# The neural basis of flexible semantic cognition revealed by different modes of semantic retrieval

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# Abstract

Semantic cognition allows us to deploy our conceptual knowledge to support our thoughts and behaviour. It not only enables us to make sense of perceptual information (Lambon Ralph, Jefferies, Patterson, & Rogers, 2017), but also helps us to build thoughts that are decoupled from the external environment (Smallwood & Schooler, 2015). We can also selectively focus on particular aspects of conceptual knowledge to suit our current context or goal (Badre & Wagner, 2002). In this way, semantic cognition has multiple 'modes' that are perceptually-coupled or decoupled, as well as focussed on a predefined goal or context-driven. This flexibility in semantic retrieval is a key capacity within semantic cognition. However, we still lack a clear understanding of how this flexibility comes about. This thesis sought to investigate the neural mechanisms underlying flexible semantic cognition. The first and second empirical chapters examine how semantic cognition supports perceptual-coupled and decoupled mental states. The third empirical chapter examines how goal-directed and context-driven patterns of semantic retrieval are established. The data suggest that lateral temporal sites within the default mode network (DMN), implicated in semantic representation, can form different patterns of functional connectivity with both input regions (i.e., visual cortex) and other DMN regions to support perceptual-coupled and decoupled mental states (Chapters 2 and 3). DMN contributes to both externally-oriented and internally-directed tasks (Chapter 3). Goal-directed semantic retrieval is primarily achieved through the gating of task-relevant input regions (i.e., visual cortex; Chapter 4). Collectively, the findings of this thesis reveal that flexibility of retrieval comes from (i) diverse patterns of functional coupling with semantic regions that produce distinct semantically-driven thought and behaviour, and (ii) control processes applied to the unimodal input systems, based on their relevance to current goals.

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## Author's Declaration

I, Meichao Zhang, declare that this thesis is a presentation of original work and I am the sole author, under the joint supervision of Prof. Beth Jefferies and Prof. Jonny Smallwood. This work has not previously been presented for an award at this, or any other, University.

The empirical work presented in this thesis has been published or is currently under review in the following peer-reviewed journals:

**Zhang, M.,** Savill, N., Margulies, D. S., Smallwood, J., & Jefferies, E. (2019). Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading. *Scientific reports*, *9*(1), 1-13.

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**Zhang, M.,** Wang, X., Varga, D., Krieger-Redwood, K., Smallwood, J., Jefferies, E. Distinct default mode network subsystems show similarities and differences in the effect of task focus across reading and autobiographical memory. (in preparation)

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**Zhang, M.,** Savill, N., Margulies, D. S., Smallwood, J., & Jefferies, E. (2019). Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading. *Poster presented at 25th Annual Meeting of the Organisation for Human Brain Mapping Conference, Rome, Italy.*

**Zhang, M.,** Savill, N., Margulies, D. S., Smallwood, J., & Jefferies, E. (2019). Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading. *Poster presented at Experimental Psychology Society Conference, London, UK.*

# Supervisor's Declaration

As the primary supervisor of Meichao Zhang, I can confirm that this thesis is primarily the work of the candidate. Where I am named as co-author, this is due to my role in editing and supervising. The role of other collaborators has been detailed in the acknowledgements section for each empirical chapter.

# Chapter 1: Introduction and Review of the literature

Semantic cognition allows us to use our conceptual knowledge to support different thoughts and behaviours. It not only enables us to make sense of the information from the external world, such as recognising words and objects (Corbett, Jefferies, Ehsan, & Lambon Ralph, 2009; Lambon Ralph et al., 2017), but also helps us build internal trains of thought that are fully independent of the events in the environment, such as when we daydream about a holiday, or when we mind-wander during reading (Smallwood & Schooler, 2015; Zhang, Savill, Margulies, Smallwood, & Jefferies, 2019). In this way, we may have different 'modes' of semantic retrieval, which are perceptually-coupled or decoupled from the world around us. The ability to successfully drive semantic retrieval from external inputs, for example, when we are reading, understanding speech or searching for a particular object in the environment, is likely to be critical to our capacity to do well in these tasks. It might be less important for our retrieval of autobiographical memories, since in this situation, semantic cognition is more internally-focussed. The capacity to guide semantic retrieval using either sensory or internal memory representations, depending on the circumstances, is a key aspect of flexibility in semantic cognition.

For each given concept, we have rich semantic knowledge and it is unnecessary to retrieve all this knowledge in any given context. Since only some of the knowledge is relevant at any one time, we need to be able to 'shape' semantic retrieval to suit the circumstances (Davey, Cornelissen, et al., 2015; Jefferies, 2013; Lambon Ralph et al., 2017). We can also direct semantic retrieval according to our goals (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2002; Wagner, Paré-Blagoev, Clark, & Poldrack, 2001), selectively focussing attention on particular aspects of knowledge that align with these goals. In addition, we can achieve a timely release from one goal-directed pattern of retrieval and rapidly establish another when the goal switches, such as when we change topics during conversation (Caplan & Dapretto, 2001). Therefore, flexibility is a key capacity within semantic cognition which not only allows us to focus appropriately on input modalities or internal representations such as episodic memory, but also allows us to focus on different aspects of our knowledge about concepts even when the inputs and outputs we are using for a task are unchanged. This type of flexibility in semantic cognition is thought to be supported by control processes interacting with semantic representations but the neural basis of these semantic control processes is still poorly understood.

Much past work on "semantic memory" has focussed on representations – for example, the role of heteromodal 'hub' regions and unimodal sensory/motor regions in understanding the features of concrete concepts. Less work has examined different patterns of semantic retrieval, and how these are tailored to the circumstances, and very little has examined the role of brain regions beyond the left inferior frontal gyrus in semantic flexibility, which for many years has been argued to be important for semantic control. Consequently, this thesis aims to describe the neural basis of flexible semantic cognition by employing different patterns of retrieval that are: i) perceptually-coupled and decoupled and ii) goal-directed vs. context-driven, with a focus on the contribution of large-scale distributed networks in the brain. This chapter will review the literature considering (i) the neural basis of semantic knowledge, (ii) the large-scale neural networks underpinning semantic cognition, and (iii) the flexibility of semantic cognition. In addition, this chapter provides a summary of the aims of the thesis and an overview of the empirical work.

## 1.1. The neural bases of semantic knowledge

Extensive studies have investigated where and how semantic knowledge is represented in our brain. While most theories about the neural basis of semantic representation acknowledge the important role of modality-specific regions in sensory and motor cortex, the "hub-and-spoke" view also proposes that there are "convergence zones" where the information from different modalities is integrated into more abstract and heteromodal semantic representations. The anterior temporal lobe (ATL) is the key candidate for this amodal semantic hub, with its role supported by converging evidence from neuropsychological, neuroimaging, and transcranial magnetic stimulation (TMS) studies (Coccia, Bartolini, Luzzi, Provinciali, & Lambon Ralph, 2004; Jefferies, 2013; Lambon Ralph et al., 2017; Pobric, Jefferies, & Lambon Ralph, 2010a, 2010b). Our rich conceptual knowledge also captures different types of connections between concepts, and there are differing views about how these different types of semantic relation are represented in the brain. This section reviews the studies relevant to the neural bases of (i) semantic representation and (ii) distinct semantic relations.

### *1.1.1. Semantic representation*

#### *1.1.1.1. Distributed-only view and hub-and-spoke view*

Over a lifetime, humans accumulate semantic knowledge about the world via verbal and non-verbal experiences, including general facts, concepts, and word meanings. Multimodal experiences, including action and sensory perception, are the “core ingredients” for constructing concepts, which are thought to draw on specific sensory and motor representations (Binder et al., 2016; Martin, 2016). Accordingly, many researchers propose an “embodied” view that suggests that semantic representation relies on these unimodal sensory and motor features (Barsalou, 1999; Martin, 2007; Pulvermüller, 2005). Functional neuroimaging studies that support this view reveal that the retrieval of specific perceptual or action knowledge elicits activation in the corresponding perceptual and motor cortical areas (Chao, Haxby, & Martin, 1999; Goldberg, Perfetti, & Schneider, 2006; Hauk, Johnsrude, & Pulvermüller, 2004; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995). For example, reading the words “lick”, “pick”, or “kick” led to differential activation in the areas along the motor strip that either were directly adjacent to or overlapped with the areas activated by actual movement of the tongue, fingers, or feet (Hauk et al., 2004). Some patient studies indicate that cortical lesions in the sensory-motor system can also affect conceptual processing (Bonner & Grossman, 2012; Dreyer et al., 2015; Trumpp, Kliese, Hoenig, Haarmeier, & Kiefer, 2013). For example, one patient with a focal lesion in left auditory association cortex showed a specific impairment of perceptual and conceptual processing of sounds from everyday objects (Trumpp et al., 2013). These findings suggest that our semantic representation is grounded in action and perception and relies upon access to distributed modality-specific cortex.

In the classical “distributed-only” view, it is assumed that semantic representations arise from the direct interactions between modality-specific regions without a common transmodal region (see Figure 1.1 A; e.g., Martin, 2007). However, it has been found that sensory and motor activation in isolation is not sufficient for semantic processing (e.g., Bedny, Caramazza, Grossman, Pascual-Leone, & Saxe, 2008). Moreover, this view has also been challenged by the evidence from neuropsychological data. These studies revealed that modality-specific content can be disrupted as shown by impairments to modality-specific processing, while conceptual processing is not measurably affected (Hodges, Spatt, & Patterson, 1999; for a review see Mahon & Caramazza, 2005; Rapcsak, Ochipa, Anderson, & Poizner, 1995; Rosci, Chiesa, Laiacona, & Capitani, 2003). For example, an apraxia case with posterior parietal lesions reported by Rapcsak et al. (1995) was unable to produce transitive movements, but showed remarkably well preserved abstract knowledge of tool function and action. This dissociation between impairments in using objects correctly and preserved conceptual knowledge of either objects or the functions associated with the objects indicates that conceptual representation is not *only* captured by the sensory-motor systems.

Consequently, many researchers have proposed that there are "convergence zones" where the information from different modalities is integrated into more abstract and multimodal semantic representations (e.g., Binder & Desai, 2011; Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Lambon Ralph et al., 2017; Patterson, Nestor, & Rogers, 2007). In this "hub-and-spoke" view, concepts rely on interactions between sensory-motor and abstract modality-independent representations (see Figure 1.1 B). According to this view, damage to these "convergence zones" would lead to catastrophic impairments in different aspects of semantic processing. This view is supported by the findings from patients with lesions in inferior and lateral temporal cortex, particularly patients with semantic dementia, which is characterised by a progressive temporal lobe atrophy focussed on anterior ventrolateral regions and loss of semantic memory. These patients have a wide range of difficulties in semantic processes, including retrieving names or action knowledge of objects, categorizing objects, identifying the colour or sound of objects, acquiring new conceptual knowledge, or judging the similarities between objects, even though their perceptual and visuospatial abilities are strikingly preserved (Coccia et al., 2004; Garrard & Carroll, 2006; Hodges, Patterson, Oxbury, & Funnell, 1992; Hoffman, Evans, & Lambon Ralph, 2014; Jefferies & Lambon Ralph, 2006; for a review see Lambon Ralph & Patterson, 2008; Mummery et al., 2000;

Rogers & Friedman, 2008; Snowden, Thompson, & Neary, 2004). Moreover, for some patients with semantic dementia, who show significant deficits of object naming and visual semantic tasks, their ability to use objects is also impaired and this impairment is positively correlated with deficits of naming and semantic knowledge (Hodges, Bozeat, Lambon Ralph, Patterson, & Spatt, 2000; Hodges et al., 1999). These findings suggest anterior ventrolateral temporal cortex acts as a "semantic hub", which plays a critical role in amodal semantic representation, with damage to this site leading to impaired performance on any given semantic task.

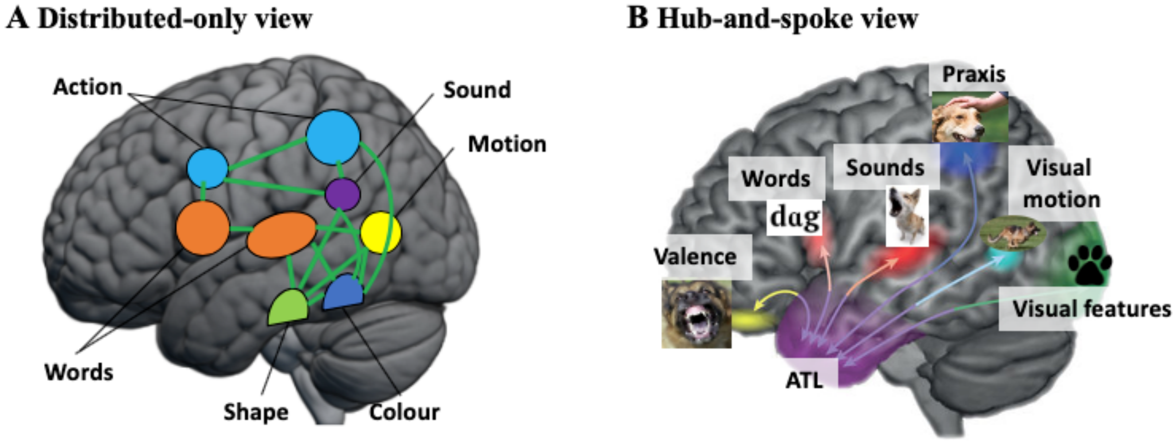

***Figure 1.1.*** The neuroanatomical sketch of distributed-only view and hub-and-spoke view. **A)** The distributed-only view suggests that the semantic representation system comprises widely distributed sensorimotor brain areas, along with the direct interactions between modality-specific regions. **B)** The hub-and-spoke view proposes that, in addition to the semantic knowledge represented by sensory-motor system, there is a amodal hub in anterior temporal lobe, where the inputs from modality-specific brain areas converge, supporting the abstraction and generalization of concepts at modality-independent level. The distributed-only model and hub-and-spoke model were adapted from Patterson et al. (2007) and Lambon Ralph et al. (2017), respectively.

#### *1.1.1.2. Semantic hub: the anterior temporal lobes (ATL)*

There is particularly strong evidence that the ATL forms a cross-modal hub to represent heteromodal concepts following the convergence of different sources of modality-specific information, representing visual, auditory, motor and valance features (see Figure 1.1 B; Lambon Ralph et al., 2017;

Visser, Jefferies, Embleton, & Lambon Ralph, 2012). ATL is engaged by semantic tasks irrespective of input modality and conceptual category (Binney, Embleton, Jefferies, Parker, & Lambon Ralph, 2010; Marinkovic et al., 2003; Vandenberghe, Price, Wise, Josephs, & Frackowiak, 1996; Visser & Lambon Ralph, 2011). Different tasks employing distinct perceptual inputs are initiated by modality-specific systems, which then converge in ATL (Marinkovic et al., 2003). In healthy participants, the inhibitory stimulation of ATL generates a category-general impairment whereas inhibitory stimulation of a region of parietal cortex linked to praxis induces a category-specific deficit related to the function of this region (Pobric et al., 2010b). Moreover, the results from multivoxel pattern analysis show that ATL encodes object properties that are abstracted away from perceptual properties and integrates featural information across modality-specific information sources (Coutanche & Thompson-Schill, 2015; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016; Peelen & Caramazza, 2012). The ATL also shows a diverse patterns of intrinsic connectivity at rest with modality-specific brain areas as well as areas implicated in multimodal semantic cognition that are allied to the default mode network (DMN), such as angular gyrus. The DMN is also thought to be a heteromodal network relevant for memory (see section 1.2.1). This pattern is strongest in the anterior middle and inferior temporal gyri (Guo et al., 2013; Jackson, Hoffman, Pobric, & Lambon Ralph, 2016; Murphy et al., 2017). For patients with semantic dementia, poor semantic task performance is predicted by both ATL atrophy and the reduced connectivity of this site with modality-specific processing nodes (Guo et al., 2013). This body of work provides convergent evidence that ATL is a heteromodal ‘hub’ supporting semantic representation across tasks and allowing mapping between different input and output modalities.

The function of ATL is not homogeneous, but varies across distinct subregions. Consistent with this view, while posterior superior temporal gyrus (STG) has a strong preference for verbal/auditory materials, and posterior inferior temporal gyrus (ITG) has a strong preference for visual inputs, middle temporal gyrus (MTG) shows a multimodal response across different input modalities (Visser et al., 2012): this region is thought to provide a crucial interface for multimodal conceptual integration. It has been suggested that there might be two gradients of information integration within the temporal lobes: one laterally, from STG and ITG into heteromodal MTG, and one from posterior to anterior temporal cortex (Visser et al., 2012). It has also been found that ventral ATL (ITG and MTG) could classify the meaning of words, but not their presentation modality (Murphy et al., 2017). Convergence of different inputs in ventral ATL gives rise to a heteromodal response in ITG, when more posteriorly this structure is dominated by visual inputs (Visser et al., 2012). A recent review paper emphasised the graded nature of conceptual representations: different types of inputs to ATL may be combined in a graded fashion, with those ATL regions that are equally engaged by all different inputs forming the most heteromodal concepts (Lambon Ralph et al., 2017). In line with this view, it has been shown that superior parts of ATL connect more to auditory/somatosensory regions, ventralmedial ATL has stronger connection to visual brain areas, and anterolateral ATL exhibits greater connectivity with semantically-relevant parts of the default mode network, including inferior frontal gyrus and anterior cingulate cortex that are related to controlled semantic processing (Jackson, Bajada, Rice, Cloutman, & Lambon Ralph, 2018; Jackson et al., 2016; Pascual et al., 2015). This differential functional connectivity from ATL subregions might allow its functionality to vary in a graded manner. The ventrolateral ATL remains important for all domains because it connects equally to these different systems (Lambon Ralph et al., 2017).

### *1.1.2. Semantic relations*

#### *1.1.2.1. Taxonomic and thematic relations*

Concepts in our semantic memory are not stored in isolation, but are connected to each other in various ways (Arias-Trejo & Plunkett, 2013). Taxonomic and thematic relations are two important manners of conceptual organization (Borghi & Caramelli, 2003; Estes, Golonka, & Jones, 2011; Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013). Taxonomic relations could be depicted as a hierarchical structure of concepts connected by semantic similarities that are based on shared features, with concepts that have more common features often being taxonomically related (e.g. *dog* and *cat* both belong to the animal category and share features such as having fur and four legs; Hashimoto, McGregor, & Graham, 2007; Murphy, 2010; Rogers & McClelland, 2004); while thematic relations are based on extrinsic relations between concepts such as temporal, spatial, causal or functional relations (Estes et al., 2011). Thematically-related words frequently co-occur in the same episodes or events and play complementary roles (e.g., *dog* and *leash* frequently appear in the same episode; Estes et al., 2011; Goldwater, Markman, & Stilwell, 2011; Mirman & Graziano, 2012a, 2012b). Switching between these two types of relationships is effortful: the response is slower when the dominant relationship in consecutive trials switches to another type (i.e., taxonomic to thematic, or thematic to taxonomic), compared with trials where the dominant relation type remains the same (Landrigan & Mirman, 2018), indicating that taxonomic and thematic semantic processing are supported by different representations or processing mechanisms.

#### ***1.1.2.2. Dual hub or one hub for different semantic relationships?***

Neuropsychological and neuroimaging studies have not yet converged on a consistent view of the neural bases of these different semantic relations. There are some findings suggesting that the ATL is particularly important for the processing of taxonomic relations, while the temporoparietal junction (TPJ) is essential for the processing of thematic relations (Bedny, Dravida, & Saxe, 2014; de Zubicaray, Hansen, & McMahon, 2013; Geng & Schnur, 2016; Kalénine et al., 2009; Mirman & Graziano, 2012a; Schwartz et al., 2011). This view, that there are multiple heteromodal 'hubs' that act as stores for different types of semantic knowledge, is known as the Dual Hub framework (see Figure 1.2 A; Davis & Yee, 2019; de Zubicaray et al., 2013; Schwartz et al., 2011). This view is supported by the evidence from patient and neuroimaging studies that reveal the neural dissociations of different relationships and distinctive contribution of these regions to different aspects of semantic knowledge (Geng & Schnur, 2016; Kumar, 2018; Mirman & Graziano, 2012a; Schwartz et al., 2011; Tsagkaridis, Watson, Jax, & Buxbaum, 2014). For example, in one large-scale study of patients with poststroke language impairment (aphasia), they found that taxonomic picture-naming errors ("pear" in response to "apple") localized to the left anterior temporal lobe and thematic picture-naming errors ("worm" in response to "apple") localized to the left temporoparietal junction (Schwartz et al., 2011). However, there are some neuroimaging studies failing to reveal this ATL-TPJ dissociation pattern and showing the involvement of ATL in thematic semantics and the activation in TPJ influenced by taxonomic relations (Kumar, 2018; Lewis, Poeppel, & Murphy, 2015; Peelen & Caramazza, 2012; Sachs, Weis, Krings, Huber, & Kircher, 2008; Sass, Sachs, Krach, & Kircher, 2009; Teige et al., 2019). For example, an fMRI study found enhanced activation for thematic relatedness and response suppression for taxonomic relatedness in left superior temporal sulcus (Sass et al., 2009). One patient study even found an exact opposite pattern, with the ATL lesions associated with thematic disturbance while posterior lesions associated with taxonomic disturbance (Semenza, Bisiacchi, & Romani, 1992). It might be there is no consistent neural dissociation between different types of conceptual knowledge, the distinction lies in the dynamic coordination of different neural processes rather than the localization of particular brain regions (Skipper-Kallal, Mirman, & Olson, 2015).

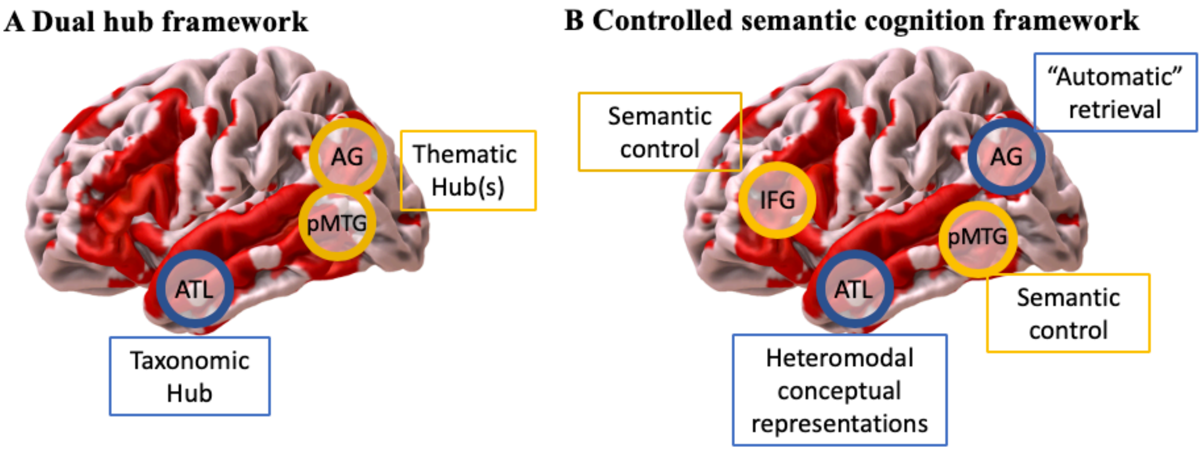

***Figure 1.2.*** The neuroanatomical sketch of dual hub and controlled semantic cognition frameworks. The regions shown in red are implicated in semantic processing by a meta-analysis in Neurosynth using the term "semantic" (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). **A)** The dual hub theory suggests that there are multiple heteromodal 'hubs' that act as stores for different types of semantic knowledge, with the ATL as taxonomic hub while the temporoparietal conjunction (including AG and pMTG) as thematic hub. **B)** The controlled semantic cognition framework alternatively proposes that ATL represents both taxonomic and thematic relations, and that pMTG and AG support automatic and controlled aspects of semantic processes respectively. This figure was adapted from Jefferies, Thompson, Cornelissen, and Smallwood (2020).

An alternative view, the Controlled Semantic Cognition framework (Lambon Ralph et al., 2017) proposes that a single ATL semantic hub encompasses all aspects of knowledge, while the posterior

MTG (pMTG) and Angular Gyrus (AG) within temporal-parietal cortex respond to more controlled and more automatic aspects of semantic retrieval respectively (see Figure 1.2 B). By this view, the difference between taxonomic and thematic retrieval trials can be eliminated when the control demands are matched between conditions. In line with this view, recent research suggests that ATL supports *both* taxonomic and thematic information: healthy participants show activation for both types of relationships in neuroimaging studies, especially when difficulty is matched (Jackson, Hoffman, Pobric, & Lambon Ralph, 2015; Teige et al., 2019), and both types of tasks can be disrupted by inhibitory TMS to this region (Pobric et al., 2010a, 2010b). Moreover, patients with semantic dementia, who have relatively focal ATL atrophy, show more severe semantic degradation for infrequent as opposed to frequent thematic associations, and for fine-grained as opposed to coarse taxonomic distinctions (Jefferies & Lambon Ralph, 2006; Jefferies et al., 2020). Therefore, the same dissociation between ATL and temporo-parietal lesions has been associated with loss of semantic knowledge versus deregulated retrieval (Coccia et al., 2004; Corbett et al., 2009; Corbett, Jefferies, & Lambon Ralph, 2011; Tsagkaridis et al., 2014). By this view, patients with temporal-parietal lesion who made thematic errors (such as responding ‘leash’ to a picture of a ‘dog’) might be failing to constrain their responses, since thematic associations are strongly related to the target and yet not an appropriate response. Patient with ATL atrophy are unlikely to make these errors since they have lost the semantic knowledge that would be required to produce them. These above findings suggests that the ATL, as a heteromodal semantic hub, supports *both* taxonomic and thematic semantic processing. A recent TMS study found distinct contributions of regions within TPJ: the pMTG contributes to the controlled retrieval of conceptual knowledge, while AG is critical for the efficient automatic retrieval of specific semantic information (Davey, Cornelissen, et al., 2015). The inhibitory stimulation of pMTG could selectively disrupt executively demanding semantic judgements with semantic decisions based on strong associations being unaffected (Whitney, Kirk, O'sullivan, Lambon Ralph, & Jefferies, 2010), and the implication of this site in semantic control has also been revealed by a recent meta-analysis (Noonan et al., 2013), its role in semantic control will be discussed in the context of a wider semantic control network (in section 1.2.2.1). These results further revealed that pMTG and AG are not a simple “thematic hub”, but support different components of semantic cognition. Similarly, a recent MEG study which was conducted by

Lewis et al. (2015) showed that although only taxonomic relations were associated with ATL activation, both taxonomic and thematic relations influenced the activation of temporoparietal junction. The TPJ may play a less specific role in representing conceptual relations (Lewis et al., 2015), yet different regions within this territory may have specific and diverse roles in conceptual retrieval.

Taken together, these studies show that while there is still controversy about the number and function of heteromodal semantic hubs, the differential involvement of ATL and TPJ in taxonomic and thematic semantic systems may arise from different semantic processes, rather than separate knowledge stores.

#### ***1.1.2.3. Diverse roles of temporoparietal junction in semantic processing***

There are differences in the functional contributions of temporoparietal regions – pMTG and AG – to semantic processing. As the above mentioned, pMTG supports controlled aspects of semantic retrieval (also see semantic control network section below; Davey, Cornelissen, et al., 2015; Noonan et al., 2013). Previous studies have revealed that this site also plays an important role in processing of complex action knowledge, like associations between actions and meanings (e.g., Bedny et al., 2014; Kable, Kan, Wilson, Thompson-Schill, & Chatterjee, 2005; Kalénine, Buxbaum, & Coslett, 2010; Kiefer et al., 2012; Kilner, 2011; Mahon et al., 2007; Tranel, Kemmerer, Adolphs, Damasio, & Damasio, 2003; Wallentin et al., 2011). One fMRI study found that both action and manipulable object judgments caused greater activity than animal judgments in pMTG (Kable et al., 2005). In a large-scale neuropsychological study with 131 chronic left hemisphere stroke patients, lesions to primary somatosensory cortices and the inferior parietal lobule were associated with impaired performance on action production, whereas lesions to lateral temporo-occipital cortex were associated with impairment on action recognition; in contrast, damage to pMTG was linked to impairment on both action production and recognition (Tarhan, Watson, & Buxbaum, 2015), indicating a rough gradient from modality-specific to abstract representations of action in posterior temporal cortex. These findings suggest that pMTG represents action knowledge that is important for thematic relations. However, little is known about the specific role of this region in thematic semantic processing. It might be that both roles of pMTG (i.e., action knowledge and controlled semantic retrieval) are crucial for linking thematic relations. It has been proposed that tasks tapping event semantics often require greater shaping of conceptual retrieval since this aspect of knowledge is inherently flexible (Jefferies et al., 2020). Any given concept can play different roles in events and scenarios, and therefore connect to diverse concepts via different thematic relations. For example, “candle” can be linked to “cake” via the event of “birthday party”, “church” via the event of “funeral”, and “table” via the event of “dinner”. Consequently, this flexibility in linking thematically related concepts requires not only action knowledge, but also additional semantic control processes supported by pMTG.

