:  
 603 The Default Mode Network Supports Cognition that Is Independent of  
 604 Immediate Perceptual Input. *PLoS One*, 10(6), e0132209.  
 605 doi:10.1371/journal.pone.0132209

606 Krieger-Redwood, K., Jefferies, E., Karapanagiotidis, T., Seymour, R., Nunes, A., Ang,  
 607 J. W., . . . Smallwood, J. (2016). Down but not out in posterior cingulate  
 608 cortex: Deactivation yet functional coupling with prefrontal cortex during  
 609 demanding semantic cognition. *Neuroimage*, 141, 366-377.  
 610 doi:10.1016/j.neuroimage.2016.07.060

611 Lambon Ralph, M. A., Jefferies, E., Patterson, K., & Rogers, T. T. (2017). The neural  
 612 and computational bases of semantic cognition. *Nat Rev Neurosci*, 18(1), 42-  
 613 55. doi:10.1038/nrn.2016.150

614 Leech, R., Braga, R., & Sharp, D. J. (2012). Echoes of the brain within the posterior  
 615 cingulate cortex. *J Neurosci*, 32(1), 215-222. doi:10.1523/JNEUROSCI.3689-  
 616 11.2012

617 Leech, R., & Sharp, D. J. (2014). The role of the posterior cingulate cortex in cognition  
 618 and disease. *Brain*, 137(Pt 1), 12-32. doi:10.1093/brain/awt162

619 Margulies, D. S., Ghosh, S. S., Goulas, A., Falkiewicz, M., Huntenburg, J. M., Langs, G.,  
 620 . . . Smallwood, J. (2016). Situating the default-mode network along a  
 621 principal gradient of macroscale cortical organization. *Proc Natl Acad Sci U S*  
 622 *A*, 113(44), 12574-12579. doi:10.1073/pnas.1608282113

623 Mesulam, M. M. (1998). From sensation to cognition. *Brain*, 121 ( Pt 6), 1013-1052.

624 Moscovitch, M., Cabeza, R., Winocur, G., & Nadel, L. (2016). Episodic Memory and  
 625 Beyond: The Hippocampus and Neocortex in Transformation. *Annu Rev*  
 626 *Psychol*, 67, 105-134. doi:10.1146/annurev-psych-113011-143733

627 Murphy, K., Birn, R. M., Handwerker, D. A., Jones, T. B., & Bandettini, P. A. (2009).  
628 The impact of global signal regression on resting state correlations: are anti-  
629 correlated networks introduced?. *Neuroimage*, 44(3), 893-905.

630 Murphy, C., Rueschemeyer, S. A., Watson, D., Karapanagiotidis, T., Smallwood, J., &  
631 Jefferies, E. (2017). Fractionating the anterior temporal lobe: MVPA reveals  
632 differential responses to input and conceptual modality. *NeuroImage*, 147,  
633 19-31.

634 Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you  
635 know? The representation of semantic knowledge in the human brain.  
636 *Nature Reviews Neuroscience*, 8(12), 976-987.

637 Poerio, G. L., Sormaz, M., Wang, H. T., Margulies, D., Jefferies, E., & Smallwood, J.  
638 (2017). The role of the default mode network in component processes  
639 underlying the wandering mind. *Social cognitive and affective neuroscience*,  
640 nsx041.

641 Price, A. R., Bonner, M. F., Peelle, J. E., & Grossman, M. (2015). Converging evidence  
642 for the neuroanatomic basis of combinatorial semantics in the angular gyrus.  
643 *Journal of Neuroscience*, 35(7), 3276-3284.

644 Rugg, M. D., & Vilberg, K. L. (2013). Brain networks underlying episodic memory  
645 retrieval. *Curr Opin Neurobiol*, 23(2), 255-260.  
646 doi:10.1016/j.conb.2012.11.005

647 Schacter, D. L., & Addis, D. R. (2007). The cognitive neuroscience of constructive  
648 memory: remembering the past and imagining the future. *Philos Trans R Soc*  
649 *Lond B Biol Sci*, 362(1481), 773-786. doi:10.1098/rstb.2007.2087

650 Schwartz, M. F., Kimberg, D. Y., Walker, G. M., Brecher, A., Faseyitan, O. K., Dell, G.  
651 S., ... & Coslett, H. B. (2011). Neuroanatomical dissociation for taxonomic and  
652 thematic knowledge in the human brain. *Proceedings of the National*  
653 *Academy of Sciences*, 108(20), 8520-8524.