By contrast, AG has the opposite profile to pMTG in the face of manipulations of control demands, it plays a critical role in conceptual combination irrespective of input modality (Bemis & Pylkkänen, 2013; Price, Bonner, Peelle, & Grossman, 2015; Price, Peelle, Bonner, Grossman, & Hamilton, 2016). For example, transcranial direct current stimulation (tDCS) to an fMRI-guided region-of-interest in the left AG can selectively modulate integrative processes in semantic memory (Price et al., 2016). Moreover, AG is specifically sensitive to semantic information carried by the verb (Boylan, Trueswell, & Thompson-Schill, 2015), and the activation of this region is greater for relational combinations, for example, “mountain lake” where “mountain” is not an attribute but an object bearing a spatial relation with “lake” (Boylan, Trueswell, & Thompson-Schill, 2017). This might suggest that AG is more sensitive to combinatorial semantic processing and event understanding. In addition, AG is a heteromodal semantic memory region which also contributes to the retrieval of episodic and semantic information. It has been found that AG is involved in the retrieval of spatial and temporal features of a scene (Bonnici, Richter, Yazar, & Simons, 2016). The sensitivity of AG to thematic relations might be also related to its involvement in event and scene processing, and sensitivity to contextual detail (Mirman, Landrigan, & Britt, 2017). Collectively, these studies demonstrate that both pMTG and AG support the processing of thematic knowledge, yet they might have distinct roles in this process.

### *1.1.3. Overall Summary*

Concepts bind together diverse features associated with objects and events. Key regions implicated in semantic representation include ATL as a heteromodal ‘hub’ and ‘spoke’ regions, representing modality-specific features of objects. Consequently, it has been argued that ATL might be particularly critical for taxonomic relations which are based on shared features; however, this view remains controversial and the evidence is weak (e.g., Hoffman, Jones, & Lambon Ralph, 2012). In addition, the role of temporoparietal cortex in semantic cognition is complex and unclear, but there is some evidence that pMTG and AG are particularly important for event semantics and conceptual combinations, despite showing differing patterns of activation and deactivation. The representation of different aspects of knowledge and the question of how we can recall particular aspects at different points in time is key to flexibility within semantic cognition. One possibility is that ATL represents *both* thematic and taxonomic relations and then interacts differently with other brain networks, giving rise to distinct patterns of retrieval that focus on shared features, or the way concepts are used or found together. Alternatively, this information may be captured by distinct brain circuits, and flexible and adaptive patterns of semantic retrieval may emerge from the capacity to engage relevant brain networks and the mechanisms that allow us to retrieve particular aspects of conceptual knowledge. Control processes, discussed below, may be also critical in allowing the taxonomic or thematic knowledge required by a task to be brought to the fore.

### 1.2. Neural networks underpinning semantic cognition

It has been proposed that semantic cognition depends on the interaction between two principal systems: first, conceptual knowledge is represented in widely distributed brain regions including both heteromodal hub(s) and spokes; and second, control processes manipulate the activation within the representational system to retrieve the semantic information that is appropriate for the current goal or context (Lambon Ralph et al., 2017). Moreover, recent research has revealed that semantic cognition is supported by several distributed neural networks. These large-scale networks include the default mode network, semantic control network and multiple-demand network, which differently contribute to these components of semantic cognition. This section reviews the relevant studies corresponding to each of these networks.

### *1.2.1. Default mode network (DMN)*

#### *1.2.1.1. The role of DMN in semantic cognition*

The DMN was first defined as a network of regions that consistently exhibit deactivation during a wide variety of attention-demanding, goal-directed tasks, when compared with brain activity during relaxed non-task states, such as resting with eyes closed or simple visual fixation (Raichle et al., 2001). This network consists of bilateral and largely symmetrical brain areas, in the medial and lateral temporal cortex, medial prefrontal cortex, medial and lateral parietal cortex (see Figure 1.3 A). These areas form a coherent network at rest, as revealed by studies of large-scale intrinsic brain organisation (e.g., Fox et al., 2005; Greicius, Krasnow, Reiss, & Menon, 2003; Yeo et al., 2011).

DMN is now associated with memory-guided heteromodal aspects of cognition (Andrews-Hanna, Reidler, Sepulcre, Poulin, & Buckner, 2010; Jackson et al., 2016; Margulies et al., 2016; Sestieri, Corbetta, Romani, & Shulman, 2011; Spreng, Mar, & Kim, 2009). Recent macroscale decompositions of brain connectivity at rest have helped characterize the neural regions that are important for heteromodal memory representations in a more formal way (Margulies et al., 2016). Margulies et al. (2016) described a principal gradient of functional connectivity by characterizing the principal components describing the maximum variance in functional connectivity patterns, with one end of this gradient anchored by systems implicated in sensory and motor systems and the other end by transmodal association regions, corresponding to the DMN (see Figure 1.3 B). These DMN regions are situated at the furthest distance from the systems involved in perception and action in both functional connectivity and anatomical space, and the location of DMN is also equidistant from all sensorimotor systems (Margulies et al., 2016). Such regions are therefore able to support the integration of diverse features from multiple sensorimotor regions, which is important for heteromodal aspects of cognition that require a broaden information integration, such as semantic and episodic memory (e.g., Lambon Ralph et al., 2017; Rugg & Vilberg, 2013).

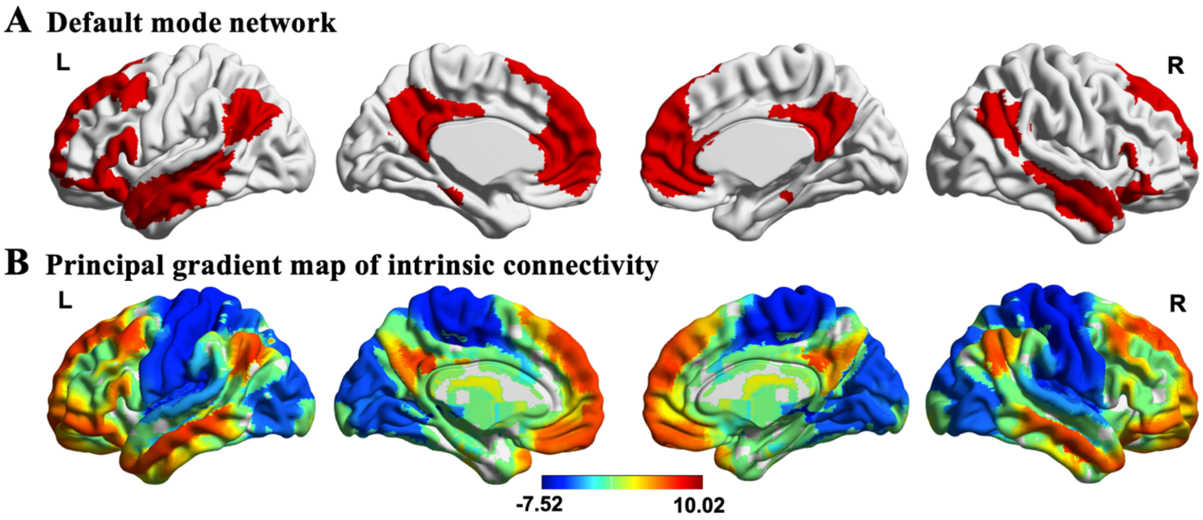

***Figure 1.3.*** **A)** The default mode network (DMN; in red) defined by Yeo et al. (2011) in a 7-network parcellation of whole-brain intrinsic connectivity for 1000 brains. **B)** Principal gradient map of intrinsic connectivity from Margulies et al. (2016) capturing the transition between unimodal regions (cold colours) and heteromodal regions corresponding to the DMN (warm colours). L = Left hemisphere; R = Right hemisphere.

The ATL, important for conceptual representation, is allied with the DMN in terms of its pattern of connectivity at rest (Jackson et al., 2016). Another DMN region, AG, is also thought to be essential to conceptual representation (Binder, Desai, Graves, & Conant, 2009; Koenig & Grossman, 2007). This region appears to have widespread white matter connectivity, expected for a heteromodal integrative region: it is situated at the convergence of major white matter pathways connecting sensory and motor association areas as well as language and episodic memory regions of the frontal, parietal, and temporal lobes (Caspers et al., 2011; Turken & Dronkers, 2011; Uddin et al., 2010). Both ATL and AG contribute to the retrieval of strong associations (Davey, Cornelissen, et al., 2015; Humphreys & Lambon Ralph, 2014; Lau, Gramfort, Hämäläinen, & Kuperberg, 2013), such as linking dog with cat. This view is also supported by a recent study, revealing that regions within DMN, including ATL and AG, exhibit stronger response when the conceptual combinations are highly overlapping in long-term semantic memory (e.g., *strawberry* and *raspberry*; Wang, Margulies, Smallwood, & Jefferies, 2020). Both of these regions are essential for conceptual combinations and are thought to support semantic retrieval in coherent contexts (Hoffman, Binney, & Lambon Ralph, 2015; Price et al., 2015). For example, it was found that the process of combining concepts to form meaningful representations specifically modulates neural activity in angular gyrus, independent of the modality of the semantic content integrated (Price et al., 2015). Moreover, DMN regions also support states of semantic information integration that constrain ongoing semantic cognition (Lanzoni et al., 2020). While the DMN typically deactivates to demanding tasks (Anticevic et al., 2012), the involvement of DMN in semantic tasks seems unlikely to be simply explained by task difficulty. For example, in a feature matching task conducted by Wang, Margulies, et al. (2020), the DMN regions still showed stronger response to the harder non-matching trials when the items were semantically related (e.g., matching apple and banana based on shape feature), even though global semantic similarity was no longer associated with task decisions. Therefore, the implication of DMN in semantic cognition might specifically reflect its role in supporting conceptual processing, instead of its sensitivity to task demand or difficulty.

The regions in DMN are important for semantic cognition, perhaps because these brain regions are situated far along an information-processing hierarchy which captures the separation in both the physical and intrinsic connectivity between unimodal (e.g., sensorimotor areas like visual cortex) and heteromodal regions as the above mentioned (see Figure 1.3 B; Margulies et al., 2016; Margulies & Smallwood, 2017), allowing (i) the integration of multiple types of features and (ii) the abstraction of knowledge from experience in the physical world. This enables the regions within the DMN to represent abstract information that goes beyond the sensory input, which is important in tasks where contextually-derived meaning is important. By this view, the DMN regions, acting as hubs of integration across multiple sensory modalities, can be driven by a wide range of different external and internal inputs, explaining why these regions of cortex show "echoes" of multiple networks in their patterns of intrinsic connectivity (Leech, Braga, & Sharp, 2012; Leech, Kamourieh, Beckmann, & Sharp, 2011).

#### *1.2.1.2. The engagement of DMN in different mental operations*

The DMN can play diverse roles in cognition. Typically, the DMN shows deactivations relative to baseline when people are asked to perform a wide range of cognitive tasks (Raichle et al., 2001), consistent with its original designation as a "task-negative network". This network has been linked to spontaneously occurring, internal oriented mental processes (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007), such as daydreaming, mind-wandering, and stimulus-independent thoughts (Andrews-Hanna, Reidler, Huang, & Buckner, 2010; Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016). DMN regions increase their activation during spontaneous thought (Christoff, Ream, & Gabrieli, 2004). Furthermore, it has been found that spontaneous thoughts undermine the encoding of external information: focusing on the internal world causes a decoupling of conscious thoughts from perceptual inputs (Smallwood, 2011). For example, it is well-established that when we are reading, we sometimes drift off from focussing on the meaning of the text, and start to mind-wander: the more that this happens, the poorer our comprehension (Smallwood et al., 2013; Smallwood, McSpadden, & Schooler, 2008). This account of DMN function emphasises "perceptual decoupling": DMN shows activation when attention is coupled to internal as opposed to external representations.

The recruitment of DMN is not specific to spontaneous cognition; it is also implicated in deliberate, goal-directed mental states, including imagination (Østby et al., 2012), creativity (Beaty et al., 2014; Kühn et al., 2014) and memory retrieval (for review, see Buckner, Andrews‐Hanna, & Schacter, 2008; Spreng et al., 2009) that do not require a strong attentional focus on the perceptual inputs. Moreover, DMN regions also contribute to externally-focused, goal-directed tasks, such as reading comprehension (Smallwood et al., 2013), semantic decisions (Krieger-Redwood et al., 2016), and demanding working memory tasks (Murphy et al., 2018; Vatansever, Menon, Manktelow, Sahakian, & Stamatakis, 2015) that are driven by words or pictures presented in the external world. These findings provide converging evidence that the DMN is not "task negative", but also supports cognitively-demanding mental operations and tasks that involve perceptual coupling. Both mind-wandering and the tasks supported by DMN might involve the more abstract forms of representation that can arise from the high-level integration of information.

#### *1.2.1.3. Subsystems within the DMN*

It has been shown that there are distinct, yet interacting, subsystems within DMN (see Figure 1.4; Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Yeo et al., 2011). One of the DMN subsystems, termed *the dorsal medial subsystem,* comprises lateral temporal cortex, temporal pole, dorsal medial prefrontal cortex, temporoparietal junction, and lateral prefrontal regions including superior/inferior frontal gyrus, ventrolateral prefrontal cortex. Given its important functional role in semantic cognition, particularly the lateral temporal cortex and left inferior frontal gyrus within this subsystem (see below for detailed discussion about the distinct functional roles of DMN subsystems), this subsystem is referred to in this thesis as the "*lateral temporal subsystem*"; while a *medial temporal subsystem* consists of hippocampus, parahippocampal cortex, restrosplenial cortex, and posterior inferior parietal lobe. Along the cortical midline, posterior cingulate cortex, medial prefrontal cortex, and AG, are thought to exhibit strong functional coupling with both subsystems and act as critical *core* to allow information to transfer between subsystems (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Andrews-Hanna, Smallwood, & Spreng, 2014). Andrews-Hanna et al. (2010) provided initial evidence for multiple subsystems within DMN. In this study, she used hierarchical clustering analyses to partition resting-state functional connectivity and task-related fMRI data from eleven left-lateralised and midline DMN regions into two separable subsystems (corresponding to lateral temporal subsystem and medial temporal subsystem), with each subsystem highly correlated with midline core DMN regions. This finding was then replicated by Yeo et al. (2011) by using whole-brain clustering approaches, showing stronger functional connectivity within subsystems than between subsystems.

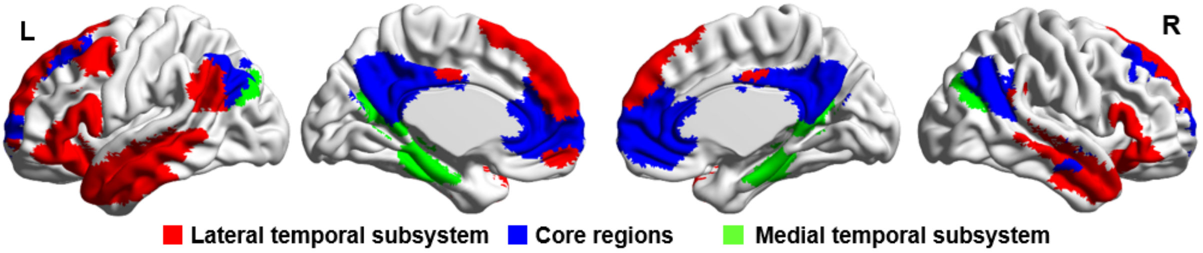

***Figure 1.4.*** **Subsystems within default mode network.** Subsystems were defined by Yeo et al. (2011) in a 17-network parcellation of whole-brain functional connectivity for 1000 brains, and labelled in line with Andrews-Hanna et al. (2010): the medial temporal subsystem is shown in green, core DMN is shown in blue and the lateral temporal subsystem is shown in red. L = Left hemisphere; R = Right hemisphere.

Based on the components within each subsystem, these multiple subsystems within DMN might serve distinct cognitive functions. The brain regions within the *medial temporal subsystem* are important for autobiographical and episodic memory (e.g., Bird & Burgess, 2008; Horner, Bisby, Bush, Lin, & Burgess, 2015; Nyberg et al., 1996; Steinvorth, Levine, & Corkin, 2005). It has been found that the hippocampus binds together the diverse elements forming an event (Horner et al., 2015), and contains significantly more episodic information than adjacent structures (Chadwick, Hassabis, Weiskopf, & Maguire, 2010). These findings suggest that the medial temporal regions support the binding of such information into integrated representations, which is critical for the retrieval of episodic and autobiographical memory (e.g., Eichenbaum, Sauvage, Fortin, Komorowski, & Lipton, 2012; Kirwan, Bayley, Galván, & Squire, 2008; Nyberg et al., 1996; Rugg & Vilberg, 2013; Staresina, Henson, Kriegeskorte, & Alink, 2012; Steinvorth et al., 2005). In contrast, the regions in the *lateral temporal subsystem* are implicated in the representation and retrieval of conceptual knowledge (Badre & Wagner, 2002; Jackson et al., 2016; Jefferies, 2013; Lambon Ralph et al., 2017; Noonan et al., 2013). As mentioned previously, ATL within lateral temporal cortex acts as heteromodal semantic hub supporting the integration of multiple sources of modality-specific information, allowing us to extract abstract conceptual knowledge (e.g., Lambon Ralph et al., 2017; Patterson et al., 2007). Another site within this subsystem, in the anterior left inferior frontal gyrus, plays an important role for controlled semantic retrieval (e.g., Badre & Wagner, 2002, 2007). It has been found that a critical core DMN region, medial prefrontal cortex, was functionally coupled with other DMN regions during autobiographical memory recall, prospection, and theory of mind tasks (Spreng et al., 2009). The variations in connectivity from both medial and lateral temporal lobe region with the posterior cingulate cortex is also associated with different patterns of spontaneous thoughts (Smallwood et al., 2016). The spatial patterns within this posterior site are correlated when encoding and rehearsing the same video clip, and this strength of correlation can predict the number of details recalled later (Bird, Keidel, Ing, Horner, & Burgess, 2015). These studies suggest that the posterior DMN core acts as a representational hub that integrates information represented in medial and lateral temporal lobe. Taken together, the above findings suggest that the *lateral temporal* and *medial temporal DMN subsystems* relate to long-term semantic and episodic memory systems in the brain respectively, while core DMN regions might allow the information to be transferred and integrated across these subsystems.

An alternative view is that the DMN consists at least two spatially juxtaposed networks with clear spatial distinctions along the anterior and posterior midline (Braga & Buckner, 2017; Braga, Van Dijk, Polimeni, Eldaief, & Buckner, 2019), which have often been described as functional hubs of convergence. This view is supported by the evidence from intrinsic functional connectivity within the individual, which enables the fine spatial details to be preserved without the blurring associated with group averaging (Braga & Buckner, 2017; Braga et al., 2019). A key distinction between these two parallel interdigitated DMN networks identified by Braga and Buckner (2017) is that one is coupled with the posterior parahippocampal cortex within the medial temporal lobe, whereas the other one is not, suggesting that they might be functionally specialized. Given that DMN is implicated in a broad set of internally oriented tasks (Buckner & Carroll, 2007; Spreng et al., 2009), it has been proposed that these multiple DMN networks might have a common processing mode that is dependent on internally constructed rather than externally constrained representations, with each separate network specialized for a distinct processing domain (for a review see Buckner & DiNicola, 2019). By this view, there is a need to revisit the role of the putative role of core DMN regions that act as functional hubs for information flow across subsystems, since these regions, especially midline core including medial prefrontal cortex and posterior cingulate cortex, have now been shown to participate in multiple separate, spatially juxtaposed networks (Braga & Buckner, 2017; Braga et al., 2019). However, this view also raises questions about how diverse information is integrated and transferred in the brain, such as when we recollect episodic memory. Collectively, both of these above views suggest that the DMN is not a functional homogeneous single network, but is composed of multiple distinct subsystems with each subnetwork serving distinct cognitive processes.

#### *1.2.1.4. Diverse functional connectivity of semantic regions within DMN*

Lateral temporal regions show strong intrinsic connectivity with both primary visual cortex and other DMN regions, in both rest and task states (Jackson et al., 2016; Murphy et al., 2017). This finding might reflect the fact that the heteromodal conceptual store, supported by ventrolateral anterior temporal cortex, plays a role in spontaneous thought (Smallwood et al., 2016) as well as externally-oriented semantic tasks such as object recognition and reading comprehension (Chiou & Lambon Ralph, 2016a; Lambon Ralph et al., 2017; Spitsyna, Warren, Scott, Turkheimer, & Wise, 2006; Xu, Kemeny, Park, Frattali, & Braun, 2005). Functional connectivity from temporal lobe regions also predicts individual differences in both self-generated thoughts and externally presented tasks that involve conceptual processing (Poerio et al., 2017; Smallwood et al., 2013; Smallwood et al., 2016). Variation in functional connectivity from both medial and lateral temporal lobe regions with medial DMN core is associated with individual differences in patterns of spontaneous thought (Smallwood et al., 2016). Increasing task focus on reading comprehension is associated with functional connectivity from temporal cortex to anterior medial prefrontal cortex (Smallwood et al., 2013). When the medial temporal DMN regions linked to episodic memory are functionally coupled with lateral temporal DMN regions implicated in conceptual processing, participants show poor external engagement, but are better at task that depend on memory retrieval (Poerio et al., 2017). Together these findings suggest that the DMN regions implicated in conceptual processing may functionally couple with both input modalities and other DMN sites relevant to other memory systems, influencing how effectively participants can engage in different forms of conceptual processing.

#### *1.2.1.5. Summary*

These findings suggest that the DMN is implicated in opposing mental states – both internally-generated mental states, such as spontaneous thoughts and memory-based tasks – and externally-oriented aspects of semantic cognition that allow us to understand the world and guide our actions. However, it is still unclear how the DMN supports opposing mental states like mind-wandering (internally-generated and perceptually-decoupled) and reading comprehension (i.e., externally-generated and perceptually-coupled). It might be that ATL and AG within the DMN support coherent semantic combinations. Internally-generated patterns of retrieval may often be more coherent, while more conflicting information can be encountered in external tasks; this might lead to greater involvement of the DMN regions in internally-oriented cognition. In externally presented tasks, there is typically a stronger response in DMN when the knowledge that is needed is well-aligned with the strongest representations in long-term memory, or when the task evokes more coherent patterns of retrieval in which different features strongly predict each other. These effects do not appear to be fully explained by reduced task difficulty. Furthermore, different patterns of ATL connectivity might support internal and external semantic retrieval. The balance between these two patterns of functional connectivity, and consequently whether semantic cognition tends to be driven by the external world or become perceptually decoupled, might give rise to differences between people in the extent to which they stay focused on understanding words and objects around them, or start to mind-wander. Similarly, the capacity to elicit different patterns of connectivity at different points in time might relate to mental flexibility – i.e. the extent to which different patterns of retrieval can be produced at different points in time, depending on the circumstances.

### *1.2.2. Semantic control network*

#### *1.2.2.1. The role of semantic control network in semantic cognition*

When there is less coherence or the information that is required by a task is not the strongest in memory, additional control processes may be needed to constrain semantic retrieval (Badre et al., 2005; Jefferies, 2013; Teige et al., 2019; Wang, Margulies, et al., 2020; Whitney, Kirk, O'Sullivan, Lambon Ralph, & Jefferies, 2012). The retrieval of relatively weak global associations is a good example of such a task: non-dominant semantic features are required in the absence of a strong supporting context. For example, to link *snow* with *salt*, it is necessary to establish a linking context from the concepts themselves (such as cleaning snow) and then to retrieve features relevant to this context. Semantic control might also be required when comprehending ambiguous words, allowing activation to be focussed on the relevant interpretation (Mollo, Jefferies, Cornelissen, & Gennari, 2018; Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007), when there are many strong distractors presented (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997), and when irrelevant information is primed before the semantic decision (Moss et al., 2005; Zhang et al., 2004), since these manipulations make it harder to home in on a useful pattern of semantic retrieval to support the current task.

Substantial evidence indicates that left inferior frontal gyrus (LIFG) and posterior middle temporal gyrus (pMTG) are critical for the controlled retrieval of semantic knowledge (Badre et al., 2005; Badre & Wagner, 2007; Demb et al., 1995; Noonan et al., 2013; Noppeney & Price, 2004; Whitney et al., 2010; Zhang et al., 2004). Repetitive TMS studies show that inhibitory stimulation of LIFG and pMTG elicits equivalent disruption of executively-demanding semantic decisions (Davey, Cornelissen, et al., 2015; Whitney et al., 2010, 2012). For patients with stroke aphasia, damage to these distributed control sites elicits impairments of controlled semantic retrieval (Harvey, Wei, Ellmore, Hamilton, & Schnur, 2013; Jefferies, Baker, Doran, & Lambon Ralph, 2007; Jefferies & Lambon Ralph, 2006; Noonan, Jefferies, Corbett, & Lambon Ralph, 2010; Robinson, Blair, & Cipolotti, 1998; Stampacchia et al., 2018; Thompson et al., 2017). Moreover, in a neuroimaging meta-analysis, LIFG and pMTG were the sites activated most strongly and consistently across many different contrasts designed to tap semantic control (Noonan et al., 2013). In this study, when high-control semantic tasks were contrasted with demanding phonological judgements, pMTG and the anterior part of LIFG showed a specifically semantic response (Noonan et al., 2013). In one positron emission tomography (PET) study, LIFG was also specifically recruited during semantic processing (but not phonological decisions), and its activation was modulated by the difficulty of the semantic judgement (Roskies, Fiez, Balota, Raichle, & Petersen, 2001). These findings suggest that semantic control may be distinct from other aspects of language or domain-general control. Apart from LIFG and pMTG, dorsal aspects of angular gyrus and pre-supplementary motor area (SMA) also contribute to the controlled retrieval of conceptual knowledge (Davey, Cornelissen, et al., 2015; Noonan et al., 2013; Whitney et al., 2010). The above findings suggest that the distributed regions within semantic control network (see Figure 1.5) direct semantic retrieval so that it is appropriate for the current task or context.

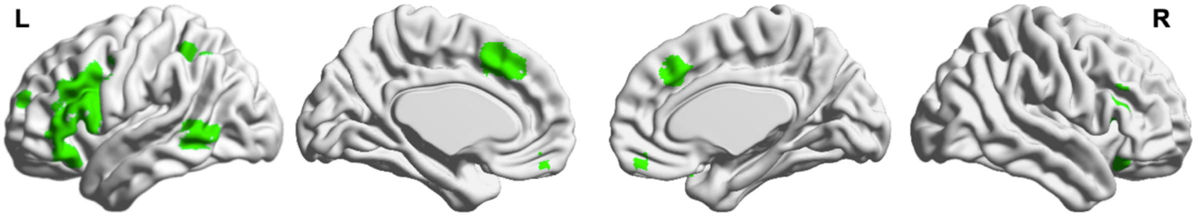

***Figure 1.5.*** The semantic control network defined by Noonan et al. (2013), in a formal meta-analysis of 53 studies that manipulated executive semantic demands. L = Left hemisphere; R = Right hemisphere.

Recruitment of this network is maximised when non-dominant information or weak associations must be retrieved, or there is competition or ambiguity (Davey, Cornelissen, et al., 2015; Davey et al., 2016; Demb et al., 1995; Noonan et al., 2013; Noppeney & Price, 2004; Teige et al., 2019; Wagner et al., 2001; Whitney et al., 2010; Zempleni et al., 2007; Zhang et al., 2004). For example, LIFG activation increases with semantic retrieval demands and with the level of control required during retrieval (Wagner et al., 2001). LIFG and pMTG exhibit greater activation when participants are asked to match words based on the specific sensory-motor features, such as colour and action (Badre et al., 2005; Davey et al., 2016). In contextually driven ambiguity resolution, LIFG also supports comprehension; the increases in activation for ambiguous contexts versus congruent contexts in LIFG is correlated with the amount of semantic interference experienced by individuals (Hoenig & Scheef, 2009; Zempleni et al., 2007). In these studies, the increased activation of controlled regions is driven by the need to suppress irrelevant competing semantic information or to inhibit the dominant meaning of words, which enables semantic retrieval to be focussed on aspects of knowledge that are *not the strongest* responses for the inputs.

It has been proposed that controlled retrieval of task- or context-appropriate semantic information relies upon the dynamic interaction between the semantic representation system and control processes (Chiou, Humphreys, Jung, & Lambon Ralph, 2018; Jefferies, 2013; Lambon Ralph et al., 2017). In a recent study, LIFG changed its pattern of connectivity according to the task, connecting more to visual colour regions during demanding colour matching trials, and to ATL during easier globally-related semantic trials (Chiou et al., 2018). This control of the semantic representation system might be critical for retrieving the appropriate aspect of semantic knowledge to suit the current context or goal (Lambon Ralph et al., 2017; Noonan et al., 2010; Noonan et al., 2013). However, it is still unknown how controlled semantic cognition is achieved through interactions between semantic representations and control processes. Particularly, where control is applied to the semantic representation system, the heteromodal semantic hub or unimodal spoke regions. A recent computational model of controlled semantic cognition suggested that efficient controlled semantic cognition is best achieved in model where semantic control exerts more direct influence over shallower elements of the representational network (e.g., spokes), rather than deep network layers (e.g., multimodal semantic hub; Jackson, Rogers, & Lambon Ralph, 2019). This view suggests that control processes might directly modulate the activation in spoke regions within semantic network to constrain semantic retrieval. Alternatively, given the findings mentioned above that LIFG interacts with both hub and spoke regions across tasks (Chiou et al., 2018), the way retrieval is controlled might also depend on the task context, such as if there is specific goal to direct retrieval focussing on particular aspect of conceptual knowledge. Taken together, control over semantic representation is essential for the flexible retrieval of task-appropriate semantic information.

#### *1.2.2.2. Functional subdivisions in LIFG*

As previously reviewed, LIFG has been implicated in control processes that constrain semantic retrieval in a task-appropriate fashion (Badre & Wagner, 2002; Noonan et al., 2013; Thompson-Schill et al., 1997; Whitney et al., 2012). The function of this region is not homogeneous, Badre and his colleagues have suggested that different regions of LIFG have dissociable roles in semantic retrieval (Badre et al., 2005; Badre & Wagner, 2007). This view distinguishes between a *controlled semantic retrieval* that activates when semantic knowledge cannot be retrieved automatically and a *selection process* that supports domain-general selection, including semantic knowledge, from among competitors (Badre et al., 2005): *Controlled semantic retrieval* process depends on activation in anterior parts of LIFG and lateral temporal cortex, allowing retrieval of relevant semantic information from semantic stores; while a more general *selection process* is mediated by more posterior and superior regions of LIFG to resolve competition among active representations (Badre et al., 2005; for a review see Badre & Wagner, 2007). This functional subdivision in LIFG is supported by the evidence that sub-regions within LIFG show distinct patterns of structural and functional connectivity: ventral LIFG connects broadly to lateral temporal cortex, by contrast, dorsal LIFG connects with central executive network regions, including adjacent dorsal lateral prefrontal gyrus (Barredo, Verstynen, & Badre, 2016). This finding is consistent with the possibility that anterior IFG is linked to controlled memory retrieval (potentially across both semantic and episodic domains; Barredo et al., 2016), while posterior dorsal IFG, potentially extending into the domain-general control areas, is implicated in selection within and potentially beyond the semantic domain, and supports phonological as well as semantic tasks (Poldrack et al., 1999; Snyder, Feigenson, & Thompson-Schill, 2007; Wagner et al., 2001).

#### *1.2.2.3. Connectivity between DMN and semantic control network*

DMN is often anti-correlated with the regions implicated in cognitive control (Fox et al., 2005), consistent with the view that this network is important for automatic memory retrieval. However, both the DMN and semantic control network are involved in controlled semantic retrieval (Krieger-Redwood et al., 2016; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010). Functional connectivity of posterior cingulate cortex (PCC) in DMN with dorsolateral prefrontal cortex (PFC) was increased when participants performed demanding semantic tasks, even as the PCC deactivated (Krieger-Redwood et al., 2016). This is in line with a recent finding that the DMN can show an increase in activity during a large and demanding switch in task set (Crittenden, Mitchell, & Duncan, 2015). These studies show that although the DMN is anti-correlated with control networks, under some circumstances these networks work together: for example, in controlled semantic retrieval, both of these networks are likely to be required. The semantic control sites, anterior IFG and pMTG, fall between the DMN and executive control network on the cortical surface and show patterns of positive intrinsic connectivity to both of these large-scale networks (Davey et al., 2016; Noonan et al., 2013). These sites are at a nexus linking anterior temporal regions supporting heteromodal semantic representations with prefrontal regions supporting control processes (Davey et al., 2016). This may allow the integration of these two components of semantic cognition.

#### *1.2.2.4. Summary*

These findings suggest that a largely distributed left-lateralised semantic control network plays a critical role in controlled semantic retrieval, particularly, when the required semantic information cannot be automatically brought to fore. However, it is unclear if all difficult semantic tasks (e.g., verbal vs. non-verbal) rely on the same semantic control network, or if there are differences between different tasks. Also, we know relatively less about the specific role of this network in *proactive* semantic control, if the neural basis of this top-down control draws on the same semantic control mechanism as the manipulations of semantic control demands. These control processes are thought to dynamically interact with the semantic representation system by manipulating the activation within this system (e.g., Chiou et al., 2018; Lambon Ralph et al., 2017), which might consequently alter the dynamic interaction between hub and spokes to constrain semantic retrieval in a task- or context-appropriate fashion. However, it is still unknown if the control is applied to the heteromodal semantic hub (i.e., ATL) or spoke regions (e.g., visual spoke) within this representational network. It might depend on task context: for the top-down control, control might be applied to the relevant spoke regions (Jackson et al., 2019); when the retrieval is constrained by current context (i.e., stimuli-driven), control might interact with semantic hub to constrain semantic retrieval (Chiou et al., 2018). Moreover, the distinctive functions of LIFG might also contribute to these different types of semantic retrieval: the anterior part of this region might be more important for controlled semantic retrieval, while the posterior part of this site might play an important role in goal-directed semantic retrieval.

### *1.2.3. Multiple-demand network (MDN)*

#### *1.2.3.1. The role of MDN in cognitive control*

The multiple-demand network (MDN; see Figure 1.6 A) includes parts of dorsolateral prefrontal cortex, precentral regions, regions in and around intraparietal sulcus, parts of insular cortex, presupplementary/supplementary motor cortex, inferior posterior temporal and adjacent occipital regions. This network supports executive control across domains (Crittenden & Duncan, 2014; Duncan, 2010), regardless of whether mental operations utilise conceptual knowledge or not. Using a series of demanding cognitive tasks, Fedorenko et al. (2013) demonstrated the engagement of MDN regions across tasks including arithmetic, working memory, and inhibiting irrelevant information. The manipulation of task demands evokes broad activation in frontoparietal regions, regardless of the task (Crittenden & Duncan, 2014; Cusack, Mitchell, & Duncan, 2010; Stiers, Mennes, & Sunaert, 2010). The engagement of MDN also varies with cognitive load; it shows a degree of functional differentiation with greater activation in posterior MDN regions especially at a lower load, but a more broadly co-recruitment beyond posterior MDN (i.e., including the inferior MDN regions), with increased challenge or incentive (Shashidhara, Mitchell, Erez, & Duncan, 2019). The functional connectivity pattern of this network could flexibly shift according to task demands and facilitate adaptive task performance (Cole et al., 2013; Stiers et al., 2010). These studies show that MDN plays a central role in general-domain cognitive control and adaptive implementation of task demands.

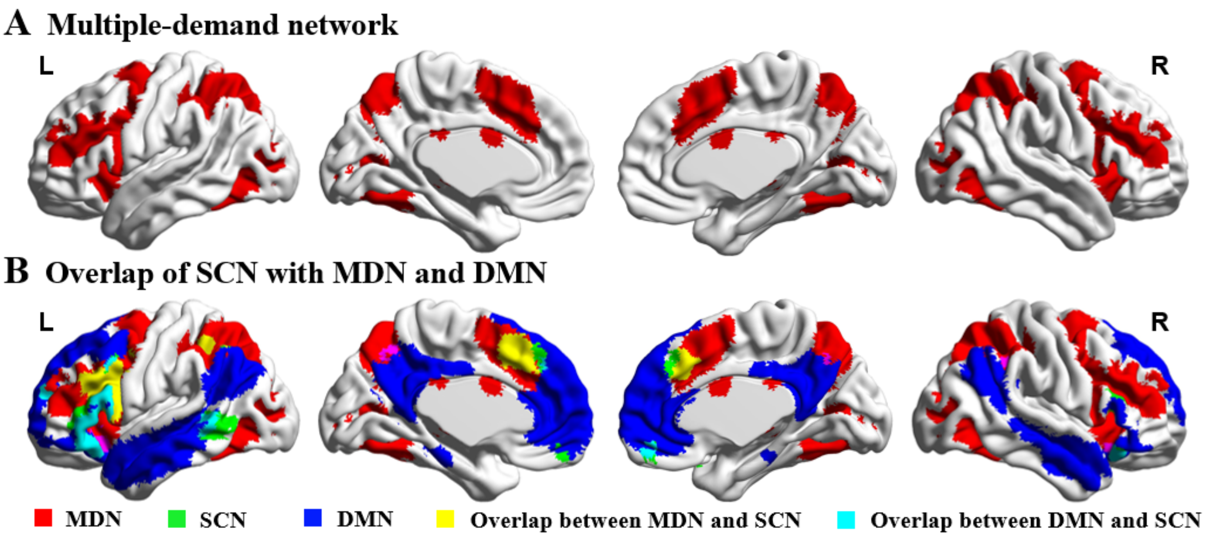

*Figure 1.6.* **A)** The multiple-demand network defined by the response to difficulty across a diverse set of demanding cognitive tasks (Fedorenko et al., 2013). **B)** The semantic control network is intermediate between the default mode network (DMN; in blue with overlap in cyan with SCN) and multiple demand network (MDN; in red with overlap in yellow with SCN). The network maps are fully saturated to emphasize the regions of overlap. L = Left hemisphere; R = Right hemisphere.

Moreover, the MDN network is thought to support our intended behaviour by adaptively coding information that is currently relevant (Duncan, 2010). Accordingly, this network is proposed to represent information in a task-dependent fashion. In line with this view, it has been shown that MDN regions, particularly the inferior frontal sulcus and intraparietal sulcus, could adaptively represent task features that are relevant to goal-directed behaviour (Crittenden, Mitchell, & Duncan, 2016; Woolgar, Hampshire, Thompson, & Duncan, 2011; Woolgar & Zopf, 2017). In one study using multiple cognitive tasks, although there was common activation in frontal-insular regions in all tasks, each task invoked a unique response pattern across the voxels in these areas (Stiers et al., 2010). This finding is confirmed by a recent study, which further revealed that voxels with the same task preference still functionally coupled during execution of non-preferred tasks and exhibited stronger functional connectivity during rest which was similar across participants, indicating task demand-specific MDN voxel assemblies (Stiers & Goulas, 2018). When performing a task with multiple-step episodes (e.g., the task "make stew" consisted of "take food from fridge", "wash vegetables", "chop vegetables", "cook on stove"), MDN showed positive activity throughout the episode, with separate peaks for successive steps and preferentially represented step-level information (Wen, Duncan, & Mitchell, 2020), suggesting its involvement in setting up and executing individual cognitive operations. Overall, these findings provide evidence that this network is important for goal maintenance during goal-directed behaviour.

#### *1.2.3.2. The interaction of MDN with DMN and semantic control network*

While the semantic control network partially overlaps with MDN (see Figure 1.6 B), this network is spatially distinct from regions engaged in domain-general control, since semantic control peaks, in pMTG and anterior ventral IFG, lie outside MDN (Badre et al., 2005; Davey et al., 2016; Wang, Margulies, et al., 2020). The semantic control network is spatially intermediate between MDN and DMN (Davey et al., 2016; see Figure 1.6 B). For example, LIFG overlaps with MDN in posterior and dorsal parts and with DMN in anterior and ventral parts. It has been found that pMTG, identified by the conjunction of activation in global semantic associations and action feature matching tasks, exhibited greater functional coupling with inferior regions of the left frontal prefrontal cortex that included aspects of both the DMN and the MDN, and this site also connected with DMN and MDN regions at rest (Davey et al., 2016). This finding is consistent with the functional subdivisions of LIFG, with anterior parts of LIFG supporting controlled retrieval from lateral temporal cortex while posterior parts of LIFG supporting selection processes of relevant information (Badre et al., 2005). These findings suggest that the semantic control sites interact with both DMN and MDN, implicated in automatic semantic processing and executive control, which might allow more flexible patterns of semantic retrieval.

This domain-general executive control network is also thought to interact with semantic representations to support controlled aspects of semantic cognition (Chiou et al., 2018; Thompson et al., 2018), which may be essential for control over conceptual retrieval. In one neuropsychological study with multimodal semantic assessments, patients with dysexecutive syndrome showed similar patterns of poor task performance to semantic aphasia patients; they also showed strong effects of distractor strength, cues and miscues, and probe-target distance on comprehension (Thompson et al., 2018). This supports the view that semantic retrieval relies upon interaction between executive control and semantic representations. A recent study, manipulating shared physical similarity of word pairs parametrically, showed a graded response to semantic similarity during a feature matching task, from heteromodal DMN, through semantic control sites, to MDN regions: stronger feature similarity elicited more activation in DMN regions while weaker feature similarity elicited greater activation in regions linked to executive control and unimodal processing (Wang, Margulies, et al., 2020). These studies highlight the importance of executive control for supporting semantic retrieval. Recent pathway analyses of white-matter DTI and resting-state fMRI data suggest the semantic control network and MDN may, to some extent, form a 'single functional module' arising from their physical white-matter connections (Jung, Cloutman, Binney, & Lambon Ralph, 2017). For example, pMTG has strong white-matter connectivity to both lateral prefrontal regions and intraparietal sulcus (Binney, Parker, & Lambon Ralph, 2012; Jung et al., 2017). It might be that semantic retrieval draws on both networks to support controlled semantic retrieval, but the recruitment of these regions depends on the circumstances.

#### *1.2.3.3. Summary*

MDN and the semantic control network may play different roles in controlled semantic retrieval. MDN is implicated in goal maintenance during tasks (Crittenden et al., 2016), which may be crucial for goal-directed semantic retrieval (Krieger-Redwood et al., 2016). In contrast, the semantic control network is important for shaping semantic retrieval to suit the context (Davey et al., 2016; Thompson, Henshall, & Jefferies, 2016), giving rise to an overlap between the semantic control network and regions implicated in understanding actions and events, which are also guided by context (Davey, Rueschemeyer, et al., 2015; Thompson et al., 2017). Therefore, MDN might be crucial when a goal for semantic retrieval must be maintained and effortfully implemented, while the semantic control network may be essential for identifying and shaping contexts in which concepts are weakly associated. This gives us another hypothesis that controlled semantic cognition may depend on flexible recruitment of both these control networks, however, the degree of separation between these networks remains unclear.

## 1.3. Flexibility of semantic cognition: different modes of semantic retrieval

Flexible semantic retrieval plays an important role in supporting our behaviours and thoughts. We deploy our conceptual knowledge to make sense of incoming information from the external world (e.g., comprehending what we are reading) and to travel in our internal world (e.g., daydreaming about our summer holiday). In these situations, our semantic retrieval can be perceptually coupled or decoupled from the world around us. We can also focus on retrieving particular aspects of conceptual knowledge that are relevant to our current goals or context. In this way, controlled semantic retrieval can be goal-directed, if we know in advance what we need to retrieve, or context-driven, if we do not have a clear goal in mind but we encounter information that is hard to make sense of, for example, because concepts we encounter together are only weakly associated, or diverge from recently-retrieved meanings. In this section, we describe the flexibility of semantic cognition achieved different modes of semantic retrieval, defined by at least two different dimensions: whether semantic cognition is perceptually coupled or decoupled; and whether semantic control is engaged in a retroactive or proactive fashion.

### *1.3.1. Perceptually-coupled and decoupled semantic retrieval*

#### *1.3.1.1. Perceptual-coupled semantic retrieval*

Conceptual knowledge represented in ATL is crucial for us to make sense of perceptual inputs (Caramazza & Mahon, 2003; Lambon Ralph et al., 2017; Patterson et al., 2007), such as comprehension of what we are reading or listening to (Friederici, Meyer, & Von Cramon, 2000; Keidel, Oedekoven, Tut, & Bird, 2018; Reich, Szwed, Cohen, & Amedi, 2011; Saur et al., 2008; Spitsyna et al., 2006). When object perception and identification is more difficult, for example, when pictures are blurred, knowledge has an even strong effect on perceptual analysis and facilitates recognition (Collins & Olson, 2014). It has been proposed that there are different pathways supporting increasingly abstract levels of perceptual-to-meaning processing: the ventral visual stream, projecting from primary visual cortices to lateral and ventral occipital-temporal regions, is responsible for mapping visual inputs onto conceptual representations (Doniger et al., 2000; James, Culham, Humphrey, Milner, & Goodale, 2003; Spitsyna et al., 2006); similarly, a dorsal route, connecting the superior temporal lobe and premotor cortices, is mainly restricted to sensory-motor mapping of sound to articulation, whereas linguistic processing of sound to meaning requires temporofrontal interaction transmitted via the ventral route (Saur et al., 2008). Therefore, the ATL at the top of these processing streams captures the meaning of what we perceive (Gauthier, Eger, Hesselmann, Giraud, & Kleinschmidt, 2012; Spitsyna et al., 2006).

It has been shown that word and object recognition involves interactive-activation between the heteromodal hub in ATL and visual cortex (Carreiras, Armstrong, Perea, & Frost, 2014; Clarke & Tyler, 2014; Nobre, Allison, & McCarthy, 1994; Pammer et al., 2004; Tyler et al., 2013). For example, an MEG study performed by Clarke, Taylor, Devereux, Randall, and Tyler (2013) showed that initial coarse representations based on perceptual and shared semantic information (i.e., shared features like *has eyes*) are predominantly underpinned by the initial feedforward processing in visual cortex at an early processing stage, while recurrent activity largely involving the anterior and posterior temporal lobes is associated with integrating the concept's more distinctive features (i.e., distinctive features like *has a hump*) at a late stage, which together allows for conceptual differentiation and object identification. The co-recruitment of ATL and spoke regions is also interactively weighted by task demands (Chiou & Lambon Ralph, 2016b). In a recent TMS study, it was found that the congruency effect was significantly attenuated by inhibitory stimulation to the lateral occipital cortex but unaffected by ATL stimulation in a perceptually based size comparison task, by contrast, both lateral occipital cortex and ATL stimulation eradicated the otherwise robust effect in a conceptual size comparison task (Chiou & Lambon Ralph, 2016b). This finding highlights the co-recruitment of semantic hub and visual spoke is crucial when the context stipulates access to object identity and fine-grained size comparison at a conceptual level. In addition, the ATL can also dynamically form flexible long-range networks with functionally specialised spoke regions to retrieve particular aspect of conceptual knowledge, such as connecting with action spoke in contexts that emphasise action affordance (Chiou & Lambon Ralph, 2019). Taken together, these studies suggest that perceptual-coupled conceptual retrieval relies on dynamic and flexible interaction between heteromodal semantic hub and unimodal regions, which enables us to make sense of the world around us.

#### ***1.3.1.2. Perceptual-decoupled semantic retrieval***

As reviewed above, studies have also suggested that conceptual retrieval has a perceptually-decoupled mode, such as during mind-wandering or episodic/autobiographical memory recall (e.g., Estefan et al., 2019; Markowitsch, 1995; Smallwood et al., 2016; Smith et al., 2006; Svoboda, McKinnon, & Levine, 2006). Semantic knowledge is thought to be essential in building the detailed content that characterises spontaneous thought (Smallwood et al., 2016). In line with this view, it has been shown that the propensity to mind wander in a memory-based constructive manner was associated with increased connectivity between the bilateral temporal pole with the bilateral hippocampal gyrus (O'Callaghan, Shine, Lewis, Andrews-Hanna, & Irish, 2015). There is also evidence suggesting that semantic knowledge can contributes to episodic memory (e.g., Craik & Tulving, 1975). For example, the activation of ATL is associated with emotional memory retrieval (Dolan, Lane, Chua, & Fletcher, 2000). Patients with semantic dementia show impairments on both episodic and semantic memory tests and their semantic memory deficits correlate with deficits in episodic future thinking (Duval et al., 2012; Irish, Addis, Hodges, & Piguet, 2012; Simons, Graham, & Hodges, 2002). It has been claimed that recall of verbal and nonverbal episodic memory is differentially dependent on semantic and perceptual information, with verbal tasks more reliant on conceptual knowledge, since these inputs include little perceptual information that can act as a basis for encoding into episodic memory (Graham, Patterson, Powis, Drake, & Hodges, 2002). These studies suggest the contribution of semantic knowledge to perceptually decoupled mental states.

#### *1.3.1.3. Summary*

Semantic cognition can be both perceptually-coupled and decoupled. These different modes of conceptual processing can be in competition, for example, when people start mind-wandering while reading, which impairs the ongoing reading comprehension (Smallwood et al., 2013; Smallwood, McSpadden, et al., 2008). It is still unknown how semantic representations support these different patterns of conceptual processing. As previously mentioned, the lateral temporal lobe sites can form functional connectivity with both input regions and other DMN regions relevant to other memory systems (Jackson et al., 2016; Murphy et al., 2017; Smallwood et al., 2016). The balance between these two patterns of functional connectivity might influence whether semantic cognition is perceptually-coupled or decoupled. In this way, shared semantic representations might flexibly support different mental states. Alternatively, there may be relatively little neural overlap between perceptually-coupled and decoupled semantic retrieval if these states draw on distinct heteromodal hubs within DMN.

### *1.3.2. Goal-directed and context-driven semantic retrieval*

Semantic retrieval is constantly changing from moment-to-moment and is inextricably linked to the current context or goals (e.g., Damian, Vigliocco, & Levelt, 2001; Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill, 2011; Kalénine, Shapiro, Flumini, Borghi, & Buxbaum, 2014; Witt, Kemmerer, Linkenauger, & Culham, 2010). While relevant information may be retrieved relatively automatically in a supportive context, we also have the capacity to deliberately focus our retrieval efforts on a particular subset of our knowledge, when we have established prior goals for semantic retrieval. In addition, we can understand non-dominant meanings even when information is presented unexpectedly; for example, we can understand words even when the topic of conversation shifts without warning, and we have to identify a new linking context. Both context-driven (i.e., less constrained) and goal-driven semantic retrieval require control and might reflect additional 'modes' of semantic retrieval with distinct neurobiological underpinnings.

#### *1.3.2.1. Context-driven semantic retrieval*

Previous studies have shown that context can influence the degree to which conceptual knowledge is activated. For example, Kalénine et al. (2014) found that responses were significantly faster when the use- or move-related action of categorized object (i.e., natural vs. aritefact) was compatible with the naturalistic visual contexts that evoked either use- or move-related actions. This compatibility effect suggests that action evocation during conceptual object processing is biased toward context-relevant actions. In an fMRI study, participants were asked to judge which of the two objects was more similar to the third object in terms of colour, the level of detail of colour knowledge was manipulated by comparing either the three objects from the same colour category (i.e., requiring more detailed colour knowledge) or from different colour categories (i.e., requiring less detailed colour knowledge). They found that the activation of brain areas that support perception varied with the degree of perceptual resolution required by the task; the perceptual task requiring the highest resolution involved perceptual areas more than the verbal task that could be performed on the basis of more abstracted knowledge (Hsu et al., 2011), demonstrating that the task context can influence the degree to which colour knowledge is retrieved. Rahman and Melinger (2011) also found that providing ad hoc contexts for thematic relations (e.g., *fishing trip*) elicited interference amongst a set of thematically-related items to be named, which was otherwise only found for taxonomically-related sets. Patients with semantic control deficits also benefit from constraining cues but also show negative effects of miscueing contexts (Jefferies, Patterson, & Lambon Ralph, 2008; Lanzoni et al., 2019; Noonan et al., 2010). These studies suggest that conceptual activation can be influenced by task context, highlighting the flexible and adaptive nature of semantic cognition.

In sentence comprehension and production, sentential context also constrains access to relevant semantic information (Damian et al., 2001; Glucksberg, Kreuz, & Rho, 1986; Moss & Marslen-Wilson, 1993). In a cross-modal priming study,  Moss and Marslen-Wilson (1993) found that access to semantic content of concepts was affected by the preceding sentential context, particularly these semantic property targets (e.g., semantic property *stings* of the prime word *bee*) showed greater priming in sentence biasing to a specific semantic property (e.g., Sentence "*The child was hurt by the bee*" to bias toward the semantic property *stings*) than in a neutral condition. Sometimes even only the presence of verbs and adjectives are effective in enhancing a specific aspect of the meaning of a word (Tabossi, 1982). However, an ambiguity still can be accessed if the sentential context places insufficient constraints on the semantic features of its contextually congruent meaning, even in a context biasing the dominant meaning of ambiguous words (Tabossi, 1988). These findings suggest that sentential context also carries tremendous importance in constraining semantic retrieval.

In addition to the task and sentential contexts, semantic retrieval can be also driven by the presented stimuli to retrieve relevant aspects of conceptual knowledge. In a semantic relatedness judgement task, for example, participants are asked to determine if taxonomic or thematic associates are meaningfully related to target words or report which type of semantic relationship is preferred (e.g., Kalénine et al., 2009; Lewis et al., 2015; Sachs et al., 2008; Teige et al., 2019; Whitmore, Shore, & Smith, 2004). In this case, participants need to retrieve either taxonomic or thematic semantic knowledge to link each presented word pair. In some studies designed to tap to controlled semantic retrieval, weakly related word pairs are used to manipulate semantic control demands (e.g., Badre et al., 2005; Davey, Cornelissen, et al., 2015; Teige et al., 2019; Wagner et al., 2001). In this situation, non-dominant aspects of conceptual knowledge are required to identify these weak associations, and consequently successful selection requires additional control processes to suppress the strong competitors. Shaping semantic retrieval based on presented stimuli is a more stimuli-driven or bottom-up process, which might be more automatic or more controlled, depending on the strength of associations. As previously reviewed, these more automatic vs. controlled contextually-guided aspects of conceptual retrieval draw on different neural correlates, with the heteromodal regions, such as ATL and AG, being more important for automatic aspects of semantic retrieval while regions within the semantic control network, for example, LIFG and pMTG, being critical for controlled aspects of conceptual retrieval (e.g., Davey, Cornelissen, et al., 2015; Noonan et al., 2013; Teige et al., 2019).

#### *1.3.2.2. Goal-directed semantic retrieval*

In our daily life, we usually have clear ideas about what aspect of semantic information we need to suit the circumstances. For example, when we want to put a nail into a hard wall, thematic knowledge of "hammer" would be activated to support our behaviour; while when we want to buy a "hammer" from the hardware store, our taxonomic knowledge would enable us to locate the right area in the shop and then select the most appropriate type of hammer. We can also flexibly direct our semantic retrieval based on topics during conversation (Caplan & Dapretto, 2001). Therefore, semantic retrieval can be directed according to our goals and expectations to constrain which aspects of semantic information come to mind. There are some studies asking participants to retrieve particular aspects of conceptual knowledge to match word pairs, like colour or action features (Davey, Rueschemeyer, et al., 2015; Wang, Margulies, et al., 2020). In some of these tasks, a semantically-related concept is presented as a distractor to increase competition , for example, selecting which of the two words "*tongue*" and "*bone*" is most similar to the target word "*tooth*" in terms of colour. In these paradigms, the retrieval of goal-relevant information posits a high demand on semantic control processes to suppress either the strongest aspects of semantic information or the semantic related options. Consequently, the activation in semantic control sites, like LIFG, might be driven by these needs. This limits our current understanding of proactive semantic control processes that people can employ when they know which aspects of their knowledge they should retrieve in advance.

#### *1.3.3.3. Summary*

Taken together, these studies provide evidence that semantic retrieval is a dynamic and variable process, which can be directed by the current context or goal to flexibly retrieve relevant aspects of knowledge. Semantic control processes are thought to be important for focussing on the retrieval of currently relevant information. However, it is still unclear how these control processes interact with the semantic representation system to generate different modes of controlled semantic retrieval. There are at least two ways in which control processes could interact with the semantic representation system to retrieve relevant semantic knowledge. One possibility is that control processes directly modulate the activation of heteromodal representations in ATL to retrieve semantic information linked to the current context or goal; another possibility is that these control processes might mediate the activation of modality-specific spoke regions to shape semantic retrieval; this would tailor the retrieval of concepts within the heteromodal store as low-level perceptual processes indirectly affect the activation of semantic representations (Jackson et al., 2019). The difference between these two modes of controlled retrieval (i.e. top-down and goal driven vs. bottom-up and context-driven) might relate to where and how control processes are applied to conceptual representations, with the control of spokes being more feasible when people have clear ideas about what aspect of knowledge they should retrieve (Jackson et al., 2019).