654 Seghier, M. L. (2013). The angular gyrus: multiple functions and multiple  
655 subdivisions. *Neuroscientist*, 19(1), 43-61. doi:10.1177/1073858412440596

656 Simanova, I., Hagoort, P., Oostenveld, R., & Van Gerven, M. A. (2014). Modality-  
657 independent decoding of semantic information from the human brain.  
658 *Cerebral cortex*, 24(2), 426-434.

Smallwood, J. (2013). Distinguishing how from why the mind wanders: a process-occurrence framework for self-generated mental activity. *Psychol Bull*, 139(3), 519-535. doi:10.1037/a0030010

Smith, S. M. (2002). Fast robust automated brain extraction. *Hum Brain Mapp*, 17(3), 143-155. doi:10.1002/hbm.10062

Spreng, R. N. (2012). The fallacy of a "task-negative" network. *Front Psychol*, 3, 145. doi:10.3389/fpsyg.2012.00145

Spreng, R. N., DuPre, E., Selarka, D., Garcia, J., Gojkovic, S., Mildner, J., . . . Turner, G. R. (2014). Goal-congruent default network activity facilitates cognitive control. *J Neurosci*, 34(42), 14108-14114. doi:10.1523/JNEUROSCI.2815-14.2014

Spreng, R. N., Gerlach, K. D., Turner, G. R., & Schacter, D. L. (2015). Autobiographical Planning and the Brain: Activation and Its Modulation by Qualitative Features. *J Cogn Neurosci*, 27(11), 2147-2157. doi:10.1162/jocn\_a\_00846

Spreng, R. N., Stevens, W. D., Chamberlain, J. P., Gilmore, A. W., & Schacter, D. L. (2010). Default network activity, coupled with the frontoparietal control network, supports goal-directed cognition. *Neuroimage*, 53(1), 303-317. doi:10.1016/j.neuroimage.2010.06.016

Vatansever, D., Menon, D. K., Manktelow, A. E., Sahakian, B. J., & Stamatakis, E. A. (2015). Default mode network connectivity during task execution. *Neuroimage*, 122, 96-104. doi:10.1016/j.neuroimage.2015.07.053

Visser, M., Jefferies, E., Embleton, K. V., & Ralph, M. A. L. (2012). Both the middle temporal gyrus and the ventral anterior temporal area are crucial for multimodal semantic processing: distortion-corrected fMRI evidence for a double gradient of information convergence in the temporal lobes. *Journal of Cognitive Neuroscience*, 24(8), 1766-1778.

Visser, M., Jefferies, E., & Lambon Ralph, M. A. (2010). Semantic processing in the anterior temporal lobes: a meta-analysis of the functional neuroimaging literature. *J Cogn Neurosci*, 22(6), 1083-1094. doi:10.1162/jocn.2009.21309

Visser, M., & Ralph, M. L. (2011). Differential contributions of bilateral ventral anterior temporal lobe and left anterior superior temporal gyrus to semantic processes. *Journal of Cognitive Neuroscience*, 23(10), 3121-3131.

- Wagner, I. C., van Buuren, M., Kroes, M. C., Gutteling, T. P., van der Linden, M.,  
 Morris, R. G., & Fernandez, G. (2015). Schematic memory components  
 converge within angular gyrus during retrieval. *Elife*, 4, e09668.  
 doi:10.7554/eLife.09668
- Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., .  
 . . Buckner, R. L. (2011). The organization of the human cerebral cortex  
 estimated by intrinsic functional connectivity. *J Neurophysiol*, 106(3), 1125-  
 1165. doi:10.1152/jn.00338.2011
- Zhang, Y., Brady, M., & Smith, S. (2001). Segmentation of Brain MR Images Through a  
 Hidden Markov Random Field Model and the Expectation-Maximization  
 Algorithm. *IEEE Transactions on Medical Imaging*, 20(1), 45-57.