## 1.4. Aims of the thesis

Making gainful use of conceptual knowledge to comprehend inputs and inform action in a variable environment, as well as to sustain meaningful patterns of internal thought that are independent of the environment, requires flexibly retrieval and selection from our stored semantic knowledge. However, the neural mechanisms underlying the flexibility of semantic processing are poorly understood. Therefore, this thesis focusses on how this flexibility of semantic retrieval comes about, by employing different modes of semantic retrieval: perceptually coupled and decoupled tasks, and goal-directed and context-driven semantic retrieval. Based on the previous studies, we propose two possibilities. ***The first possibility is that different patterns of connectivity from regions implicated in semantic representation are pivotal to our capacity to produce diverse semantically-driven thought and behaviour***. A recent fMRI study has shown that the ventral ATL region associated with conceptual representation connects to both visual cortex and DMN (Murphy et al., 2017). This may suggest that the regions important for semantic representation form different patterns of functional connectivity to support perceptually-coupled and decoupled mental states, which not only enables us to understand the environment around us, but also helps us navigate our own internal world. ***A second possibility is that***

***semantic retrieval may flexibly recruit different networks in different modes of semantic retrieval***. It has been found that the semantic control network can heighten its connectivity with relevant components of the representation system: when the task involved pairing semantically-unrelated objects based on their colour, the IFG, an important site for semantic control, exhibited greater connectivity with a color-concept area; in contrast, when the task involved linking weakly-associated word pairs, the IFG exhibited greater connectivity with the ATL (Chiou et al., 2018). This study indicates that controlled semantic cognition relies upon dynamic and flexible interactions between the control networks and semantic representation systems. By this view, this interaction process might depend on the recruitment of networks implicated in control (i.e., the semantic control network and multiple-demand network) and semantic representation (e.g., the default mode network). Therefore, the dynamic and flexible recruitment of different networks in different modes of semantic retrieval may enable the flexibility of semantic cognition. This thesis will focus on examining these possibilities to provide new insights into flexible semantic cognition.

## 1.5. Thesis overview

This thesis aims to examine the neural basis of flexible semantic retrieval by employing different patterns of retrieval, i) perceptually-coupled and decoupled and ii) goal-directed and context-driven semantic retrieval, with a focus on the contribution of large-scale distributed networks in the brain. Across three different studies, we explored both the resting-state and task-state functional connectivity and neural correlates that support different patterns of semantic retrieval.

Study 1 (Chapter 2) explored whether individual differences in intrinsic connectivity at rest linked to both perceptually-coupled and decoupled conceptual processing. In this study, we used mind-wandering whilst reading task outside the scanner. Often, as we read, we find ourselves thinking about something other than the text; this tendency to mind-wander is linked to poor comprehension and reduced subsequent memory for texts. This task conflict offers us an opportunity to understand the role of DMN in semantic representation in both on-task (or perceptually-coupled) and off-task (or perceptually-decoupled) states (Study 2 (Chapter 3) also separates these alternatives by collecting ratings of task focus during reading comprehension and autobiographical memory recall tasks). Using a combination of task-based and resting-state fMRI, we found that diverse patterns of intrinsic connectivity from the middle temporal gyrus, a lateral DMN site, are linked to both reading and mind-wandering.

Based on the findings of Study 1, Study 2 (Chapter 3) further examined the neurocognitive architecture that supports these different patterns of perceptually-coupled and decoupled retrieval using task-based fMRI, with a focus on the role of distinct DMN subsystems. Instead of recording participants' behavioural performance outside scanner, in this study the participants were asked to either comprehend sentences, immediately preceded by a letter string (e.g., xxxx) or memory recall cue (e.g., holiday), or recall their generated personal memories during the presentation of letter strings or irrelevant sentences, inside the scanner. After each reading and memory recall trial, they were asked to provide ratings of task focus. Using this paradigm, we revealed that regions within lateral temporal DMN subsystem, associated with semantic cognition, particularly lateral temporal sites and inferior frontal gyrus, are involved in both reading comprehension and memory recall, and the diverse patterns of functional connectivity from this common DMN site with task-relevant regions allows semantic cognition to support these different mental states. Importantly, the DMN contributes to supporting on-task states in both perceptually-coupled and decoupled tasks (although with important differences between DMN subsystems).

Study 3 (Chapter 4) examined how we tailor semantic retrieval to suit the task demands, when a prior goal is either available or unavailable. In this way, the study explored similarities and differences between goal-directed and context-driven controlled semantic cognition. We used task-based fMRI to investigate the neural basis of this form of semantic flexibility; in particular, we asked how retrieval unfolds differently when participants have advanced knowledge of whether concepts will be linked taxonomically or thematically. In this study, participants performed a semantic relatedness judgement task: on half the trials, they were cued to search for a taxonomic or thematic link (goal-directed/top-down semantic retrieval), while on the remaining trials, they judged relatedness without knowing which type of semantic relationship would be relevant (context-driven/bottom-up semantic retrieval). We found that left inferior frontal gyrus, a site within semantic control network, showed greater activation when participants knew the trial type in advance. This task knowledge (i.e., top-down control) specifically modulated the response in visual cortex: when the goal was unknown, there was greater deactivation to the first word, and greater activation to the second word, suggesting that top-down control of semantic retrieval is primarily achieved through the gating of task-relevant ‘spoke’ regions.

# Chapter 2: Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading

**This chapter is adapted from: Zhang, M., Savill, N., Margulies, D. S., Smallwood, J., & Jefferies, E. (2019). Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading. *Scientific reports*, *9*(1), 1-13.**[1]

## 2.1. Abstract

Often, as we read, we find ourselves thinking about something other than the text; this tendency to mind-wander is linked to poor comprehension and reduced subsequent memory for texts. Contemporary accounts argue that periods of off-task thought are related to the tendency for attention to be decoupled from external input. We used fMRI to understand the neural processes that underpin this phenomenon. First, we found that individuals with poorer text-based memory tend to show reduced recruitment of left middle temporal gyrus in response to orthographic input, within a region located at the intersection of default mode, dorsal attention and frontoparietal networks. Voxels within these networks were taken as seeds in a subsequent resting-state study. The default mode network region (i) had greater connectivity with medial prefrontal cortex, falling within the same network, for individuals with better text-based memory, and (ii) was more decoupled from medial visual regions in participants who mind-wandered more frequently. These findings suggest that stronger intrinsic connectivity within the default mode network is linked to better text processing, while reductions in default mode network coupling to the visual system may underpin individual variation in the tendency for our attention to become disengaged from what we are reading.

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[1] The author, Meichao Zhang, collected the behavioural data, analysed the results and wrote the article under the supervision of Prof. Beth Jefferies and Prof. Jonny Smallwood, and Dr. Nicola Savill helped to collect data and provided comments on the manuscript. Dr. Daniel Margulies provided comments on the manuscript. The resting-state data had already been collected before my PhD study and some of the behavioural data was collected by Dr. Nicola Savill.

## 2.2. Introduction

Despite the value of reading to our species, everyday experience indicates that even if we are reading for comprehension, our thoughts and feelings do not always remain tethered to the events that take place in the narrative. Indeed, multiple studies have demonstrated that off-task thinking while reading, often referred to as mind-wandering, is ubiquitous across cultures and has a measurable and reliable negative effect on reading comprehension (for examples, see Franklin, Smallwood, & Schooler, 2011; Sanders, Wang, Schooler, & Smallwood, 2017; Smallwood, McSpadden, et al., 2008). Although the frequency and consequences of off-task thinking while reading are well-documented, we lack a clear understanding of the underlying neurocognitive architecture which gives rise to this experience.

Both off-task thought and reading are thought to depend on a complex component process architecture (Lambon Ralph et al., 2017; Smallwood & Schooler, 2015). Reading involves the interaction of multiple cognitive processes (Ferstl, Neumann, Bogler, & Von Cramon, 2008; Ferstl, Rinck, & Cramon, 2005; Ferstl & von Cramon, 2001; Ferstl & von Cramon, 2002; Hasson, Nusbaum, & Small, 2007), including decoding and recognition of incoming perceptual information, semantic retrieval and discourse-level inference. The ventral visual stream, which supports increasingly abstract visual-to-semantic mappings within the temporal lobe, contributes to how we make sense of visual input (Dehaene & Cohen, 2011; Dehaene, Cohen, Morais, & Kolinsky, 2015; Spitsyna et al., 2006; Xu et al., 2005). Posterior temporal regions, such as the visual word form area, are implicated in orthographic processing (Dehaene & Cohen, 2011; McCandliss, Cohen, & Dehaene, 2003). More anterior regions of the temporal lobe exhibit a greater response to word meaning than to the visual properties of words (Gauthier et al., 2012; Patterson et al., 2007; Spitsyna et al., 2006). Contemporary accounts of semantic cognition suggest that the most anterior aspects of the ventral anterior temporal lobes (ATL) represent heteromodal concepts that are formed from the convergence of multiple meaningful inputs across modalities (Lambon Ralph et al., 2017; Murphy et al., 2017; Visser, Jefferies, & Lambon Ralph, 2010). Reading for comprehension also requires sustained attention to focus on orthographic information as the text unfolds word by word (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014; Novick, Trueswell, & Thompson-Schill, 2005; Sesma, Mahone, Levine, Eason, & Cutting, 2009; Shaywitz &

Shaywitz, 2008; Solan, Shelley-Tremblay, Ficarra, Silverman, & Larson, 2003; Thompson-Schill, Bedny, & Goldberg, 2005), with the disruption of attentional mechanisms playing a causal role in the failure of comprehension (Shaywitz & Shaywitz, 2008). Executive processes allocate and coordinate attentional resources in task performance (Baddeley, 1996; Engle, Tuholski, Laughlin, & Conway, 1999), with control over attention playing a role in governing intruding thoughts during comprehension (McVay & Kane, 2012). Neuroimaging studies have revealed that regions associated with executive control, including the left dorsolateral prefrontal cortex, show greater activation in better readers (Horowitz-Kraus, Vannest, Gozdas, & Holland, 2014; Osaka et al., 2004). Finally, reading comprehension involves conceptual processing that goes beyond single word decoding to include text-level and often discourse-level inference – such as integration of text-based information with episodic memory and real-world knowledge (Graesser, Singer, & Trabasso, 1994; Kintsch, 1988), forming what is often referred to as the situation model (Zwaan & Radvansky, 1998). Converging evidence has revealed a role for medial prefrontal cortex in inference processes while reading passages (Goel, Gold, Kapur, & Houle, 1997; Jang et al., 2013; Kim, Yoon, Kim, Lee, & Kang, 2012). Deep comprehension of texts is also associated with successful recognition and better memory for the information they contain (Kintsch, 1988; Maguire, Frith, & Morris, 1999).

Contemporary accounts of off-task thought also suggest that this experience emerges from the interaction of multiple component processes (Smallwood, 2013). At the core of the off-task state is a shift in focus away from the external task towards self-generated mental content, known as decoupling (Smallwood, 2013; Smallwood & Schooler, 2015). This process is assumed to reflect a disengagement of neural processing from external input that occurs because the attentional focus has changed, as evidenced by reductions in evoked responses to externally-presented inputs during off-task thought (Barron, Riby, Greer, & Smallwood, 2011; Kam et al., 2011; Smallwood, Beach, Schooler, & Handy, 2008). While the process of decoupling is argued to support our ability to generate thoughts unrelated to the external world, control processes are thought to be important in maintaining the integrity of the desired pattern of thoughts (McVay & Kane, 2010; Smallwood, 2013). Individuals with higher executive control tend to be better at maintaining attention to task-relevant information in attentional tasks (Turnbull et al., 2019) and whilst reading for comprehension (McVay & Kane, 2012). Recent research suggests task focus may be implemented by dorsal and ventral attention systems (Turnbull et al., 2019; Turnbull et al., 2019). The ventral attention network – in particular the left dorsolateral prefrontal cortex – plays a role in the prioritisation of cognition appropriate to the context in sustained attention tasks, while the dorsal attention network reflects a focus on tasks regardless of the context. Yet a different picture emerges from an examination of the neural correlates of on- and off-task thought during reading. In a prior study, we found that individuals who maintain a better focus on what is being read, when tested outside the scanner, show greater within-network connectivity between regions of the default mode network (Smallwood et al., 2013), thought to be important for retrieval from semantic and episodic memory (Kim, 2016). One possibility is that this difference reflects the conceptual and episodic representations that are needed for reading, which also contribute to the mental content that is generated during off-task thought (Smallwood et al., 2016).

In the current study, we used functional neuroimaging to revisit the specific neurocognitive mechanisms that contribute to individual variation in off-task thought during reading. We recruited a cohort of 69 participants and asked them to read an expository non-fiction text outside the scanner whilst keeping track of the amount of mind-wandering they experienced (Sanders et al., 2017). Immediately afterwards, participants completed a set of questions assessing their memory for information from the text. These questions required the recall of information directly presented in the text, and in some cases, the integration of additional semantic information to understand the text (Kintsch, 1988; Van Dijk, Kintsch, & Van Dijk, 1983). Although people's eyes are still scanning the text during periods of mind-wandering, we expected that during these off-task states, the orthographic input would receive less attention and subsequent semantic processing (Smilek, Carriere, & Cheyne, 2010), resulting in poorer memory for the text.

In Experiment 1, we employed a sentence-reading task in the scanner, in which participants were asked to passively view meaningful sentences or nonwords, presented on an item-by-item basis. This task was expected to activate the visual-to-semantic pathway, implicated in reading comprehension (Reich et al., 2011; Spitsyna et al., 2006) and was used to characterise receptive language function in individual participants (Barnett, Marty-Dugas, & McAndrews, 2014; Sanjuán et al., 2010). Previous studies examining the neural correlates of reading have revealed greater involvement of a temporo-frontal semantic network for meaningful versus meaningless texts, including greater activation in superior temporal gyrus/sulcus, middle temporal gyrus, angular gyrus and inferior frontal gyrus (Choi, Desai, & Henderson, 2014; Friederici, Rueschemeyer, Hahne, & Fiebach, 2003). We therefore predicted that both meaningful and meaningless orthographic inputs would elicit a response within the ventral visual pathway, with additional activation in regions within a temporo-frontal semantic network when contrasting words with nonwords. Accordingly, individual differences in memory for texts might reflect differences in conceptual retrieval, related to the contrast *words > nonwords,* and/or the extent to which people focus on reading instead of mind-wandering even when the orthographic input is meaningless, using the contrast of *nonwords > baseline*. We examined whether differences in BOLD activation during the sentence-reading tasks would predict variation in patterns of experience during reading or variation in text-based memory (both measured outside of the scanner). In Experiment 2, we collected a resting-state scan in the same individuals, allowing us to understand whether the connectivity patterns of regions identified in the first experiment varied with either mind-wandering during reading, or subsequent text-based memory. To foreshadow our results, Experiment 1 identified a region of middle temporal gyrus within the default mode network (DMN) that had reduced neural activity in response to orthographic input in individuals who had poorer memory for texts. Experiment 2 established that this region of middle temporal gyrus had stronger connectivity with regions of the medial prefrontal cortex for individuals with good text-based memory, and had weaker connectivity with regions of medial occipital cortex for individuals showing more off-task thought.

## 2.3. Materials and Methods

### *2.3.1. Participants*

Ethical approval was obtained from the Research Ethics Committees of the Department of Psychology and York Neuroimaging Centre, University of York. And all research was performed in accordance with the relevant guidelines/regulations. Sixty-nine undergraduate or postgraduate students were recruited for this study (age range 18-31, mean age = 19.87 ± 2.33, 26 males). All were right-handed native English speakers, and had normal or corrected-to-normal vision. None of them had any history of neurological impairment, diagnosis of learning difficulty or psychiatric illness. All provided written informed consent prior to taking part and received a monetary reward for their participation.

### *2.3.2. Behavioural assessment*

*Off-task frequency and text-based memory*. Following an MRI scan (details below), participants were asked to complete a battery of behavioural assessments examining their reading and off-task thought. In order to create a naturalistic reading experience, we presented the text in a printed booklet. The text was selected and shortened from Bill Bryson's "A Short History of Nearly Everything" (Smallwood et al., 2013), in font size 14, 1.5 line spacing. The passage was about the topic of geology (word count = 1050). During reading, the participants were required to note down any moments when they noticed they had stopped paying attention to the meaning of the text, by circling the word they had reached at this point. A detailed instruction booklet was used to guide the participants through the experiment. After they finished reading, they were asked to answer 17 open-ended questions, without being able to refer back to the text (Smallwood et al., 2013). For some questions, the answers were explicitly presented in the text (i.e., *How high was the annual membership fee for the geological society?* or *How old did Holmes estimate the earth to be?* or *What kind of interim business did Holmes run to be able to support his family?*), while others required text memory but also required participants to retrieve and integrate semantic information to support their understanding of the paragraph and to answer the question (i.e., *Why does the author compliment about Holmes first estimation of the age of the earth as 'quite an achievement'? or Which circumstance was responsible for delaying Holmes' work?*). The questions did not require discourse-level comprehension.

The answers to the questions were scored for accuracy by two experimenters. Responses were given a score of 1 if they contained key information, and otherwise a score of 0. The two scorers produced very similar ratings ($r = .92$, $p < .001$). The prior knowledge of geology was also assessed by two questions: 1) Have you previously studied Geology, and if so for how many years? 2) Please indicate how much you already knew about the content of the Geology text prior to reading the text based on a 0 to 10 Likert scale. The participants stated that they were unfamiliar with the content of the text ($M \pm SD = 1.47 \pm 1.75$) and had almost no Geology study during their education ($M \pm SD = 0.06 \pm 0.29$ year). There was also no correlation between these ratings with either reading assessment or off-task experiences ($ps > .1$). The experiment took approximately 30 (±5) minutes.

*Off-task experiences*. A self-report measurement, the New-York Cognition Questionnaire (NYC-Q), was also used to assess off-task behaviour during the reading task. The first section contained 22 questions about the content of thoughts (e.g., *I thought about personal worries*), rated on a scale of 1 (*Completely did not describe my thoughts*) to 9 (*Completely did describe my thoughts*). The second section contained 8 questions about the form of these thoughts (e.g., *whilst I was reading my thoughts were in the form of images*), rated on a scale of 1 (*Completely did not characterize my experience*) to 9 (*Completely did characterize my experience*) (Gorgolewski et al., 2014; Sanders et al., 2017). In the current study, we limited our analysis to the 22 questions relating to the content of off-task thought. We calculated an overall average for each participant, which is thought to reflect how much each individual was thinking off-task thoughts. In this way, we assessed both off-task frequency (i.e., the number of moments when attention was not directed towards the reading task) and the content of these experiences.

Prior to data analysis, all variables were *z*-transformed and outliers more than 2.5 standard deviations above or below the mean were identified. Using this criterion, there was one outlier for text-based memory, three outliers for off-task frequency and no outliers in the content of off-task thought questionnaire. These outlying values were imputed with the cut-off value (i.e., +/- 2.5 standard deviations above or below the mean). No participant was removed from the data analysis as a result of this process.

### ***2.3.3. Neuroimaging data acquisition***

Structural and functional data were acquired using a 3T GE HDx Excite Magnetic Resonance Imaging (MRI) scanner utilizing an eight-channel phased array head coil at the York Neuroimaging Centre, University of York. Structural MRI acquisition in all participants was based on a T1-weighted 3D fast spoiled gradient echo sequence (repetition time (TR) = 7.8 s, echo time (TE) = minimum full, flip angle = 20°, matrix size = 256 × 256, 176 slices, voxel size = 1.13 mm × 1.13 mm × 1 mm).

The sentence-reading task in Experiment 1 used single-shot 2D gradient-echo-planar imaging (TR = 3 s, TE = minimum full, flip angle = 90°, matrix size = 64 × 64, 60 slices, voxel size = 3 mm × 3 mm × 3 mm, 80 volumes). The participants passively viewed meaningful sentences (e.g., her + secrets + were + written + in + her + diary) and meaningless sequences of nonwords (e.g., crark + dof + toin + mesk + int + lisal + glod + flid), item-by-item. In total, there were 10 meaningful sentences, taken from Rodd, Davis, and Johnsrude (2005), and 10 nonword lists, matched for both word length and number of syllables. Word and nonword sets were each presented in two blocks in a pseudo-random order (i.e., a total of 4 blocks). A task instruction (e.g., Meaningful) was used to indicate the transition between different conditions. Each sequence ended with a red fixation lasting 4000-6000 ms. Each word or nonword was presented for 600 ms, followed by a 250 ms fixation before the next item was presented. A fluid-attenuated inversion-recovery (FLAIR) scan with the same orientation as the functional scans was collected to improve co-registration between subject-specific structural and functional scans.

A 9-minute resting-state fMRI scan was used in Experiment 2, recorded using single-shot 2D gradient-echo-planar imaging (TR = 3 s, TE = minimum full, flip angle = 90°, matrix size = 64 × 64, 60 slices, voxel size = 3 mm × 3 mm × 3 mm, 180 volumes). During resting-state scanning, the participants were instructed to focus on a fixation cross with their eyes open and to keep as still as possible, without thinking about anything in particular. Neuroimaging data for Experiments 1 and 2 were collected in the same session, with the resting-state sequence presented first, so that measures of intrinsic connectivity could not be influenced by the words and nonwords that were presented in the sentence-reading task. There was a break of a few minutes between these scans which allowed us to remind participants of the task requirements and set up the scanning.

### *2.3.4. Neuroimaging data pre-processing*

All functional and structural data were pre-processed using a standard pipeline and analysed via the FMRIB Software Library (FSL version 6.0, www.fmrib.ox.ac.uk/fsl). Individual FLAIR and T1-weighted structural brain images were extracted using FSL's Brain Extraction Tool (BET). Structural images were linearly registered to the MNI152 template using FMRIB's Linear Image Registration Tool (FLIRT). The sentence-reading functional neuroimaging data were pre-processed and analysed by using FSL's FMRI Expert Analysis Tool (FEAT). A standard pre-processing pipeline was applied, including motion correction via MCFLIRT, slice-timing correction using Fourier space time-series phase-shifting, and spatial smoothing using a Gaussian kernel of FWHM 6 mm. In addition, for the task-based fMRI data in Experiment 1, high-pass temporal filtering (sigma = 100 s) was applied in order to remove temporal signal drift. For the resting-state fMRI data in Experiment 2, both high-pass (sigma = 200 s) and low-pass temporal filtering (sigma = 2.8 s) were applied, in order to constrain analyses to low-frequency fluctuations.

#### ***2.3.5. Neuroimaging analysis***

##### ***2.3.5.1. Task-based fMRI analysis (Experiment 1)***

This analysis identified sites in which activation during the sentence reading task was modulated by individual differences in text-based memory, off-task frequency or the content of off-task thought (i.e., NYC-Q), measured outside the scanner. In the first-level analysis of the sentence reading task performed in the scanner, we identified voxels responding to (i) meaning and (ii) orthographic inputs devoid of meaning, through the contrasts of *Meaningful* > *Baseline*, *Meaningless* > *Baseline*, *Meaningful* > *Meaningless*, plus the reverse, for each participant. In the higher-level analysis at the group level, z-transformed behavioural data for text-based memory, off-task frequency and NYC-Q were added as explanatory variables, using FMRIB's Local Analysis of Mixed Effects (FLAME1), with automatic outlier de-weighting (Woolrich, 2008). A 50% probabilistic grey-matter mask was applied. Clusters were thresholded using Gaussian random-field theory, with a cluster-forming threshold of $z$ = 2.6 and a familywise-error-corrected significance level of $p$ = .05.

##### ***2.3.5.2. Resting-state fMRI analysis (Experiment 2)***

We next considered whether the intrinsic connectivity of regions identified in Experiment 1 predicted text-based memory and off-task thought. A cluster which showed a stronger response to orthographic input in people with good text-based memory overlapped with (i) the default mode network (DMN), which is implicated in both reading comprehension and spontaneous thought (Kim, 2016; Smallwood et al., 2016; Wirth et al., 2011), (ii) the adjacent frontoparietal network (FPN), which plays a central role in cognitive control (Cole et al., 2013), as well as (iii) the dorsal attention network

(DAN), which supports externally-directed attention (Corbetta & Shulman, 2002). We therefore masked the results of Experiment 1 by these DMN, FPN and DAN networks, defined by a parcellation of 1000 resting-state scans (Yeo et al., 2011), obtained from Freesurfer (https://surfer.nmr.mgh.harvard.edu/fswiki/CorticalParcellation_Yeo2011). This identified a region of middle temporal gyrus (MTG) within DMN, and a region of inferior temporal gyrus (ITG) in the FPN, as well as another region of inferior temporal region (ITG)/lateral occipital cortex (LOC) in the DAN. These regions were taken as seeds in a subsequent analysis of intrinsic connectivity.

We extracted the time series from the seeds and used this data as explanatory variables in whole-brain connectivity analyses at the single-subject level. Sixty-four participants were included in this analysis (five participants without intrinsic connectivity data were excluded). These functional connectivity maps were then related to individual differences in behaviour using a multiple regression model, in which z-transformed scores for text-based memory, off-task frequency and NYC-Q were added as explanatory variables. In order to control for the spurious correlations that might emerge from movement, we included two canonical components, group mean and mean framewise displacement (FD) (Jenkinson, Bannister, Brady, & Smith, 2002), as nuisance covariates in the model. Automatic outlier de-weighting was used and a 50% probabilistic grey-matter mask was applied. Clusters were thresholded using Gaussian random-field theory, with a cluster-forming threshold of $z = 2.6$ and a familywise-error-corrected significance level of $p = .05$. We also applied Bonferroni correction to account for the fact that we included three models (ITG within FPN, ITG/LOC within DAN, and MTG within DMN) and used two-tailed tests (in which behaviour could relate to both stronger and weaker connectivity). Consequently, the $p$-value accepted as significant was $p < .0083$.

## 2.4. Results

### *2.4.1. Behavioural results*

The behavioural results are summarized in Figure 2.1. Pearson's correlation analysis revealed that the online (i.e. off-task frequency; $M \pm SD = 3.38 \pm 3.79$) and retrospective measures of off-task experience (i.e. NYC-Q; $M \pm SD = 3.09 \pm 1.37$) were positively correlated ($r = .51$, $p < .001$). There was also a significant negative correlation between off-task frequency and text-based memory scores ($M \pm SD = 7.96 \pm 2.95$; $r = -.26$, $p = .029$), suggesting that frequent off-task thought interferes with reading, in line with previous findings (Sanders et al., 2017; Smallwood, McSpadden, et al., 2008). However, the retrospective mind-wandering measure was not significantly associated with text-based memory ($r = -.17$, $p = .16$).

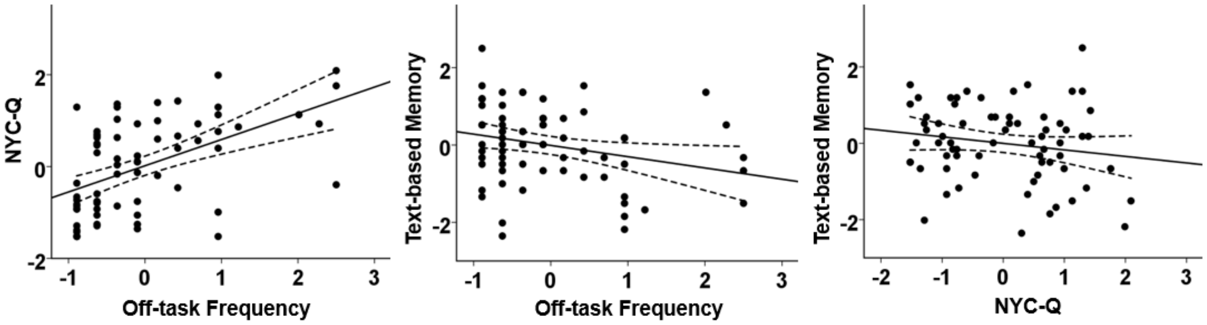


***Figure 2.1.*** **Behavioural results**. The scatterplots present the correlations between off-task frequency, NYC-Q (i.e., the content of off-task thought), and text-based memory. The error lines on the scatterplots indicate the 95% confidence estimates of the mean. Each point on the scatterplot describes a participant.

### *2.4.2. Experiment 1: Sentence-Reading task*

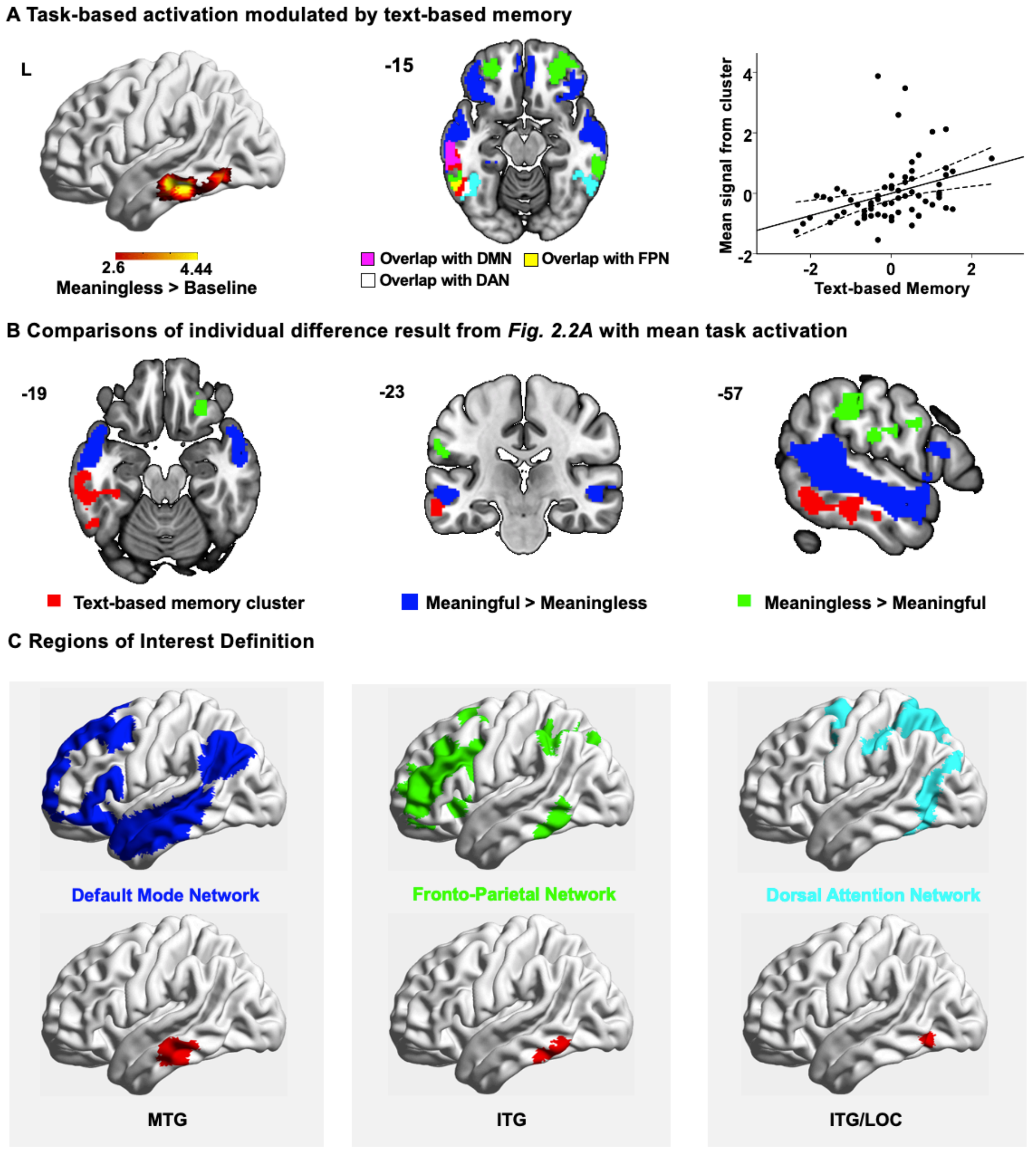
A whole-brain analysis indicated that activation in middle/inferior temporal gyrus and temporal fusiform cortex in the contrast of *Meaningless* > *Baseline* was modulated by individual differences in text-based memory, measured outside the scanner ($p = .0111$; see Figure 2.2 A). To understand the nature of this relationship, we plotted the relationship between mean % signal change in this region and text-based memory across individuals. People with better text-based memory showed a stronger response to orthographic input, even when this was not meaningful.

We did not find any clusters for the *Meaningful* > *Meaningless* contrast that varied with individual differences in either text-based memory or off-task thought. To identify whether the association with text-based memory in *Meaningless* > *Baseline* showed a similar pattern to *Meaningful* > *Baseline*, we used the cluster identified in the contrast of *Meaningless* > *Baseline* as a mask to extract the mean % signal change in the contrast of *Meaningful* > *Baseline* for each individual, then performed

Bayesian Pearson Correlation Inference analysis to quantify the relationship between the text-based memory score and activation in the *Meaningful* > *Baseline* contrast. The estimated Pearson correlation coefficient was .30, $p$ = .012, and the corresponding Bayes Factor was .46. This score is a natural ratio comparing the likelihood of no correlation with the likelihood of a correlation between text-based memory and brain activation for the *Meaningful* > *Baseline* contrast. Since the Bayes Factor score was less than 1, this suggests that there is 'moderate evidence' that the association is present in both conditions. Consequently, the effect of text-based memory on the BOLD response is most likely to reflect a generally greater response to orthographic input in participants with better text-based memory.

We compared the location of this temporal lobe cluster that reflected a stronger BOLD response to orthographic inputs in participants with good text-based memory (shown in red in Figure 2.2 B) with the main effect of meaning across the group in Experiment 1. The location of this temporal lobe, which showed an effect of individual differences, was adjacent on the cortical surface to the mean task activation in the contrast of *Meaningful* > *Meaningless* (shown in blue in Figure 2.2 B). This temporal lobe activation is implicated in visual-to-semantic processes in contemporary accounts that propose graded abstraction from unimodal visual to heteromodal conceptual representations within the temporal lobe (Lambon Ralph et al., 2017).

The cluster that showed a stronger response to orthographic input in people with better text-based memory was located at the intersection of DMN, FPN and DAN (see Figure 2.2 A). We calculated the percentage of voxels within this cluster that fell within the large-scale networks defined by Yeo et al. (2011). Of these voxels, 48.1% were within the DMN (overlap in pink), which is implicated in both reading comprehension and spontaneous thoughts (Kim, 2016; Smallwood et al., 2016; Wirth et al., 2011); 17.4% fell within the adjacent FPN (overlap in yellow), which plays a central role in cognitive control (Cole et al., 2013); and 24.8% fell within the DAN (overlap in white), which supports externally directed attention (Corbetta & Shulman, 2002). There were smaller overlaps with limbic and visual networks, 8% and 1.8% respectively, which we do not discuss further.


A Task-based activation modulated by text-based memory

B Comparisons of individual difference result from *Fig. 2.2A* with mean task activation

C Regions of Interest Definition

***Figure 2.2.*** **A) Regions modulated by text-based memory in task-based fMRI.** Participants were asked to passively read meaningful sentences and meaningless sequences of non-words. The image shows voxels that were more active for good readers for the contrast of meaningless nonwords over baseline ($z > 2.6$; $p < .05$; in red). This cluster overlaps with three large-scale brain networks: default mode network (DMN; in blue), frontoparietal network (FPN; in green), and dorsal attention network (DAN; in cyan). These networks were defined by Yeo et al. (2011), in a 7-network parcellation of whole-brain functional connectivity for 1000 brains. The network map is fully saturated to emphasize

the regions of overlap (in pink, yellow, and white). The number in the top left of the overlap map indicates the coordinate value of the corresponding plane. The scatterplot presents the correlation between the mean signal extracted from the significant cluster and text-based memory. The error lines on the scatterplot indicate the 95% confidence estimates of the mean. Each point describes an individual participant. L = Left hemisphere. **B) Comparisons of individual difference result from Fig. 2.2A with mean task activation.** The brain region in which the response to orthographic input was modulated by text-based memory (red) with the activated regions in the contrasts of *Meaningful* > *Meaningless* (blue) and *Meaningless* > *Meaningful* (green). These maps are fully saturated. All maps are thresholded at $z > 2.6$ ($p < .05$). Numbers at the top left of each panel indicate the coordinate value of the corresponding plane. **C) Definition of task-based ROIs.** The seeds used for resting-state functional connectivity in Experiment 2 were defined as the overlaps between the region in which task-based activation to meaningless orthographic input was modulated by text-based memory and three large-scale brain networks: DMN, FPN, and DAN. This gave rise to three ROIs: middle temporal gyrus (MTG) in DMN, a region of inferior temporal gyrus (ITG) in FPN, as well as a region of ITG/lateral occipital cortex (LOC) in DAN.

### *2.4.3. Experiment 2: Resting-state functional connectivity*

Since the region that showed greater responsiveness to orthographic input in people with good text-based memory fell at the intersection of three large-scale networks (DMN, FPN, DAN), we conducted a second experiment to understand whether the organisation of one of these large-scale networks also relates to individual differences in off-task thinking and reading. We therefore identified voxels that showed greater activation to orthographic input for people with good text-based memory in Experiment 1, which also fell within DMN, FPN, and DAN – implicated respectively in memory, control, and attention processes according to a commonly used whole-brain parcellation (Yeo et al., 2011). We used these DMN, FPN, and DAN regions as seeds for an analysis of intrinsic connectivity in Experiment 2 (see Figure 2.2 C).

Group-level intrinsic connectivity maps for the DMN, FPN, and DAN seed regions (i.e., irrespective of performance) are presented in Figure 2.3. To understand how the regions of positive and negative connectivity from these seed regions respectively correspond to the networks implicated in semantic, cognitive control, and attention processing, we compared these spatial maps to the meta-analytic maps generated for the terms SEMANTIC, COGNITIVE CONTROL, and ATTENTION using Neurosynth (Yarkoni et al., 2011). This revealed that regions of relatively high connectivity from DMN, FPN, and DAN seed regions respectively (shown in red in Figure 2.3) largely overlapped with regions important for these aspects of cognition according to task-based fMRI (shown in green, with the overlap in yellow).

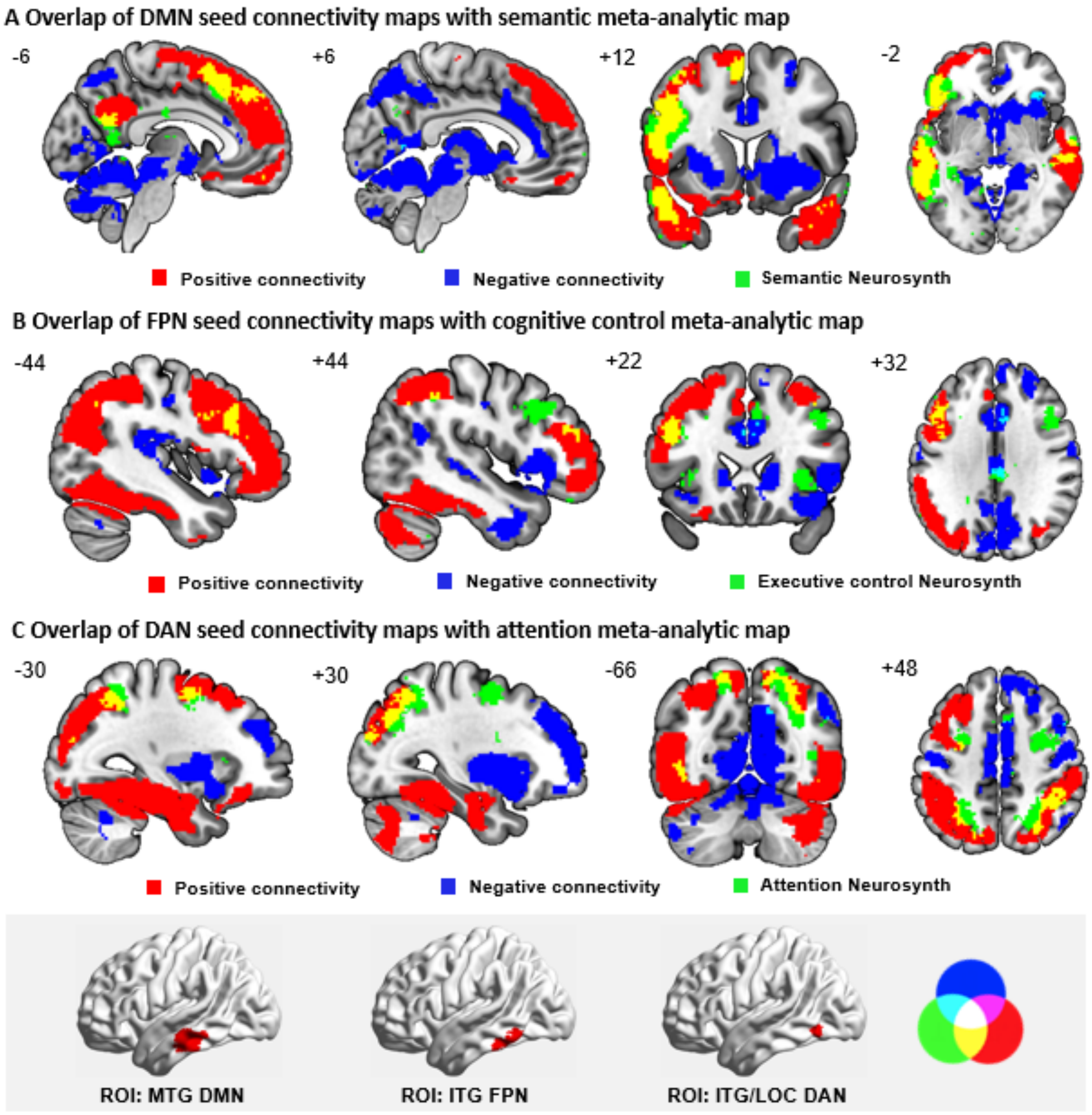


*Figure 2.3*. **A) Overlap of DMN seed connectivity maps with semantic meta-analytic map.** The group-level patterns of relatively high (in red) and low (in blue) functional connectivity from the DMN seed in MTG during resting-state fMRI (cluster correction, $z > 2.6$, $p < .05$), and the overlap of these positive and negative networks with a semantic meta-analytic map (regions in green) derived from Neurosynth (using 'semantic' as a search term). **B) Overlap of FPN seed connectivity maps with cognitive control meta-analytic map.** The group-level patterns of relatively high (in red) and low (in blue) functional connectivity from the FPN seed in ITG during resting-state fMRI (cluster correction, $z > 2.6$, $p < .05$), and the overlap of these positive and negative networks with a cognitive control meta-analytic map (regions in green) derived from Neurosynth (using 'cognitive control' as a search term). **C) Overlap of DAN seed connectivity maps with attention meta-analytic map.** The group-level patterns of relatively high (in red) and low (in blue) functional connectivity from the DAN seed in ITG/LOC during resting-state fMRI (cluster correction, $z > 2.6$, $p < .05$), and the overlap of these positive and negative networks with attention meta-analytic map (regions in green) derived from Neurosynth (using 'attention' as a search term). These maps are fully saturated to emphasize the regions of overlap. Numbers at the top left of each panel indicates the coordinate value of the corresponding plane. The bottom panel highlighted in grey shows the seed regions and the overlapping circles that indicate the colour of overlap regions. MTG = middle temporal gyrus. ITG = inferior temporal gyrus. LOC = lateral occipital cortex.

### Relationship to individual differences

We explored whether individual differences in performance on the factual questions about the text and off-task thought were associated with variation in patterns of intrinsic connectivity from these seeds. We generated functional connectivity maps for each region, for each individual, and then analysed these spatial maps using a series of multiple regression analyses that included individual scores in off-task thought (i.e., off-task frequency and NYC-Q) and text-based memory as explanatory variables. There were no significant differences in the connectivity of the FPN seed region in ITG that related to either off-task thought or text-based memory, so this site is not discussed further. There were some effects for the DAN seed in ITG/LOC but these failed to survive Bonferroni correction for the number of seeds and the two-tailed nature of our tests (see **Section 2.4.3.3.2.**).

### *2.4.3.1. Performance on factual questions related to the text*

We found that MTG connectivity was related to memory for the content of the text. Participants with better text-based memory scores showed stronger connectivity between the MTG DMN seed region and anterior cingulate cortex (cingulate gyrus and paracingulate gyrus; uncorrected $p$ = .006). This cluster is illustrated in Figure 2.4. Of the voxels within the anterior cingulate cluster that fell within the large-scale networks defined by Yeo et al. (2011), 88.3% were within DMN, 11.3 % fell within FPN, and 0.4 % fell within ventral attention network. These findings show that connectivity between different nodes of DMN is linked to better text-based memory (not poorer performance, as a task-negative theory of DMN might predict).

### *2.4.3.2. Off-task Frequency*

We also found that increasing off-task frequency was associated with weaker connectivity between MTG in DMN and visual cortex (intracalcarine cortex, precuneus cortex, and lingual gyrus; uncorrected $p$ = .006). This effect is presented in Figure 2.4. Of the voxels in this cluster that fell within one of the large-scale networks defined by Yeo et al. (2011), 100% were within the visual network. Consequently, participants with stronger intrinsic connectivity at rest between DMN and visual cortex were less likely to engage in off-task thinking while reading.

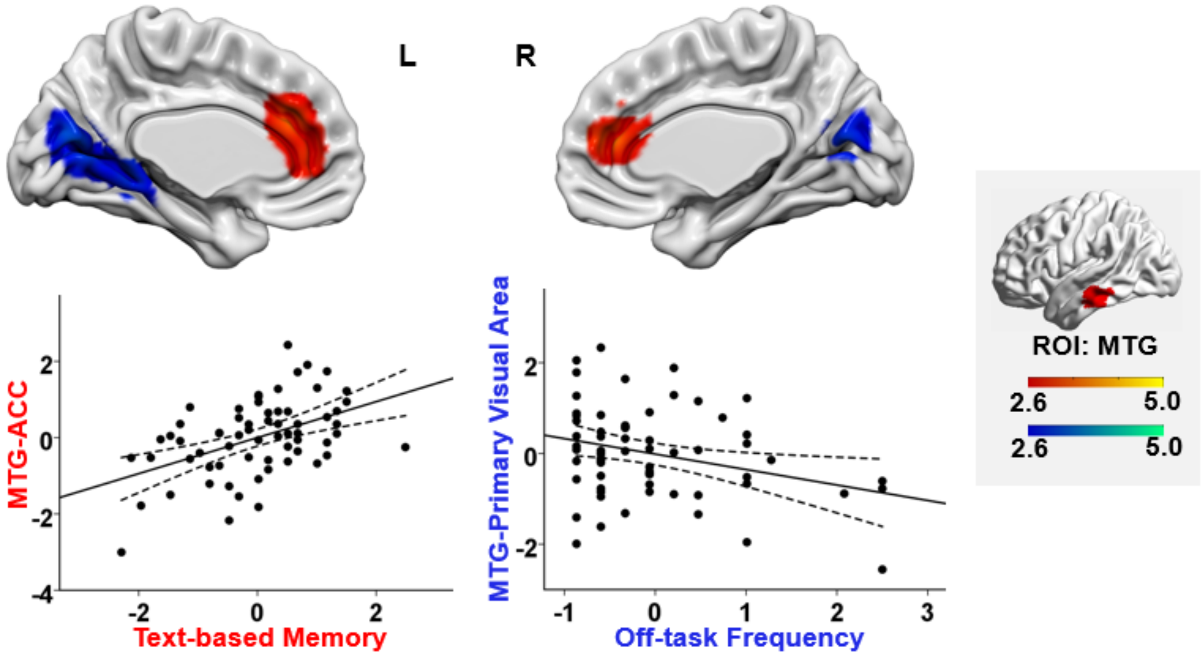


*Figure 2.4.* **Functional connectivity of MTG within DMN linked to off-task frequency and text-based memory**. The regions in red showed stronger connectivity to MTG for participants with good text-based memory, while the regions in blue showed weaker connectivity with MTG for participants with more frequent off-task thought. All maps are cluster corrected at a threshold of $z > 2.6$ ($p < .05$). The scatterplots present the correlation between behaviour (text-based memory or off-task frequency) and the average correlation with the MTG seed and the relevant cluster (beta values). The error lines on the scatterplot indicate the 95% confidence estimates of the mean. Each point describes an individual participant. The right-hand panel highlighted in grey shows the seed region and the colour bars. MTG = middle temporal gyrus; ACC = anterior cingulate cortex.

#### *2.4.3.3. Additional effects*

There were several additional effects that were significant at the whole-brain level that did not survive Bonferroni correction for the number of models and the two-tailed nature of our tests (e.g., $p >$ .0083). When considering these results, it is important to note that these may reflect Type II errors and should be considered accordingly.

#### 2.4.3.3.1. Seeding from MTG DMN region

(i) With increasing off-task thought, a mid-cingulate cortex region showed greater disconnection with MTG (uncorrected *p* = .022; see Figure 2.5). Of the voxels in this cluster that fell within the large-scale networks defined by Yeo et al. (2011), 38.1% were within the somatomotor network, 47.6% fell within the default mode network, and 7.6% and 6.7% fell within the ventral attention and frontoparietal network, respectively. This pattern in some ways resembles decoupling from the visual cortex, at a lower statistical threshold.

(ii) Increasing off-task thought was associated with greater connectivity between left inferior frontal gyrus and the DMN portion of MTG (uncorrected *p* = .044). Of the voxels within left inferior frontal gyrus that fell within the large-scale networks defined by Yeo et al. (2011), 69.5% were within the default mode network, 16.9% fell within the frontoparietal network, and 13.6% fell within the ventral attention network.

(iii) Higher NYC-Q scores were linked to greater connectivity between MTG and parahippocampal gyrus as well as temporal fusiform cortex (uncorrected *p* = .028). Of the voxels within parahippocampal gyrus that fell within the large-scale networks defined by Yeo et al. (2011), 96.6% were within the visual network and 3.4% fell within the default mode network.

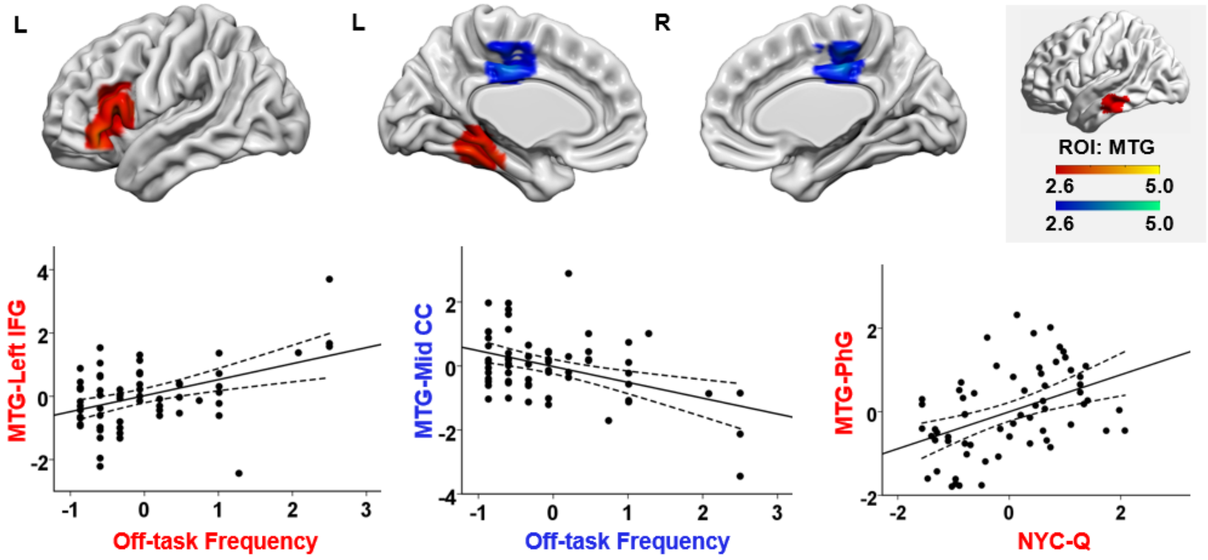


***Figure 2.5*. Additional effects of functional connectivity seeding from MTG DMN seed region**. The regions in warm colour indicate regions displaying connectivity with MTG were stronger for the

participants with frequent off-task thought or higher NYC-Q scores. And the regions in cold colour indicate regions displaying connectivity with MTG were weaker for the participants with frequent off-task thought. All maps are cluster corrected at a threshold of $z > 2.6$ ($p < .05$). The scatterplots present the relationship between the average correlation with MTG (beta values) in each region and off-task frequency, as well as NYC-Q scores. The error lines on the scatterplots indicate the 95% confidence estimates of the mean. Each point describes each participant. The upper right panel highlighted in grey shows the seed region and the colour bar. IFG = inferior frontal gyrus; Mid CC = middle cingulate cortex; PhG = parahippocampal gyrus; MTG = middle temporal gyrus.

#### 2.4.3.3.2. Seeding from ITG/LOC DAN region

Analysis of the functional connectivity of DAN in ITG/LOC showed that poor text-based memory was linked to greater connectivity between the left ITG and (i) the right lateral occipital cortex (uncorrected $p = .041$; see Figure 2.6) as well as (ii) the right inferior and middle temporal gyrus (uncorrected $p = .015$). For the voxels within the right lateral occipital cortex that fell within the large-scale networks defined by Yeo et al. (2011), 56.8% fell within the dorsal attention network, 28.4% were within visual network, 5.8% fell within default mode network, and 2.3% fell within the frontoparietal network. For the voxels within the right inferior/middle temporal gyrus that also fell within the large-scale networks defined by Yeo et al. (2011), 69.8% fell within the frontoparietal network, 29.3% were within dorsal attention network, and 0.8 % fell within the default mode network.

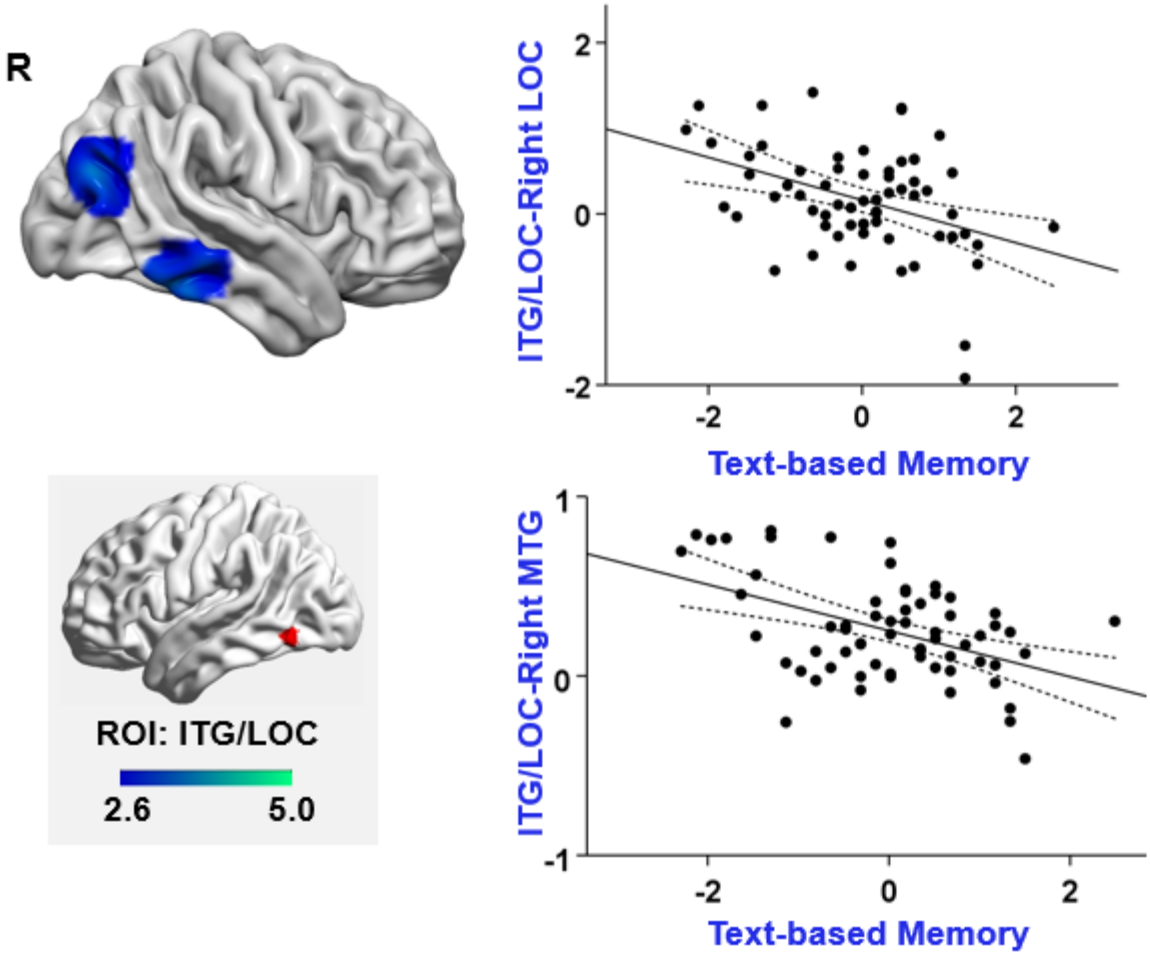


***Figure 2.6.*** **Additional effects of functional connectivity seeding from ITG/LOC DAN seed region**. The regions in cold colours indicate regions displaying weaker connectivity with ITG for participants with good text-based memory. All maps are cluster corrected at a threshold of $z > 2.6$ ($p < .05$). The scatterplots present the relationship between the average correlation with ITG (beta values) in each region and text-based memory. The error lines on the scatterplots indicate the 95% confidence estimates of the mean. Each point describes each participant. The lower left panel highlighted in grey shows the seed region and the colour bar. R = right hemisphere; Right LOC = right lateral occipital cortex; Right MTG = right middle temporal gyrus; ITG = inferior temporal gyrus.