## Figure Legends

**Figure 1.** *Experimental design.* The four different match-to-sample judgments that participants made in this experiment.

**Figure 2.** *Neural activity produced when making decisions based on meaningful objects and when decisions are made from memory.* (a) Activity elicited when decisions were made based using information from perception (b) Activity when decisions were made on the basis of information from memory and (c) when information from memory was more complex. Spatial maps were cluster corrected at  $Z = 3.1$  FWE.

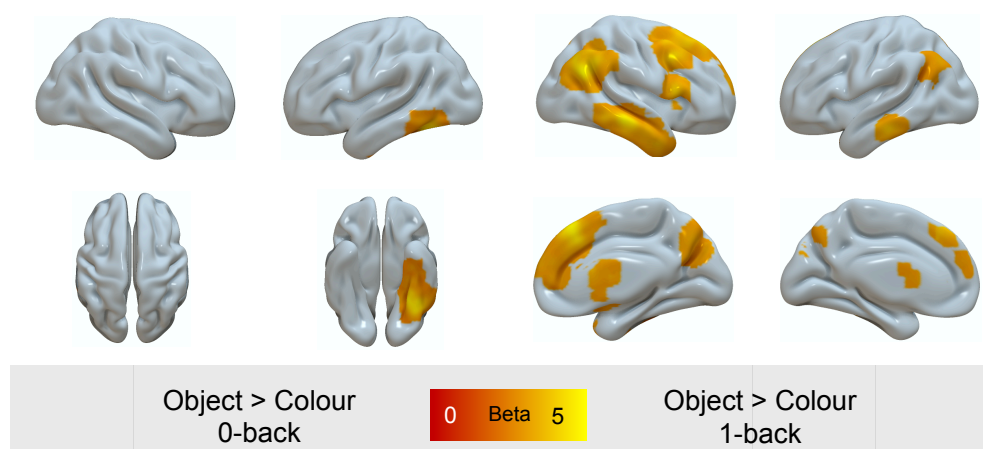
**Figure 3.** *Locating peak activity during stimulus independent decisions regarding complex stimuli.* (a) A conjunction of the neural activity when making decisions based on meaningful categories and when decisions are made in the absence of perceptual input revealed three regions: bilateral angular gyrus and in the left middle temporal gyrus. (b) Percent signal extracted from these regions revealed an additive effect (i.e. these regions responded significantly more to the object condition when information was not present on the screen compared to all other conditions). The conjunction analysis was based on whole-brain cluster corrected spatial maps from Figure 1. Error bars indicated 95% confidence intervals.

**Figure 4.** *Peak areas during stimulus independent decision regarding complex stimuli involve both regions of the default mode network (DMN) and the fronto-parietal network (FPN).* These regions show functional connectivity at rest with both the pre-supplementary cortex and the dorso-lateral pre-frontal cortex. Although the regions identified in our conjunction analysis fall within the DMN they show functional communication with regions in the FPN, including the right dorso-lateral prefrontal cortex. The spatial networks in the grey panel are from the decomposition of Yeo and colleagues. The conjunction analysis was based on whole-brain cluster corrected spatial maps from Figure 1. For the connectivity analyses spatial maps were cluster corrected at  $Z = 3.1$  FWE.

**Figure 5.** *Regions linked to during stimulus independent decisions regarding complex stimuli form localized clusters in transmodal cortex.*

**Figure 6.** *Stimulus independent decisions regarding meaningful objects leads to a whole-brain shift towards the transmodal-end of the gradient. (a) A regions-of-interest analysis using bins of the principal gradient revealed that the decisions that are made on objects rather than colours when these stimuli are not available to perception led to higher activity towards the transmodal-end of the principal gradient. (b) Decomposition using PCA revealed that this difference was related to a gradual shift in the locus of neural activity away from regions on the principal gradient related to perception and action and towards transmodal regions of cortex. Error bars indicated 95% confidence interval.*

**Supplementary material**



**Figure S1.** Comparison of complex memory representation in the presence or absence of relevant perceptual input. Spatial maps were cluster corrected at  $Z = 3.1$  FWE.