### Summary of results

Our study set out to examine the neural mechanisms that contribute to reading performance, assessed using factual questions answered from memory about the content of a text, and periods of off-task thinking during reading. Using a data-driven approach, Experiment 1 identified regions within the middle temporal gyrus that activated more for people with better text-based memory in the sentence-reading task. This region fell at the intersection of three large-scale networks – the DAN, FPN and DMN. In Experiment 2, we separated the MTG cluster into sub-regions that corresponded to each of these networks and used them in an analysis of resting-state connectivity to establish whether the intrinsic architecture of any of these regions was predictive of variation in either patterns of off-task thought or text-based memory. We found no evidence that variation in either memory for the text or off-task thought was linked to the connectivity of the FPN region. Weak evidence emerged for a role of the DAN in reading: weaker connectivity with regions of both the right angular gyrus/lateral occipital cortex and right middle temporal gyrus was linked to better text-based memory, although this result did not survive correction for the number of seeds and the two-tailed nature of our tests. The strongest evidence was observed for the DMN since the MTG sub-region showed patterns of connectivity that were linked to both reading and off-task thinking. The most robust of these effects were (i) stronger connectivity with a medial prefrontal region, also in DMN, that was associated with better text-based memory, and (ii) weaker connectivity with visual cortex, linked to greater frequency of off-task thought. Together these results provide converging support for the role of multiple large-scale systems in the ability to read for meaning, and specific support for the importance of the DMN in both memory for texts, as well as for the occurrence of off-task thought during reading.

### 2.5. General discussion

We show how a region of the lateral temporal cortex within the default mode network (DMN) is implicated in both on-task processing (i.e. text processing) and off-task mental states (such as periods of off-task thought). In Experiment 1, which employed a sentence-reading task in the scanner, we found people who were better able to answer questions about a text that they had read previously showed a greater BOLD response to orthographic inputs in middle temporal gyrus (MTG) within DMN, and a region of inferior temporal gyrus (ITG) in FPN, as well as another region of ITG/lateral occipital cortex in DAN. In Experiment 2, we explored individual differences in the intrinsic connectivity of these sites. For individuals with more frequent off-task thought, MTG within DMN showed weaker connectivity with visual cortex, suggesting that perceptual decoupling may promote off-task thought. In contrast, for individuals with better text-based memory, MTG showed greater connectivity with anterior cingulate cortex, also in the DMN. These findings show that DMN regions in lateral temporal cortex have patterns of connectivity that uniquely support both reading, and states that are detrimental to making sense of what one is reading (i.e. off-task thought).

Although our results show relatively clear evidence for the involvement of the DMN in both reading and off-task thought, our study failed to find robust evidence supporting a role of the DAN or the FPN. No whole-brain results were observed for the FPN. For the DAN, better text-based memory was associated with weaker correlation between regions of the right temporal and parietal cortex that fell largely within the FPN and DAN. Although it may seem paradoxical that higher connectivity within the DAN is linked to poorer reading performance, our prior studies using a sustained attention task found lower connectivity within this system (and in particular to the same LOC cluster) was linked to a greater tendency for attention to remain coupled to the task (Turnbull et al., 2019). Moving forward, our studies suggest that it will be important to assess the neural basis of different features of experience across multiple task contexts.

Our results add to a growing body of evidence that DMN plays a complex role in reading. Our prior study found that DMN connectivity to different regions was linked to both better and poorer comprehension. The current study shows that the MTG region may be important in the capacity of the DMN to contribute to apparently opposing mental states. Our study suggests that rather than different temporal lobe regions supporting on-task and off-task semantic retrieval (for example, regions falling within FPN and DMN respectively), diverse patterns of connectivity from the same DMN region can underpin both off-task thought and reading. It has already been observed that semantic regions within temporal cortex have a pattern of connectivity to both DMN core and visual cortex (Binney et al., 2010;

Murphy et al., 2017; Visser et al., 2012) – our results suggest that both of these connections are important for good text-based memory. Our results are also broadly consistent with the recent observation that while DMN often shows a response to nonwords over words (reflecting off-task processing), these DMN regions also support semantic processes engaged in reading (Mattheiss, Levinson, & Graves, 2018).

Functionally, MTG is implicated in heteromodal aspects of cognition as the inputs along auditory and visual processing streams maximally converge here (Lambon Ralph et al., 2017; Margulies et al., 2016; Murphy et al., 2017; Visser et al., 2012). MTG responds more strongly to memory-based and meaning-based decisions, consistent with the location of this cluster at the anterior end of the ventral visual stream within the DMN (Murphy et al., 2018). In line with these studies, the anterior and middle temporal lobe have been identified as important for text comprehension (Ferstl et al., 2008; Jangraw et al., 2018; Kuperberg, Lakshmanan, Caplan, & Holcomb, 2006). Nevertheless, activation within MTG is insufficient for comprehension – our results suggest this region also needs to be strongly activated by visual inputs and to interact with other regions of DMN implicated in comprehension.

Finally, our study also provides evidence that poor reading is linked to inattention or perceptual disengagement (Smallwood, 2011, 2013). First, we found that poor memory for texts was linked to lower levels of activity in MTG in response to orthographic inputs. Since this response was identified in the meaningless condition, it is likely to be a consequence of how perceptual input rather than meaning is processed. Second, we found that the aspect of this region that fell within the DMN was less coupled to primary visual cortex for individuals who were frequently off-task while reading. Event-related potentials evoked by sensory inputs are reduced in magnitude during episodes of off-task thought, relative to on-task periods (Kam et al., 2011). The posterior core of the DMN which supports heteromodal integration (Braga, Sharp, Leeson, Wise, & Leech, 2013) also contributes to different types of spontaneous thought (Smallwood et al., 2016). The role of MTG in processing texts and in off-task thought may be similar: perceptual decoupling of MTG from visual cortex may allow this region to support off-task thought that is unrelated to the immediate external environment. This pattern is generally consistent with the cascade model of inattention (Smallwood, 2011), which argues that off-task states during reading partly reflect reductions in perceptual processing. This leads to cascading consequences affecting both comprehension and memory for texts (Smallwood, McSpadden, et al., 2008).

While DMN regions support off-task states that impair text processing, connectivity within DMN predicted good memory for texts. In people who were able to answer more factual questions about what they had read, MTG coupled more with anterior cingulate cortex, and both regions fell largely within DMN as defined by Yeo et al. (2011). Both of these regions are ‘hubs’ that integrate diverse elements of cognition (Margulies et al., 2016; Rossell, Bullmore, Williams, & David, 2001; Visser et al., 2012; Zhao et al., 2017). Anterior cingulate cortex shows graded connections at rest with both sensory and motor cortices, as well as with memory/DMN regions (Margulies et al., 2007). Extrapolating from our results, individuals who had the most efficient reading experience (i.e. who experienced less off-task thought and answered more questions about the text) would show a combination of strong within-DMN connectivity and less decoupling with the visual system. Although there are likely to be functional subdivisions within DMN, findings from our study directly concerned with attentional lapses are hard to accommodate within the commonly held view of the DMN as supporting off-task states (Mazoyer et al., 2001; Raichle et al., 2001; Shulman et al., 1997). Instead our study adds to a growing body of evidence that this system can make important contributions to external task processing (Crittenden et al., 2015; Davey, Cornelissen, et al., 2015; Murphy et al., 2018; Murphy, Wang, et al., 2019; Sormaz et al., 2018; Vatansever et al., 2017).

### 2.6. Conclusion

In conclusion, we found that dissociable patterns of activation and intrinsic connectivity in an MTG region within DMN predicted text-based memory and off-task thought. Better performance on questions about the text was associated with greater coupling of MTG with another DMN region in anterior cingulate gyrus. In contrast, greater disconnection between MTG and primary visual cortex was associated with frequent off-task thought. We conclude that DMN regions in lateral temporal cortex not only help us to process information in the external environment, but also form thoughts that can be independent from what is happening around us – however, both of these aspects of cognition are supported by a broader network of brain regions.

# Chapter 3: Distinct default mode subsystems show similarities and differences in the effect of task focus across reading and autobiographical memory

**This chapter is adapted from: Zhang, M., Wang, X., Varga, D., Krieger-Redwood, K., Smallwood, J., Jefferies, E. Distinct default mode subsystems show similarities and differences in the effect of task focus across reading and autobiographical memory. (in preparation)**[2]

## 3.1. Abstract

Semantic cognition can be both perceptually-coupled, for example, during reading, and decoupled, such as in daydreams. Mind-wandering, characterised by autobiographical memory retrieval, often interferes with externally-focussed tasks. This study investigated the neural basis of these states, when they occur in isolation and in competition, using fMRI. Participants were asked to read sentences, presented word-by-word, or to recall personal memories, as a proxy for mind-wandering. Task conflict was created by presenting sentences during memory recall, or memory cues before sentences. We found that different subsystems of the default mode network (DMN) do not fully dissociate across internally- and externally-oriented states, and they do not fully separate in terms of effects of task focus; this depends on the task. The left lateral temporal DMN subsystem, associated with semantic cognition, was activated across both tasks, and by sentence inputs even when they were task-irrelevant. In the core DMN subsystem, greater task focus corresponded with a selective pattern of activation during memory recall and deactivation during reading. Both DMN subsystems formed different patterns of functional coupling depending on the task. In this way, DMN supports both access to meaning from perceptual inputs and focussed internal cognitive states in the face of distracting external information.

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[2] The author, Meichao Zhang, designed the experiment, performed the experiment, analysed the results and wrote the article under the supervision of Prof. Beth Jefferies and Prof. Jonny Smallwood. Dr. Xiuyi Wang and Dr. Katya Krieger-Redwood provided support for data analysis and provided comments on the manuscript. Dominika Varga helped to collect data.

## 3.2. Introduction

Cognition not only enables us to make sense of the external world (Lambon Ralph et al., 2017; Patterson et al., 2007), it also supports internal thoughts that are fully independent from the surrounding environment (Smallwood & Schooler, 2015; Svoboda et al., 2006; Zhang et al., 2019). These perceptually-decoupled aspects of cognition are traditionally associated with the default mode network (DMN), which tends to deactivate when participants engage in demanding externally-presented tasks (Raichle et al., 2001). While DMN was initially characterised as "task-negative" (e.g., Fox et al., 2005; Raichle et al., 2001), it is now clear that it supports internally-focussed cognitive states – for example, thinking about the past, future, ourselves or other people (Christoff et al., 2009; Konu et al., 2020; Spreng & Grady, 2010; Spreng et al., 2009) – both when these states occur spontaneously, during mind-wandering (Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Mason et al., 2007; Smallwood et al., 2016), and in tasks such as autobiographical memory retrieval (Sheldon, Farb, Palombo, & Levine, 2016; Spreng & Grady, 2010; Spreng et al., 2009). Mounting evidence shows DMN can also support externally-oriented states (e.g., Krieger-Redwood et al., 2016; Murphy et al., 2018; Vatansever et al., 2015; Wirth et al., 2011), particularly situations when we extract meaning from perceptual inputs, such as reading (Smallwood et al., 2013; Zhang et al., 2019). This raises questions about how DMN supports diverse perceptually-coupled and decoupled states, and what happens when these are in conflict; for example, when we are reading but become distracted by internally-generated thoughts. In these circumstances, does greater task focus on reading activate or deactivate DMN?

Recent research has proposed that internal cognitive states and externally-oriented semantic tasks might activate distinct functional subdivisions within DMN (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Chiou, Humphreys, & Lambon Ralph, 2019). Patterns of intrinsic connectivity within DMN point to separable subsystems (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Yeo et al., 2011), focussed on (i) regions of lateral temporal cortex and anterior frontal gyrus, implicated in the representation and retrieval of conceptual knowledge (e.g., Badre & Wagner, 2002; Jackson et al., 2016; Lambon Ralph et al., 2017) and referred to as the "lateral temporal subsystem" here; (ii) medial temporal regions, like hippocampus, that are important for episodic memory (Nyberg et al., 1996;

Steinvorth et al., 2005) and (iii) a "core" DMN subsystem drawing on posterior cingulate cortex, medial prefrontal cortex, and angular gyrus (AG), which might allow information to be transferred between these subsystems (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Andrews-Hanna, Smallwood, et al., 2014) and which shows interdigitated connectivity to both the lateral and medial temporal subsystems (Braga & Buckner, 2017; Braga et al., 2019). ATL within the lateral temporal subsystem shows activation across semantic tasks but deactivation in non-semantic tasks, while AG in core DMN shows consistent deactivation during both semantic and non-semantic tasks (Humphreys, Hoffman, Visser, Binney, & Lambon Ralph, 2015). A similar functional dissociation across DMN subsystems was reported by Chiou et al. (2019) who found the lateral temporal DMN subsystem prefers mental activities "*interfacing with*" perceptible events, while the core DMN prefers activities "*detached from*" perceptible events.

An alternative possibility is that both internal and external states access common semantic processes within DMN. Semantic cognition is supported by a distributed neural network that partially overlaps with DMN in the ventrolateral anterior temporal lobes (ATL) and AG (Binder et al., 2009; Lambon Ralph et al., 2017). These DMN regions typically show stronger responses during more "automatic" semantic retrieval, such as the retrieval of strong associations or dominant features (Davey, Cornelissen, et al., 2015; Hoffman et al., 2015; Humphreys & Lambon Ralph, 2014; Teige et al., 2019; Teige et al., 2018). However, DMN regions also participate in controlled aspects of semantic cognition, showing stronger recruitment in demanding working memory tasks that involve decisions about meaningful objects as opposed to colour patches (Murphy et al., 2018), and increasing their connectivity to regions of executive cortex during challenging semantic conditions that involve the control of distracting information (Krieger-Redwood et al., 2016). Moreover, conceptual knowledge is implicated in both reading comprehension (Dehaene et al., 2015; Spitsyna et al., 2006) and autobiographical memory (Graham, Lee, Brett, & Patterson, 2003; Svoboda et al., 2006). Distinct patterns of functional connectivity from the same semantically-relevant DMN sites might therefore support these diverse states – with stronger coupling to visual cortex when we access conceptual information from external inputs – and stronger connectivity to other DMN regions when the focus is on internal cognitive states.

In line with this proposal, lateral temporal DMN regions can form strong intrinsic connectivity with both primary visual cortex and other DMN nodes (Murphy et al., 2017; Zhang et al., 2019). In addition, poor external engagement is linked to strong functional coupling between dorsal and medial temporal DMN subsystems (Poerio et al., 2017).

By this view, there are key similarities within DMN between internally-focussed states and externally-oriented semantic tasks. Both require patterns of cognition that are at least somewhat removed from the activation unfolding within sensorimotor cortex. According to the “graded hub and spoke” model of semantic representation (Lambon Ralph et al., 2017), concepts are formed within a heteromodal semantic hub in ventrolateral ATL that is (equi)distant from features in sensory-motor cortex (“spokes”). This allows the extraction of “deep” heteromodal similarity patterns not present within individual sensory-motor features: for example, BANANA is conceptually related to LETTUCE, even though colour features have stronger similarity with CANARY while shape features suggest a likeness with BOOMERANG (Lambon Ralph, Sage, Jones, & Mayberry, 2010; Patterson et al., 2007). Fully heteromodal concepts are thought to be processed within brain regions relatively far (and therefore insulated) from spokes, such as ventrolateral ATL (Binney et al., 2010; Murphy et al., 2017; Patterson et al., 2007; Visser et al., 2010) and left AG (Lanzoni et al., 2020; Price et al., 2015; Price et al., 2016), within DMN. This proposal is consistent with insights from decompositions of whole-brain intrinsic connectivity into “gradients”, which capture components of the brain’s functional architecture. The “principal gradient”, explaining the most variance in intrinsic connectivity, reflects the distinction between unimodal cortex and heteromodal DMN, and is also correlated with geodesic distance from primary sensorimotor landmarks on the cortical surface (Margulies et al., 2016; Vidaurre, Smith, & Woolrich, 2017). Along with semantic cognition, this separation of DMN from sensorimotor cortex might be necessary for the maintenance of cognitive states that are entirely independent from the external environment; for example, when thinking about a past or future holiday. The anatomical location of DMN at a maximum distance from sensorimotor cortex might therefore explain the contribution of regions within DMN to both semantic and perceptually-decoupled cognition.

Here, we provide a novel characterisation of the responsiveness of lateral temporal and core DMN subsystems to an external semantic task (reading) and a perceptually-decoupled state (autobiographical memory), considering the effects of task focus when these cognitive states are in competition. Participants were asked to either comprehend sentences presented word-by-word, or recall personal memories. We also characterised how responses in these subnetworks are modulated by fluctuating task focus, presenting irrelevant sentences on autobiographical memory trials, and irrelevant autobiographical memory cues on reading trials, and collecting ratings of the extent to which participants were able to focus on the primary task. In this way, irrelevant autobiographical memory cues were used to elicit the kinds of cognitive states that occur when our minds wander during reading. We tested for common task activation across the DMN subsystems, given that both reading and autobiographical memory involve access to conceptual knowledge. Analyses of functional connectivity explored how semantic DMN regions might support both perceptually-coupled and decoupled mental states. The task structure also allowed us to determine if meaningful visual inputs or memory cues activate DMN regions even when task-irrelevant, and whether DMN regions always deactivate when people are more focussed on a task (or whether these patterns vary across task states and/or DMN subsystems). To anticipate, we establish that DMN subsystems do not fully dissociate across internally- and externally-oriented states, although this dimension is relevant to their functional organisation. In addition, they do not fully separate in terms of effects of task focus; this depends on the task. Instead, DMN is organised in a way that supports both access to meaning from perceptual inputs and focussed internal cognitive states in the face of distracting external information.

## 3.3. Methods

### *3.3.1. Design*

Participants completed two tasks involving semantic retrieval: autobiographical memory and word-by-word reading comprehension. On some trials, there was conflict from the other task: retrieval from autobiographical memory unfolded whilst words were presented one by one on the screen (or while strings of the letter X were presented in the no-conflict condition), and sentence comprehension unfolded after an autobiographical cue word was presented (or when this memory cue was replaced by a string of Xs). Consequently, we employed a within-subjects 2x2 design manipulating task and conflict.

The experiment took place over two days. On Day 1, participants were asked to identify specific personal events linked to each autobiographical memory cue (words like PARTY). On Day 2, they recalled these memories when presented with the cue word in the scanner, and also completed the reading task, which involved reading factual sentences about similar concepts.

### *3.3.2. Participants*

Twenty-nine undergraduate students were recruited for this study (age-range 18-23 years, mean age ± SD = 20.14 ± 1.26 years, 6 males). All were right-handed native English speakers, and had normal or corrected-to-normal vision. None had any history of neurological impairment, diagnosis of learning difficulty or psychiatric illness. All provided written informed consent prior to taking part and received monetary/course credits compensation for their time. Ethical approval was obtained from the Research Ethics Committees of the Department of Psychology and York Neuroimaging Centre, University of York.

### *3.3.3. Materials*

One hundred and forty-four highly imageable, frequent and concrete nouns were selected to serve as key words within sentences and as cue words for autobiographical memory recall. These nouns were divided into two lists (i.e., seventy-two words for each task) that did not differ in terms of frequency ($F(1,71) = 2.85$, $p = .10$, $\eta_p^2 = .04$), imageability ($F(1,71) = .02$, $p = .88$, $\eta_p^2 < .001$), and concreteness ($F(1,71) = .09$, $p = .76$, $\eta_p^2 = .001$). The sentences were constructed by using the key words as a search term in Wikipedia to identify text that described largely unfamiliar facts about each item (Sentence Length: *Mean* ± *SD* = 20.04 ± .93 words). These sentences and the autobiographical memory cues were then divided into three sets and assigned to different conditions (with this assignment counterbalanced across participants). The sentences were assigned to (1) *Pure Reading* (i.e., reading without conflict from memory recall); (2) *Conflict Reading* (i.e., reading with conflict from memory recall) and (3) *Conflict Recall* (i.e., memory recall with conflict from semantic input). Similarly, the autobiographical memory cues were assigned to (1) *Pure Recall* (i.e., memory recall without conflict from semantic input); (2) *Conflict Recall* (i.e., memory recall with conflict from semantic input) and (3) *Conflict Reading* (i.e., reading with conflict from memory recall). The words used in these conditions were matched on key psycholinguistic variables (see Table 3.1): they did not differ in lexical frequency (CELEX database; Baayen, Piepenbrock, & Van Rijn, 1993) (Reading: $F(2,46) = .80$, $p = .46$, $\eta_p^2 = .03$; Recall: $F(2,46) = .19$, $p = .83$, $\eta_p^2 = .01$), imageability (Davis, 2005) (Reading: $F(2,46) = .20$, $p = .82$, $\eta_p^2 = .01$; Recall: $F(2,46) = 1.07$, $p = .35$, $\eta_p^2 = .04$) or concreteness (Brysbaert, Warriner, & Kuperman, 2014) (Reading: $F(2,46) = .21$, $p = .81$, $\eta_p^2 = .01$; Recall: $F(2,46) = .13$, $p = .88$, $\eta_p^2 = .01$). In addition, all the words in the three sets of sentences were comparable across these variables (see Table 3.1; Frequency: $F(2,46) = 1.40$, $p = .26$, $\eta_p^2 = .06$; Imageability: $F(2,46) = .30$, $p = .74$, $\eta_p^2 = .01$; Concreteness: $F(2,46) = .70$, $p = .50$, $\eta_p^2 = .03$). Two additional cue words were created for task practice. There was no overlap in the words presented as autobiographical cues or key words within sentences.

***Table 3.1.*** Linguistic properties of each set of key words within sentences and autobiographical memory cues, and the words within each set of sentences (*Mean* ± *SD*).

| ***Conditions*** | ***Frequency*** | ***Imageability*** | ***Concreteness*** |
|---|---|---|---|
| First set of key words for sentences | 1.31 ± .56 | 591.67 ± 34.20 | 4.74 ± .52 |
| Second set of key words for sentences | 1.47 ± .50 | 598.05 ± 27.49 | 4.72 ± .55 |
| Third set of key words for sentences | 1.29 ± .52 | 592.61 ± 44.35 | 4.64 ± .58 |
| First set of autobiographical memory cues | 1.59 ± .76 | 588.48 ± 41.20 | 4.70 ± .47 |
| Second set of autobiographical memory cues | 1.48 ± .62 | 594.64 ± 24.46 | 4.75 ± .30 |
| Third set of autobiographical memory cues | 1.54 ± .56 | 601.53 ± 23.65 | 4.73 ± .41 |
| First set of sentence materials | 2.59 ± .24 | 354.34 ± 27.41 | 2.72 ± .26 |
| Second set of sentence materials | 2.52 ± .20 | 352.40 ± 23.39 | 2.72 ± .21 |
| Third set of sentence materials | 2.48 ± .27 | 347.64 ± 35.24 | 2.80 ± .24 |

### *3.3.4. Procedure*

Testing occurred across two consecutive days with autobiographical memory generation on Day 1 and memory recall and reading in the scanner on Day 2.

***Autobiographical memory generation task on Day 1***. The participants were asked to generate their own personal memories from cue words (i.e., Party) outside the scanner. These memories could be from any time, from childhood to the day before testing. Participants were asked to identify specific events that they were personally involved in and to provide as much detail about these events as they could. These details included when and where the event took place, who was involved, what happened, and the duration. To ensure compliance with the task instructions, participants typed these details into a spreadsheet, which ensured that comparable information was recorded for the different cue words.

***Autobiographical memory recall and reading task on Day 2.*** On the following day, the participants were asked to recall their generated personal memories or read sentences for comprehension inside the scanner. In reading trials, sentences were presented word by word, after either (1) an autobiographical memory cue word (e.g., Party) associated with a personal memory outside the scanner, creating conflict between task-relevant and task-irrelevant patterns of semantic retrieval, or (2) a letter string (XXX) allowing reading to take place in the absence of conflict from autobiographical memory. We controlled the duration of the sentences by presenting the words on 15 successive slides, combining short words on a single slide (e.g., *have been* or *far better*) and presenting articles and conjunctions together with nouns (e.g., *the need*; *and toys*). In memory recall trials, participants were asked to recall autobiographical memories during the presentation of either (1) an unrelated sentence, creating conflict between task-relevant and task-irrelevant patterns of semantic retrieval or (2) letter strings (XXX) allowing autobiographical memory to take place without distracting semantic input. In this way, we manipulated potential conflict between autobiographical memory and reading comprehension. As a control condition, meaningless letter strings (i.e., xxxxx) were presented. Participants were asked to view these strings and perform a low-level baseline task (colour-change detection, common across all conditions; see below).

As shown in Figure 3.1, each trial started with a fixation cross presented for a jittered interval of 1-3s in the centre of the screen. Then either an autobiographical memory cue word or a letter string (e.g., “XXX”) appeared for 2s. Cue words and single letter strings preceded the presentation of sentences and repeated letter strings, which were presented inside a black rectangle. During the presentation of the cue word, participants were asked to bring to mind their personal memory related to this item. Next, the task instruction (i.e. READING or MEMORY RECALL) was presented for 1s to instruct the participants to focus on either reading comprehension or memory recall. Following that, sentences or letter strings were presented item-by-item, with each one lasting 600ms. On memory recall trials, participants were asked to keep thinking about their autobiographical memory, in as much detail as possible, until the end of the trial. In order to ensure the participants were maintaining attention to the presented stimuli (even when these were irrelevant and creating competition), they were told to press a button when they noticed the colour of a word or letter string change to red. There were 3 trials out of 24 trials in each condition that involved responding in this way.

After each trial, participants were asked to rate several dimensions of their experience. For autobiographical memory trials, participants were asked about task focus (i.e., How well did you focus on the recall task?), vividness (i.e., How vivid was your memory?), and consistency of their memory recall (i.e., How similar was it to your previously generated memory?). For the reading comprehension task, participants were asked the same question about task focus (i.e., How well did you focus on the reading task?), as well as about their comprehension (i.e., How well did you comprehend this sentence?), and conceptual familiarity (i.e., How familiar were you with the reading content?).

The three rating questions were sequentially presented after a jittered fixation interval lasting 1-3s. Participants were required to rate these characteristics on a scale of 1 (not at all) to 7 (very well) by pressing a button box with their right hand. They had 4s to make each response. There were no ratings for the letter string trials.

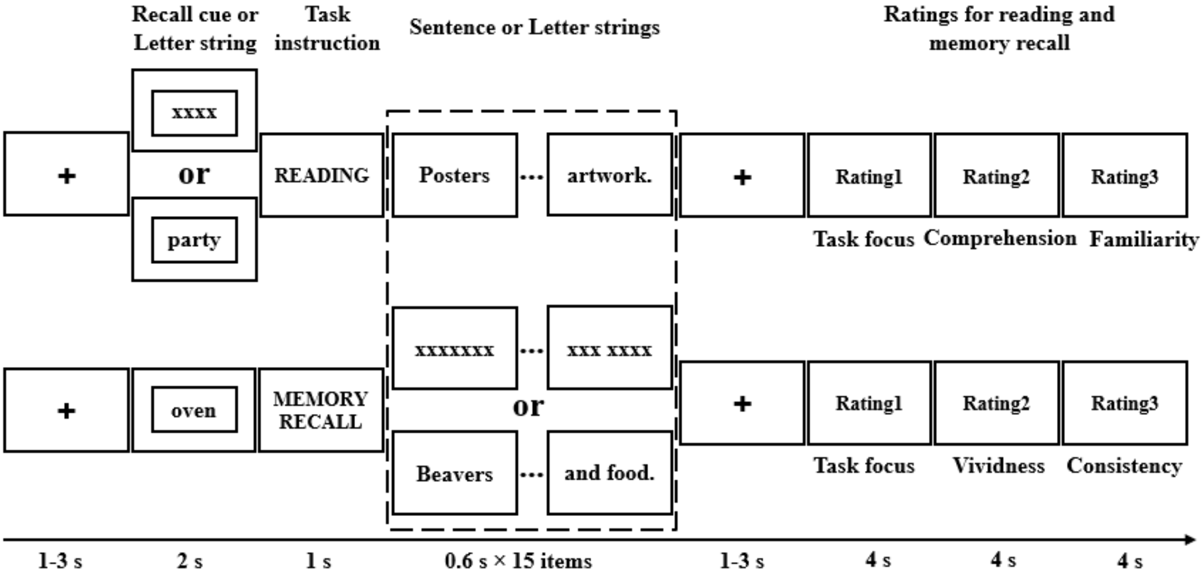


***Figure 3.1. Task illustration.*** Procedure of reading task and autobiographical memory recall in the scanner on Day2.

We examined text-based memory for the reading sentences presented in the *Pure reading*, *Conflict reading* and *Conflict recall* conditions immediately after the scanning session. Participants were presented with the cue words from the reading lists, one at a time, and were asked to try to recall any words from the sentences that they had seen inside the scanner relating to this cue word. They typed their responses. Participants were told in advance that they would be asked about the sentences that they had read in the scanner.

Stimuli were presented in four runs, each containing 30 trials: 6 trials in each of the four experimental conditions, and 6 letter string trials. Each run lasted 12.85 minutes, and trials were presented in a pseudorandom order to make sure that the trials from the same experimental condition were not consecutively presented more than three times. The runs were separated by a short break and started with a 9-second alerting slide (i.e. Experiment starts soon).

Before entering the scanner, participants completed a 6-minute task to test their memory of the generated personal memories that they came up with on the day before the scanning. In this task, each autobiographical cue was presented for 3s after a jittered interval of 1-3s in the centre of the screen, with two options (i.e., *Remembered* and *Not remembered*). Participants pressed one of two buttons on a keyboard to indicate if they could remember the memory they previously came up with and they then reviewed their generated memories to refresh themselves with the ones that were not well remembered. Next, detailed instructions were provided for the in-scanner memory recall and reading tasks. To ensure participants fully understood the task requirements, they completed an 8-trial practice block containing all types of conditions. They were given feedback about their performance and, if necessary, they repeated the practice trials (this additional training was only needed for one participant to practice providing rating responses within 4s).

### *3.3.5. Neuroimaging data acquisition*

Structural and functional data were acquired using a 3T GE HDx Excite Magnetic Resonance Imaging (MRI) scanner utilizing an eight-channel phased array head coil at the York Neuroimaging Centre, University of York. Structural MRI acquisition in all participants was based on a T1-weighted 3D fast spoiled gradient echo sequence (repetition time (TR) = 7.8 s, echo time (TE) = minimum full, flip angle = 20°, matrix size = 256 × 256, 176 slices, voxel size = 1.13 mm × 1.13 mm × 1 mm). The task-based activity was recorded using single-shot 2D gradient-echo-planar imaging sequence with TR = 3 s, TE = minimum full, flip angle = 90°, matrix size = 64 × 64, 60 slices, and voxel size = 3 mm × 3 mm × 3 mm. Data was acquired in a single session. The task was presented across 4 functional runs, each containing 257 volumes.

### *3.3.6. Pre-processing of task-based fMRI data*

All functional and structural data were pre-processed using a standard pipeline and analysed via the FMRIB Software Library (FSL version 6.0, www.fmrib.ox.ac.uk/fsl). Individual T1-weighted structural brain images were extracted using FSL’s Brain Extraction Tool (BET). Structural images were linearly registered to the MNI152 template using FMRIB's Linear Image Registration Tool (FLIRT). The first three volumes (i.e. the presentation of the 9-second-task-reminder ‘Experiment starts soon’) of each functional scan were removed in order to minimise the effects of magnetic saturation, therefore there was a total of 254 volumes for each functional scan. The functional neuroimaging data were analysed by using FSL’s FMRI Expert Analysis Tool (FEAT). We applied motion correction using MCFLIRT (Jenkinson et al., 2002), slice-timing correction using Fourier space time-series phase-shifting (interleaved), spatial smoothing using a Gaussian kernel of FWHM 6 mm, and high-pass temporal filtering (sigma = 100 s) to remove temporal signal drift. In addition, motion scrubbing (using the fsl_motion_outliers tool) was applied to exclude volumes that exceeded a framewise displacement threshold of 0.9. There were no scans with greater than 25% of the data censored for motion, and thus no participants or scans were excluded from the univariate analysis due to excessive motion.

### *3.3.7. Univariate analysis of task-based fMRI data*

The analysis examined the common and differentiated brain regions that are important for reading comprehension and autobiographical memory retrieval. We also identified the response to conflict when participants either read the sentence with or without an autobiographical memory cue and recalled their generated memories with or without conflict from sentence presentation. Consequently, the model included two factors within a 2x2 design: (1) Task (Reading Comprehension vs. Autobiographical Memory Recall), and (2) Conflict (No Conflict vs. Conflict). In addition, we included task focus ratings on each trial as a parametric regressor to identify brain responses that related to how well participants had been able to engage with the reading and memory recall tasks.

The pre-processed time-series data were modelled using a general linear model, using FMRIB's Improved Linear Model (FILM) correcting for local autocorrelation (Woolrich, Ripley, Brady, & Smith, 2001). 9 Explanatory Variables (EV) of interest and 9 of no interest were modelled using a double-Gaussian hemodynamic response gamma function. The 9 EVs of interest were: (1) *Pure Reading* (i.e., no conflict from memory recall) and (2) *Conflict Reading* (i.e., conflict from memory recall), (3) *Pure Recall* (i.e., no conflict from semantic input) and (4) *Conflict Recall* (i.e., conflict from semantic input), (5) Letter String Baseline, (6-9) Task Focus ratings for each of the four experimental condition as a parametric regressor. Our EVs of no interest were: (10) Cue words related to the generated memories and (11) Letter strings before the presentation of task instructions, Task instructions for (12) *Pure Reading,* (13) *Conflict Reading*, (14) *Memory Recall* and (15) *Letter String* baseline trials, and (16) Fixation (the inter-stimulus fixations between the sentences or letter strings and the ratings questions, when some semantic retrieval may have been ongoing), and (17) Responses to catch trials (which included all time points with responses across conditions), and (18) Ratings (including all the rating questions across experimental conditions). EVs for each condition commenced at the onset of the first word of the sentence or the first letter string (when meaningless items were presented over the same period), with EV duration set as the presentation time (9s). The parametric EVs for Task Focus ratings had the same onset time and duration as the EVs corresponding to the four experimental trials, but in addition included the demeaned Task Focus ratings value as a weight. The fixation period between the trials provided the implicit baseline.

In addition to contrasts examining the main effects of Task (Reading Comprehension vs. Autobiographical Memory Recall), and Conflict (No Conflict vs. Conflict), we included all two-way interaction terms for both the main experimental conditions and Task Focus Ratings, and comparisons of each experimental condition with the letter string baseline. The four sequential runs were combined using fixed-effects analyses for each participant. In the higher-level analysis at the group level, the combined contrasts were analysed using FMRIB's Local Analysis of Mixed Effects (FLAME1), with automatic outlier de-weighting (Woolrich, 2008). A 50% probabilistic grey-matter mask was applied. Clusters were thresholded using Gaussian random-field theory, with a cluster-forming threshold of $z = 3.1$ and a familywise-error-corrected significance level of $p = .05$.

### *3.3.8. Psychophysiological interaction analysis*

In the formal conjunction analysis of the contrast maps of each experimental condition against the letter string baseline, we identified that inferior frontal gyrus and lateral temporal cortex regions within the lateral temporal DMN subsystem were involved in both tasks. Also, the core DMN regions are more important for autobiographical memory recall identified by the contrast of tasks. In order to establish how these DMN subsystems support both reading and memory recall, we conducted psychophysiological interaction (PPI) analysis.

The lateral temporal DMN conjunction and core DMN regions from *Autobiographical memory > Reading* contrast map were used as the seeds and their time series were extracted. Consequently, we ran two separate models with each DMN subsystem as a seed to examine its functional connectivity. For each model, we included all the regressors in the basic task model described above (18 regressors and motion regressor), a PPI term for each of the four experimental conditions (*Pure Reading*, *Conflict*

*Reading*, *Pure Recall*, and *Conflict Recall*), a PPI term for the Task Focus ratings for each experimental condition (to reveal which regions showed increased connectivity as task focus increased), as well as the time series of DMN subnetwork seed, using the generalized psychophysiological interaction (gPPI) approach (McLaren, Ries, Xu, & Johnson, 2012). The regressors were not orthogonalized. This analysis applied the same contrasts and cluster forming threshold as the univariate model. Therefore, we performed the contrasts examining the main effects of Task (Reading Comprehension vs. Autobiographical Memory Recall), and Conflict (No Conflict vs. Conflict), and two-way interaction effect for both the main experimental conditions and Task Focus Ratings. We also applied Bonferroni correction to account for the fact that we included two models (seeding from common activation within lateral temporal DMN and core DMN sites), the *p*-value consequently accepted as significant was $p < 0.025$. For the analysis to test relationship between functional connectivity and behavioural performance (i.e., ratings inside the scanner and sentence recall outside the scanner), all variables were z-transformed and outliers more than 2.5 standard deviations above or below the mean were identified and imputed with the cut-off value (i.e., +/- 2.5) prior to data analysis.

## 3.4. Results

### *3.4.1. Results outline*

First, we describe the behavioural results. Second, we report univariate analyses in which we identify brain regions showing activation and deactivation during reading and autobiographical memory recall, relative to a letter string baseline. We consider the location of this activation/deactivation along the principal gradient capturing the separation between heteromodal and unimodal cortex (Margulies et al., 2016). Third, we describe (i) commonalities and differences across autobiographical memory and reading tasks; and (ii) effects of task conflict and task focus – i.e., regions in which activation correlated with rated focus on each trial. To anticipate, we found that both reading and autobiographical memory elicited activation at both the top and bottom ends of the principal gradient of cortical organisation, in sensorimotor areas like visual cortex and heteromodal semantic regions that were equally far up the principal gradient. However, the tasks elicited strikingly different patterns of deactivation. These task similarities and differences are compared to previously-described DMN subsystems: both tasks elicited activation within a subnetwork of DMN focussed on left lateral temporal cortex, while core DMN regions (e.g. posterior cingulate cortex and medial prefrontal cortex) showed activation during memory recall and deactivation during reading. The parametric effect of task focus revealed that both activation and deactivation within core DMN can be beneficial to cognition. Finally, PPI analysis established how common DMN regions within lateral temporal subsystem show different patterns of connectivity during reading comprehension and memory recall.

### *3.4.2. Behavioural results*

**Catch trials**: Participants detected the majority of colour-change catch trials, showing that they were paying attention to inputs presented on the screen. Repeated-measures ANOVAs examining accuracy, RT, and response efficiency (i.e., RT divided by accuracy), and assessing the effects of Task (Reading vs. Autobiographical memory recall) and Conflict (No conflict vs. Conflict), revealed there were no differences in colour-change detection rates across conditions (see Figure 3.2 A); trials with no response were excluded from the RT analysis (24.4%). There was no main effect of Task (Accuracy: $F(1,28) = 1.54$, $p = .22$, $\eta_p^2 = .05$; RT: $F(1,28) = 1.92$, $p = .18$, $\eta_p^2 = .06$; Response efficiency: $F(1,28) = .35$, $p = .56$, $\eta_p^2 = .01$), no main effect of Conflict (Accuracy: $F(1,28) = .27$, $p = .61$, $\eta_p^2 = .01$; RT: $F(1,28) = 2.83$, $p = .10$, $\eta_p^2 = .001$; Response efficiency: $F(1,28) = 1.22$, $p = .28$, $\eta_p^2 = .04$), and no interaction (Accuracy: $F(1,28) = .85$, $p = .36$, $\eta_p^2 = .03$; RT: $F(1,28) = 1.27$, $p = .27$, $\eta_p^2 = .04$; Response efficiency: $F(1,28) = .95$, $p = .34$, $\eta_p^2 = .03$).

We also performed paired-samples *t*-tests (Bonferroni-corrected for four comparisons) comparing colour-change detection for each experimental condition with the letter string baseline (RT: $M \pm SD = .53 \pm .17$ s; Accuracy: $M \pm SD = 74.7 \pm 24.5$ %; Response efficiency: $M \pm SD = .85 \pm .57$). Responses to baseline trials were significantly faster than for reading or recall trials ($t(28) > 2.84$, $p < .009$). For both accuracy and response efficiency, there were no significant differences between the experimental tasks and the letter string baseline data ($t(28) < 1$).

**Ratings**: Figure 3.2 B summarises the ratings participants provided after each trial. For Task Focus ratings, a 2 by 2 repeated-measures ANOVA revealed main effects of both Task ($F(1,28) = 4.76$,

$p$ = .038, $\eta_p^2$ = .15) and Conflict ($F$(1,28) = 44.28, $p$ < .001, $\eta_p^2$ = .61): people rated their task focus as higher for the reading task, and they were more focussed on both tasks when there was no conflict. There was no interaction between these factors, $F$(1,28) = .12, $p$ = .73, $\eta_p^2$ = .004.

Paired-samples *t*-tests were used to examine the effect of task conflict on other ratings (which were different across the two tasks). People rated their sentence comprehension as higher when there was no task conflict ($t$(28) = 3.22, $p$ = .003). There was no difference in participants' rated familiarity with the information in the sentences across conditions ($t$(28) = 1.45, $p$ = .16). The participants also rated their autobiographical memories as more vivid ($t$(28) = 6.02, $p$ < .001) and more consistent with their previously generated memories ($t$(28) = 2.86, $p$ = .008) when there was no task conflict.

Pearson's correlation analysis revealed that these different ratings were highly correlated. For reading, task focus correlated with comprehension ($r$ = .71, $p$ < .001), comprehension correlated with familiarity ($r$ = .41, $p$ < .001) and task focus correlated with familiarity ($r$ = .29, $p$ < .001). For autobiographical memory, task focus correlated with vividness ($r$ = .68, $p$ < .001), vividness correlated with consistency ($r$ = .54, $p$ < .001) and task focus correlated with consistency ($r$ = .47, $p$ < .001). For this reason, only the parametric effect of task focus was included in the fMRI analysis.

**Post sentence recall**: We also calculated the percentage of words recalled correctly for each sentence across *Pure Reading*, *Conflict Reading*, and *Conflict Recall* conditions, since memory for the text was expected to relate to task focus. The *Pure Reading* condition had better recall ($M \pm SD$ = 15 ± 9 %) than the *Conflict Reading* condition ($M \pm SD$ = 12 ± 8 %; $t$(28) = 2.93, $p$ = .007), while the poorest memory for the text occurred in the *Conflict Recall* condition ($M \pm SD$ = 2 ± 3 %), when participants were actively trying to ignore the sentence ($t$(28) = 6.08, $p$ < .001). The percentage of words recalled in the reading task was positively correlated with task focus (*Pure Reading*: $r$ = .30, $p$ < .001; *Conflict Reading*: $r$ = .29, $p$ < .001) and comprehension (*Pure Reading*: $r$ = .10, $p$ = .009; *Conflict Reading*: $r$ = .37, $p$ < .001). These results taken together show that conflict from the autobiographical memory cues impaired sentence recall outside the scanner.

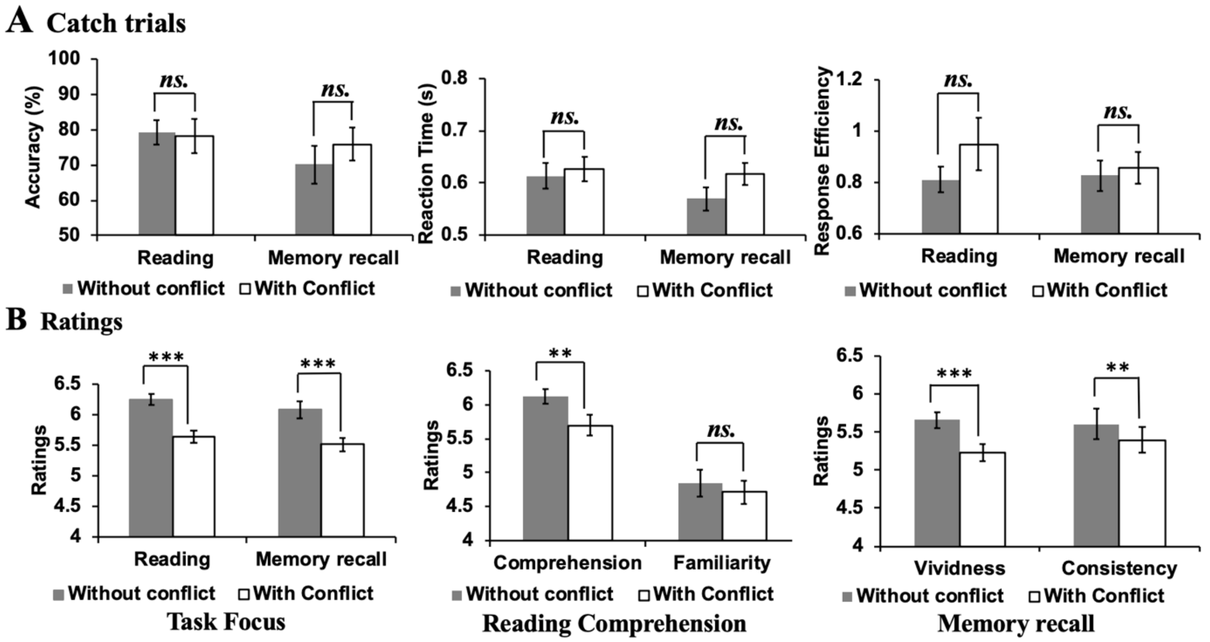


*Figure 3.2*. **Behavioural results. A)** Accuracy (percentage correct, left panel) and reaction time (in seconds, middle panel), as well as response efficiency (right panel) for the catch trials in each experimental condition (*Pure Reading*, *Conflict Reading*, *Pure Recall*, and *Conflict Recall*). **B)** Ratings for task focus (left panel) in each experimental condition, comprehension and familiarity with sentence content in both reading conditions (middle panel), and vividness and consistency with previous memory in both memory recall conditions (right panel). Error bars represent the standard error. *** indicates $p < .001$; ** indicates $p < .01$; ns. indicates not significant.

### *3.4.3. fMRI results*

#### *3.4.3.1. Activation and deactivation in reading and autobiographical memory*

To identify activation and deactivation elicited by each task, we performed a formal conjunction analysis on the contrast maps of each experimental condition with the letter string baseline (providing a basic level of control for visual input and button presses; maps for each experimental condition over letter string baseline are shown in Figure A.1.1 in the appendices). For reading, the bilateral temporal regions (i.e., temporal poles, superior/middle/inferior temporal gyrus), precentral gyrus, middle/inferior frontal gyrus, temporal fusiform cortex, supplementary motor cortex, and visual cortex showed activation relative to the letter string baseline (see Figure 3.3 A; the conjunction of *Pure reading* >

*Baseline* and *Conflict reading* > *Baseline*), while bilateral middle frontal gyrus, supramarginal gyrus, medial prefrontal gyrus, anterior/posterior cingulate gyrus, and precuneus cortex showed deactivation (see Figure 3.3 B; the conjunction of *Baseline* > *Pure reading* and *Baseline* > *Conflict reading*). For autobiographical memory, middle temporal gyrus, temporal pole, middle/inferior frontal gyrus, insular cortex, supplementary motor cortex, and visual cortex showed activation compared to the letter string baseline (see Figure 3.3 C; the conjunction of *Pure recall* > *Baseline* and *Conflict recall* > *Baseline*), while supramarginal gyrus showed deactivation (see Figure 3.3 D; the conjunction of *Baseline* > *Pure recall* and *Baseline* > *Conflict recall*).

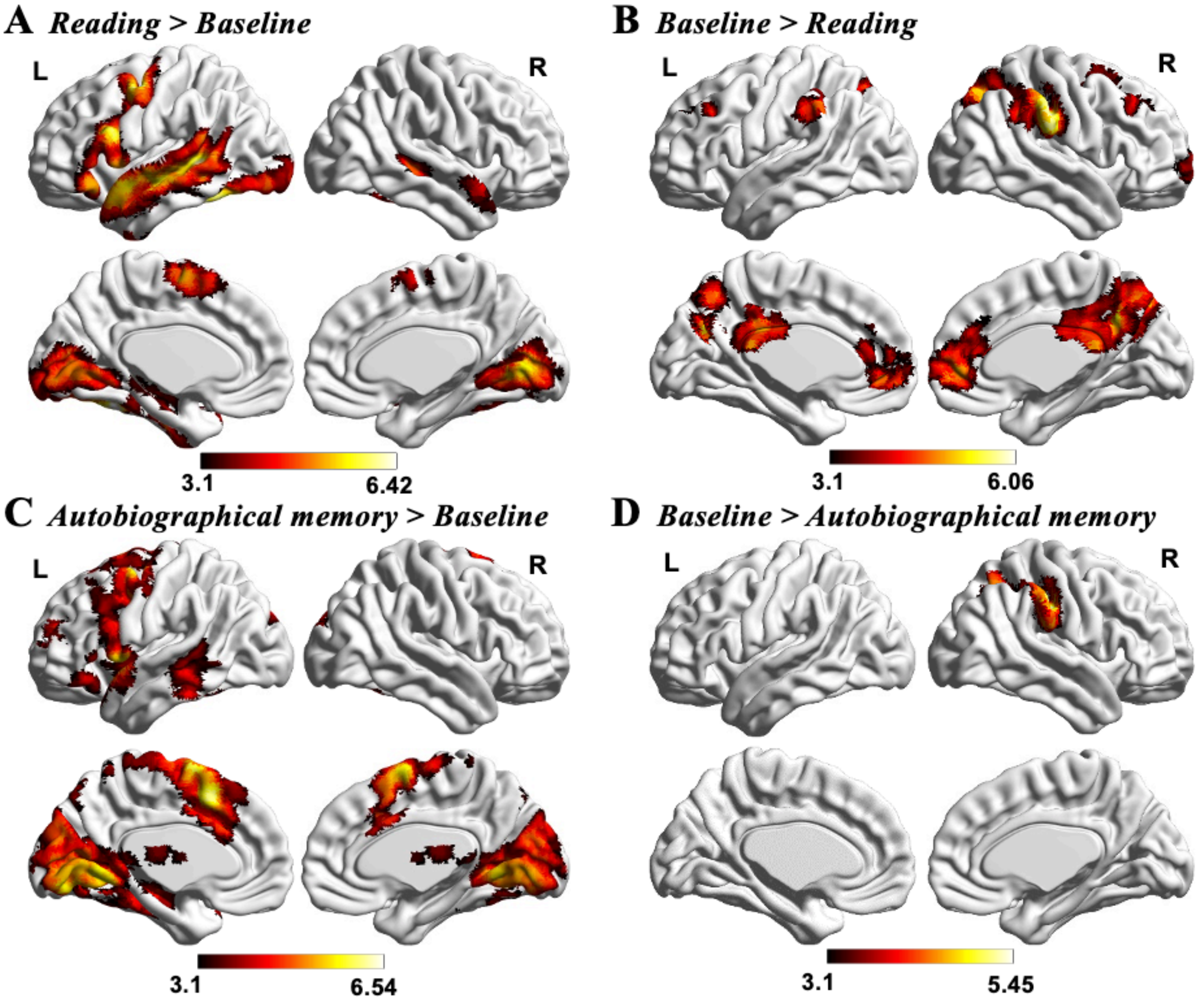
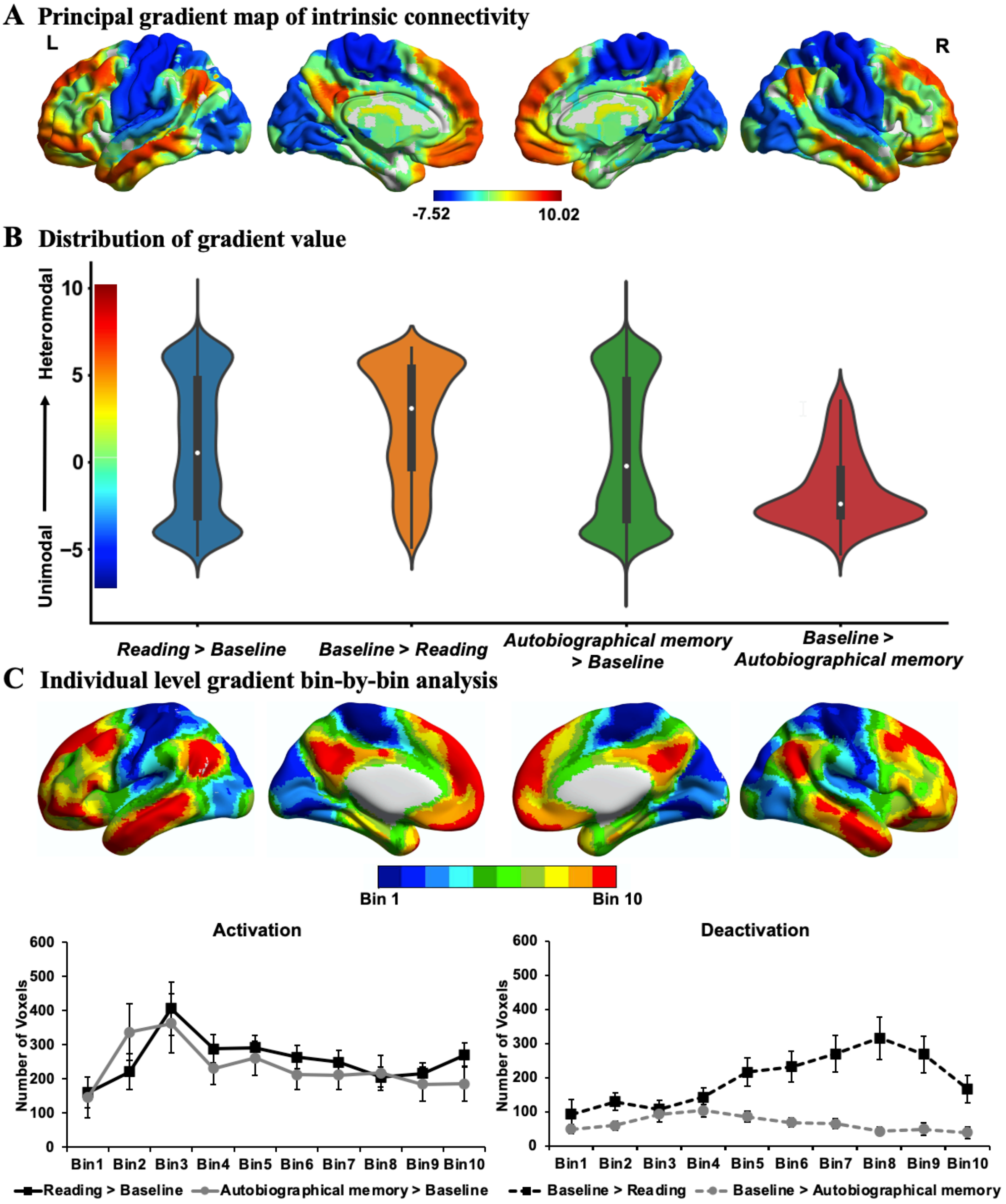


***Figure 3.3.*** **A)** ***Reading*** **>** ***Baseline*** and **B)** ***Baseline*** **>** ***Reading*** show the brain activation and deactivation during reading task relative to the letter string baseline. **C)** ***Autobiographical memory*** **>** ***Baseline*** and **D)** ***Baseline*** **>** ***Autobiographical memory*** show the brain activation and deactivation during autobiographical memory recall relative to the letter string baseline. These conjunctions were

identified using FSL's 'easythresh_conj' tool. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

Next, we extracted the principal gradient values of each voxel within the maps in Figure 3.3, to characterise the distribution of activation and deactivation in each task, relative to the low-level baseline, along the principal gradient. The principal gradient captures the separation between unimodal systems (in blue in Figure 3.4 A) and heteromodal regions within DMN (regions in red colour in Figure 3.4 A; Margulies et al., 2016). We found that both reading and autobiographical memory elicited activation in unimodal and heteromodal cortex, while reading elicited greater deactivation within the DMN (see Figure 3.4 B). We employed a bin-by-bin analysis to compare the activation and deactivation elicited by the tasks along the principal gradient. The whole-brain principal gradient map was evenly divided into 10 bins based on the rank of gradient values from the lowest to the highest values. The number of voxels within each bin that showed activation and deactivation was then counted for each participant, thresholded at $z > 2.6$ (bins with 0 activating and deactivating voxels at this threshold were 1.6% and 6.0% of the total, respectively. The same patterns were observed when replacing these 0s with mean). A 2 (Activity: *Activation* vs. *Deactivation*) by 2 (Task: *Reading* vs. *Autobiographical memory*) by 10 (Gradient bins) repeated-measures ANOVA found a three-way interaction, $F(9,252) = 6.70$, $p < .001$, $\eta_p^2 = .19$. Separate ANOVAs revealed that the interaction between Task and Bin was significant for both states of activity, with a greater interaction for deactivation, $F(9,252) = 10.75$, $p < .001$, $\eta_p^2 = .28$, compared to activation, $F(9,252) = 2.96$, $p = .002$, $\eta_p^2 = .10$. Tests of simple effects revealed that the pattern of activation was similar between reading and autobiographical memory recall along the principal gradient ($p$ values > .09 across all the bins: see Figure 3.4 C). However, reading elicited greater deactivation relative to autobiographical memory, especially towards the DMN end of the gradient (in bins 10, 9, 8, 7, 6, 5 and 2; $p$ values < .004; see Figure 3.4 C). Similar patterns of task activation and deactivation were found when the individual maps were thresholded at a lower threshold of $z > 2.3$ (bins with 0 activating and deactivating voxels at this threshold were 0.6% and 2.8% of the total, respectively; see Figure A.1.2 in the appendices). In summary, both tasks elicited activation within heteromodal DMN and sensorimotor areas, but reading also evoked greater deactivation in other DMN regions.



**A** Principal gradient map of intrinsic connectivity

**B** Distribution of gradient value

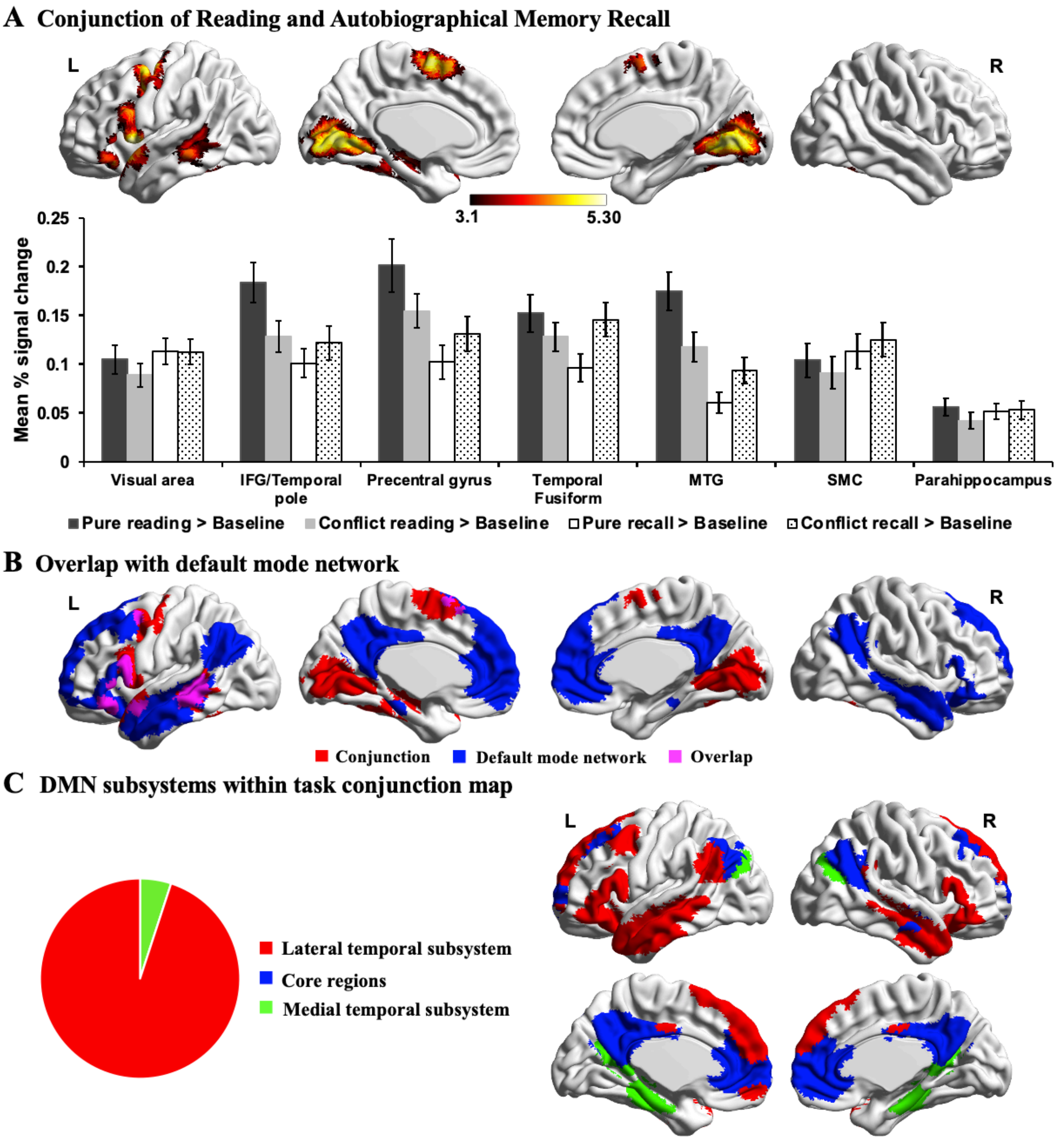
**C** Individual level gradient bin-by-bin analysis

***Figure 3.4.*** **A)** Principal gradient map of intrinsic connectivity from Margulies et al. (2016) capturing the transition between unimodal regions (cold colours) and heteromodal regions corresponding to the DMN (warm colours). **B)** The violin plots show the distribution of gradient values extracted from each conjunction map. **C)** The whole-brain map was evenly divided into 10 bins from the bottom to the top

of the principal gradient. The line charts present the activation and deactivation in each task each bin relative to the letter string baseline. Error bars represent the standard error.

### *3.4.3.2. Common activation in both reading and autobiographical memory recall tasks*

Next, we examined the brain regions activated in both reading comprehension and autobiographical memory recall tasks in a whole-brain analysis. We computed a formal conjunction across the contrast maps of each task over the letter string baseline and established that they overlapped in precentral gyrus, middle/inferior frontal gyrus, temporal pole, middle temporal gyrus, temporal fusiform cortex, supplementary motor cortex, parahippocampus and visual cortex (intracalcarine cortex and lingual gyrus; see Figure 3.5 A). The mean percentage signal change of each experimental condition over baseline in each cluster is presented in Figure 3.5 A. The lateral temporal clusters and inferior frontal gyrus largely fell within the DMN, as defined by Yeo et al. (2011) in a 7-network parcellation of whole-brain intrinsic connectivity in 1000 brains (DMN shown in blue in Figure 3.5 B with overlap in pink). As DMN is composed of multiple sub-networks, we also compared these regions of overlap with three DMN subsystems – core DMN, lateral temporal subsystem and medial temporal subsystem – defined by Yeo et al. (2011) in their 17-network parcellation of intrinsic connectivity patterns. Of those voxels which fell within DMN, 95% were within the DMN subnetwork that encompasses lateral temporal cortex, anterior and ventral portions of IFG and dorsomedial prefrontal cortex (see Figure 3.5 C with pie chart showing the percentage of overlap with each subsystem). We refer to this network as the "lateral temporal DMN subsystem" below. In summary, this analysis shows that lateral temporal DMN regions are implicated in *both* reading comprehension and autobiographical memory.



A Conjunction of Reading and Autobiographical Memory Recall

B Overlap with default mode network

C DMN subsystems within task conjunction map

*Figure 3.5.* **Conjunction analysis. A)** Conjunction of brain activation during reading comprehension and autobiographical memory recall, with this conjunction identified using FSL's 'easythresh_conj' tool. The bar chart shows the mean % signal change of each experimental condition over baseline in each identified cluster. Error bars represent the standard error. **B)** These conjunction clusters overlapped with the default mode network (DMN; in blue) defined by Yeo et al. (2011) in a 7-network parcellation of whole-brain intrinsic connectivity for 1000 brains (overlap in pink). **C)** The pie chart illustrates the percentage of voxels in the task conjunction map that overlap with each DMN subsystem. Subsystems were defined by Yeo et al. (2011) in a 17-network parcellation of whole-brain functional connectivity

for 1000 brains: the medial temporal subsystem is shown in green, core DMN is shown in blue and the lateral temporal subsystem is shown in red. The DMN conjunction largely fell within the lateral temporal subsystem of DMN. All maps were thresholded at $z > 3.1$ ($p < .05$). IFG = inferior frontal gyrus; MTG = middle temporal gyrus; SMC = supplementary motor cortex; L = Left hemisphere; R = Right hemisphere. The maps are fully saturated to emphasize the regions of overlap.

#### *3.4.3.3. Main effects in task-based fMRI*

**Effects of Task**: Next, we examined differences in activation across tasks. The contrast of *Reading* > *Autobiographical memory* elicited activation in left inferior frontal gyrus, lateral temporal cortex (including temporal poles, superior/middle/inferior temporal gyrus), and visual cortex (including occipital pole, occipital fusiform gyrus, and lateral occipital cortex; see Figure 3.6 A). In contrast, *Autobiographical memory* > *Reading* activated bilateral superior/middle frontal gyrus, frontal pole, insular cortex, medial prefrontal gyrus, anterior/posterior cingulate gyrus, precuneus cortex, angular gyrus, and lingual gyrus (see Figure 3.6 B). In order to further understand task differences across the sub-networks within DMN, we overlapped these reading and recall maps with the core, lateral temporal, and medial temporal subsystems defined by Yeo et al.'s (2011) 17-network parcellation. DMN regions highlighted by the *Reading* > *Autobiographical memory* contrast almost fully fell within the lateral temporal subsystem (see Figure 3.6 C), while the *Autobiographical memory* > *Reading* contrast showed greater overlap with core DMN regions (see Figure 3.6 D).

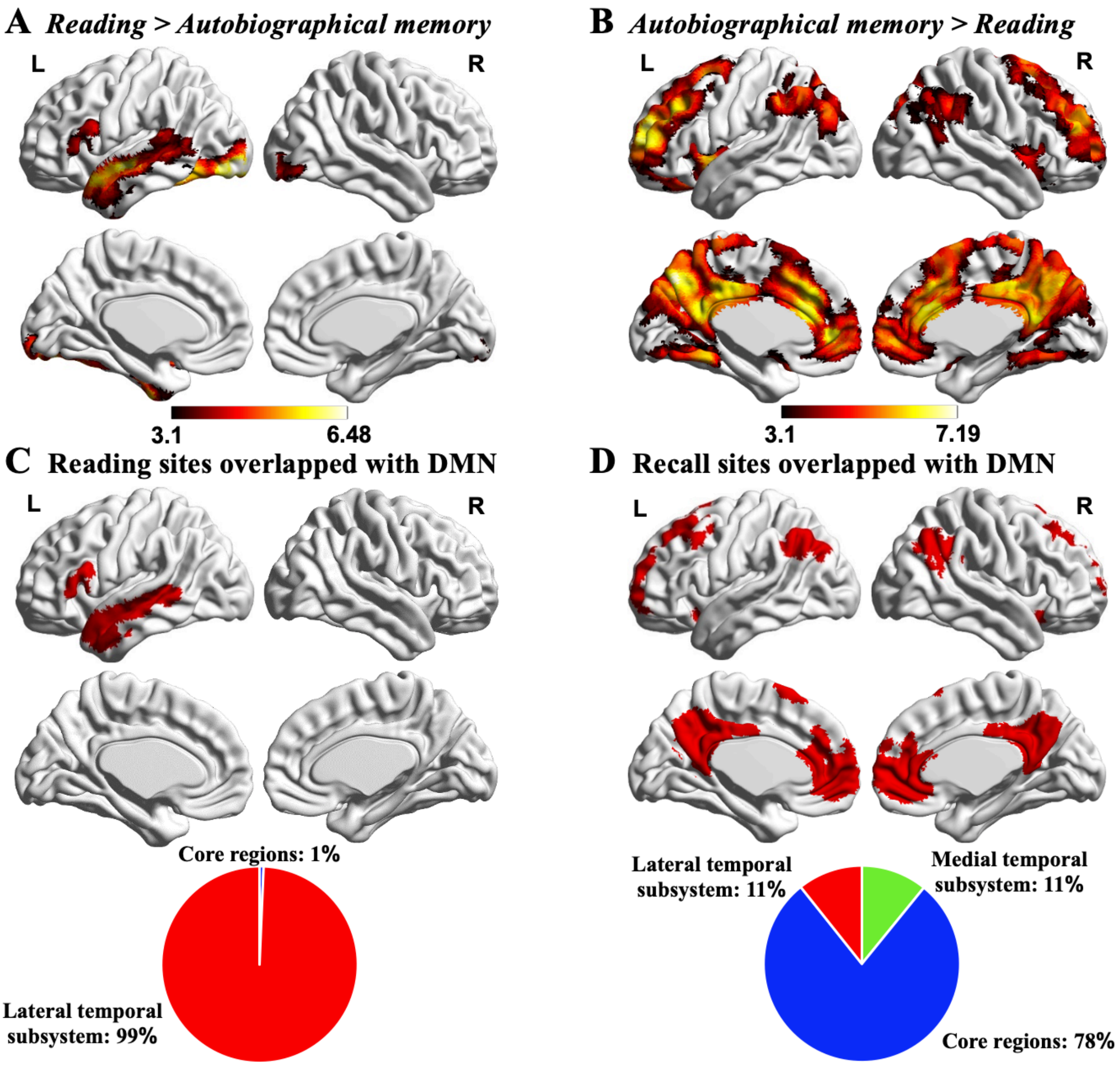


***Figure 3.6.*** **Effects of Task. A)** Significant activation in reading defined using the contrast of *Reading* > *Autobiographical memory*. **B)** Significant activation in autobiographical memory defined using the contrast of *Autobiographical memory* > *Reading*. **C-D)** The overlap of *Reading* > *Autobiographical memory* and *Autobiographical memory* > *Reading* contrast maps with DMN. The pie charts at the bottom illustrate the percentage of overlap of reading and recall maps with each DMN subsystem, respectively. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

Having established that reading and autobiographical memory recruit distinct DMN sub-systems, we asked where these tasks fall on the principal gradient of connectivity. One possibility is that the core sub-network, which was activated more strongly by autobiographical memory retrieval, is further up the gradient than reading, since in the latter task, visual input drives conceptual retrieval. Alternatively, the apex of different DMN subsystems might occupy the same position on the principal gradient. To investigate whether reading and autobiographical memory reached the same gradient apex value, we extracted the maximum gradient value for each individual participant within the task contrast maps thresholded at $z > 3.1$, masked by DMN. Four participants were excluded from this analysis because there was no relevant activation. A paired samples *t*-test showed no significant task difference in maximum DMN gradient values across people (Reading: $M \pm SD = 6.38 \pm 1.13$; Autobiographical memory: $M \pm SD = 6.51 \pm .69$; $t(24) = -.53$, $p = .60$). We also examined the DMN subnetworks themselves, and found gradient values within the lateral temporal DMN subsystem ($M \pm SD = 5.82 \pm 1.11$) were slightly higher than for core DMN ($M \pm SD = 5.39 \pm 1.51$). These results suggest that while reading elicits more activation at the unimodal end of the gradient reflecting the importance of visual input in this task, both tasks elicit activation at the heteromodal apex of the gradient.

**Effects of Conflict**: Next, we characterised the main effect of task conflict in both Reading and Autobiographical memory trials, to identify brain regions responding to the presentation of distracting information (i.e. autobiographical memory cues on reading trials, or sentences on autobiographical memory trials). We did not find any conflict effects for reading. For autobiographical memory, the parahippocampal gyrus, temporal occipital fusiform, lateral occipital cortex, precuneus cortex and anterior medial prefrontal cortex showed greater activation when there was no distracting sentence input (see Figure 3.7 A), and these midline regions were identified as important areas for autobiographical memory by the *Autobiographical memory* > *Reading* contrast (see Figure 3.7 C). Of those voxels that fell within DMN, 49% and 44% were within the core and medial temporal subnetworks within DMN, respectively, and 7% fell within the lateral temporal DMN subnetwork. In contrast, precentral gyrus, frontal pole, frontal orbital cortex, inferior frontal gyrus, superior/inferior/middle temporal gyrus, and visual cortex (including temporal occipital fusiform, and lateral occipital cortex) showed greater activation for autobiographical memory trials when there was conflict from irrelevant sentences (see Figure 3.7 B). Many of these regions were identified as key sites for reading comprehension by the *Reading* > *Autobiographical Memory* contrast (see Figure 3.7 D). Of those voxels that fell within DMN, 90% were within the lateral temporal network within DMN, and 10% fell within core DMN subsystem. These results suggest that the lateral temporal subsystem is more perceptually coupled, with stronger responses to presented sentences even when the required task was autobiographical memory. In contrast, the core DMN subsystem is more perceptually decoupled.

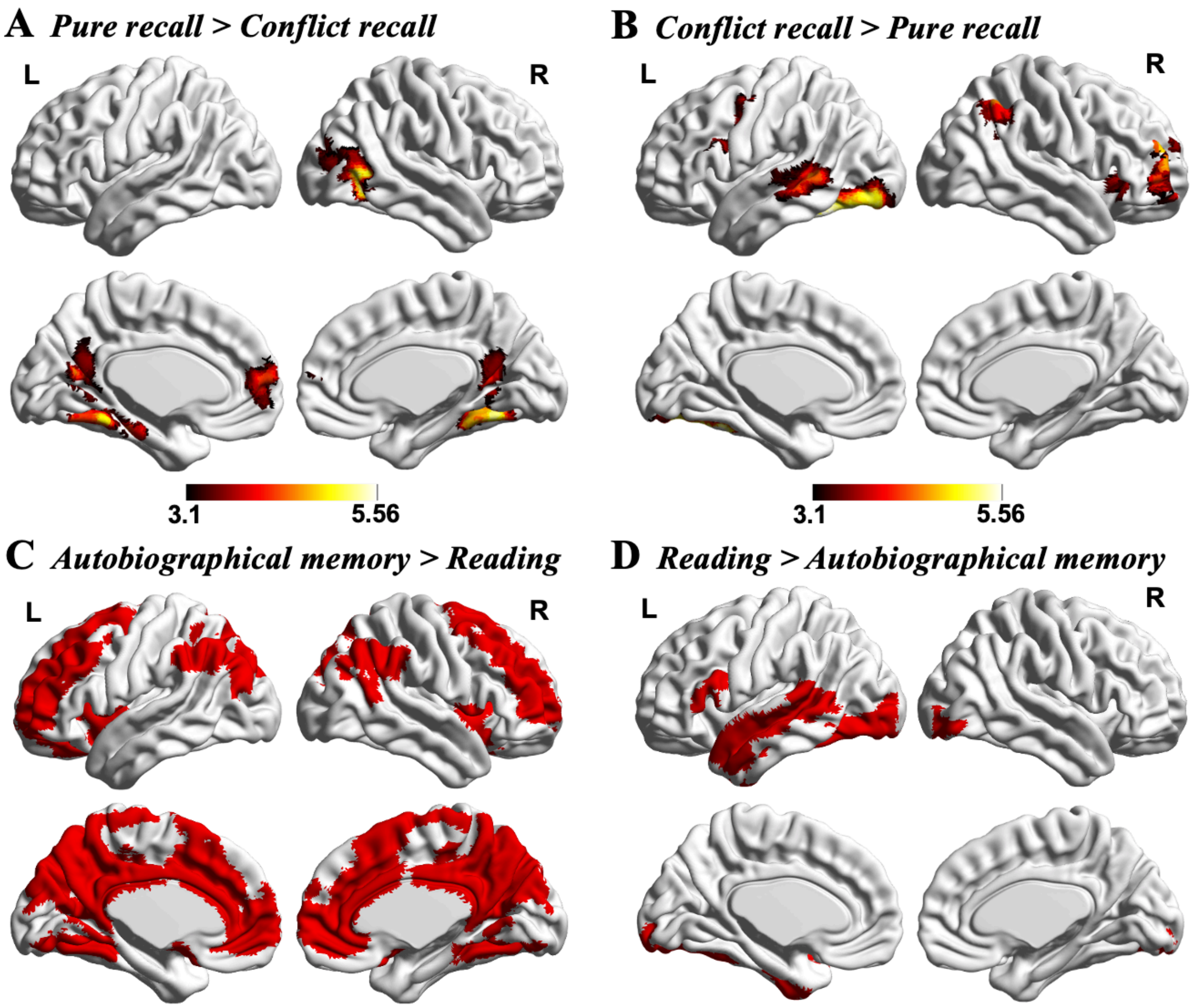


***Figure 3.7.*** **Effects of Conflict. A**) Significant activation when there was no conflict from semantic input defined using the contrast of *Pure recall* > *Conflict recall*. **B)** Significant activation when there was conflict from semantic input defined using the contrast of *Conflict recall* > *Pure Recall*. **C)** The midline regions showing greater activation to *Pure Recall* trials largely fell within areas identified as important for autobiographical memory. **D)** The stronger responses in lateral temporal cortex and visual cortex to *Conflict Recall* overlapped with regions identified as important for reading. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

### *3.4.3.4. Parametric effects of task focus*

Next, we examined the parametric effects of task focus in reading and autobiographical memory. Whole-brain parametric modelling revealed a stronger effect of task focus for autobiographical memory compared to reading in core DMN regions (including precuneus and medial prefrontal cortex), as well as in lateral occipital cortex and superior frontal gyrus (see Figure 3.8 A).

When autobiographical memory was considered in isolation, greater task focus was associated with increased activation in frontal pole, superior frontal gyrus, medial prefrontal cortex, temporal fusiform cortex, precuneus cortex, and lateral occipital cortex (Figure 3.8 B). There was also greater deactivation in right angular gyrus (Figure 3.8 C). More focussed autobiographical memory recall was therefore associated with greater activation of the medial temporal DMN subsystem plus a complex pattern of increased activation and deactivation in core DMN regions. For reading, task focus was correlated with increased deactivation in regions associated with *Autobiographical memory* > *Reading* (including bilateral middle frontal gyrus, frontal pole, insular cortex, medial prefrontal gyrus, anterior/posterior cingulate gyrus, precuneus cortex, and angular gyrus; Figure 3.8 D). The areas within DMN mainly overlapped with the core subsystem. Overall, these results suggest that greater task focus in autobiographical memory recall is linked to activation in both medial temporal and core DMN subsystems, while deactivation of the same core DMN regions is linked to greater focus during reading.

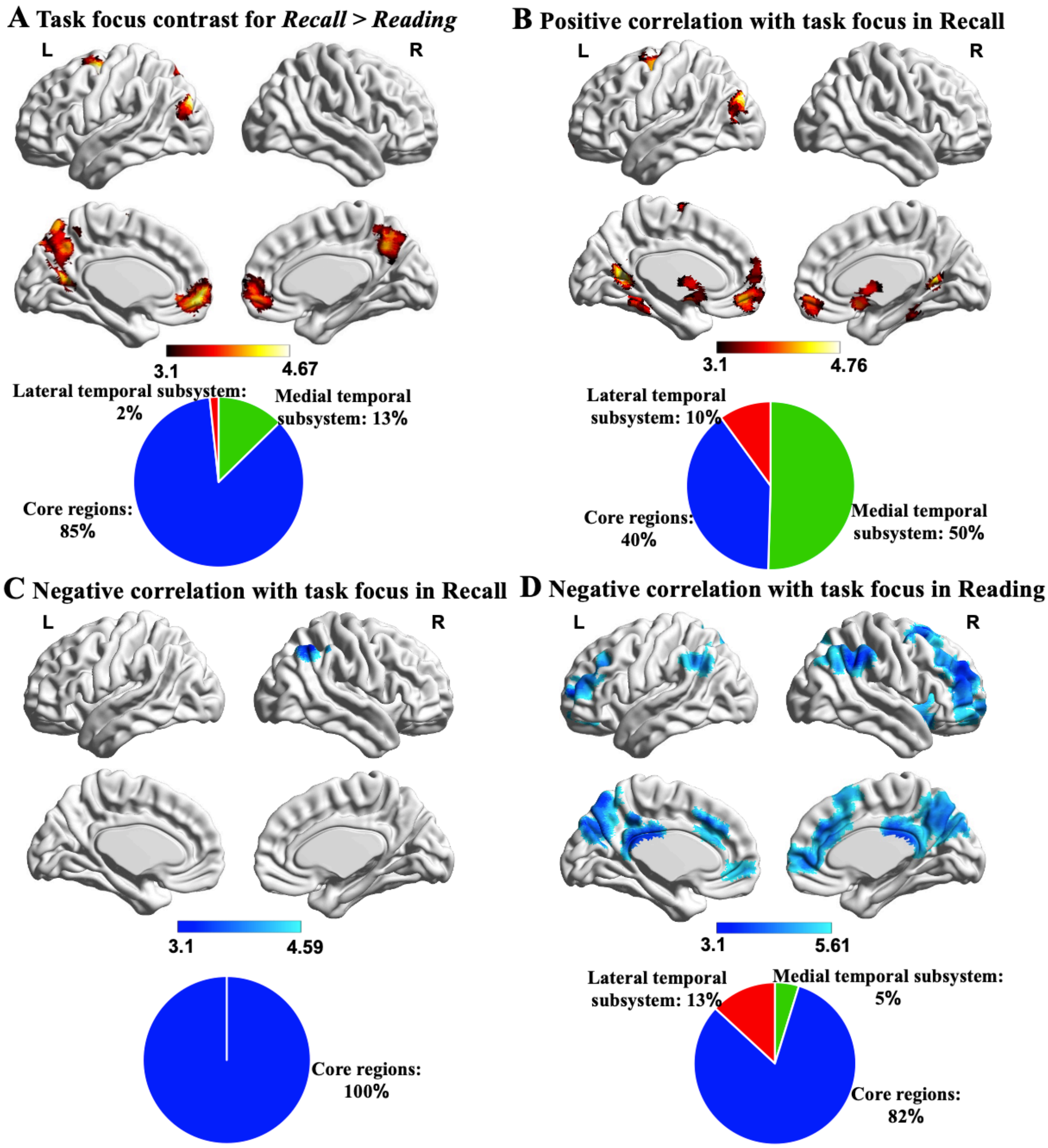


*Figure 3.8.* **Parametric effects of task focus. A)** The midline DMN core regions, lateral occipital cortex, and superior frontal gyrus showed greater task focus correlation effect for autobiographical memory recall. **B)** The midline DMN core regions, lateral occipital cortex and superior frontal gyrus showed stronger responses to better memory recall. **C)** Right angular gyrus showed increased activation when memory recall performance was poor. **D)** A wide range of regions that are important for autobiographical memory showed greater deactivation when people more focussed on reading. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

#### *3.4.3.5. Psychophysiological interaction (PPI) analysis*

To understand how different networks are flexibly formed to support reading and autobiographical memory recall, PPI analysis examined patterns of functional connectivity for common semantic regions (lateral temporal DMN subnetwork regions implicated in both tasks; see left panel in Figure 3.9 A). In a previous study, we found that a DMN site within middle temporal gyrus showed diverse patterns of intrinsic connectivity that were associated with off-task thought and comprehension (Zhang et al., 2019). Our lateral temporal DMN conjunction region showed greater connectivity with left inferior temporal gyrus (ITG), temporal occipital fusiform, and lateral occipital cortex (LOC) when comprehending sentences (Uncorrected $p < .001$; see middle panel in Figure 3.9 A), in regions previously identified by the *Reading* > *Autobiographical Memory* contrast (and without overlap with DMN regions). The same lateral temporal DMN conjunction site coupled with bilateral precuneus/posterior cingulate (Uncorrected $p < .001$), anterior cingulate cortex (Uncorrected $p = .008$), and left angular gyrus (Uncorrected $p = .014$) during autobiographical memory recall (see right panel in Figure 3.9 A), in regions previously identified by the *Autobiographical Memory* > *Reading* contrast. Of those voxels that fell within DMN, 91% were within core DMN regions.

Given that core DMN sites are thought to be critical to information transfer between subsystems (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Andrews-Hanna, Saxe, & Yarkoni, 2014), we also took the core DMN regions identified in the *Autobiographical memory* > *Reading* contrast map as a seed (see left panel in Figure 3.9 B). During autobiographical memory recall, this site showed greater connectivity with left inferior frontal gyrus (Uncorrected $p = .003$), left superior frontal gyrus (Uncorrected $p < .001$), left middle temporal gyrus/lateral occipital cortex (Uncorrected $p = .007$), and right middle temporal gyrus (Uncorrected $p = .007$; see right panel in Figure 3.9 B). Middle frontal gyrus did not survive Bonferroni correction (Uncorrected $p = .045$). Of those voxels that fell within DMN (for significant clusters), 98% fell within the lateral temporal DMN subsystem, and 2% were within core DMN. These results suggest that the lateral temporal DMN subsystem can couple with both visual areas and core DMN to support reading and autobiographical memory recall respectively. Meanwhile, core DMN can couple with lateral temporal DMN to support memory recall.

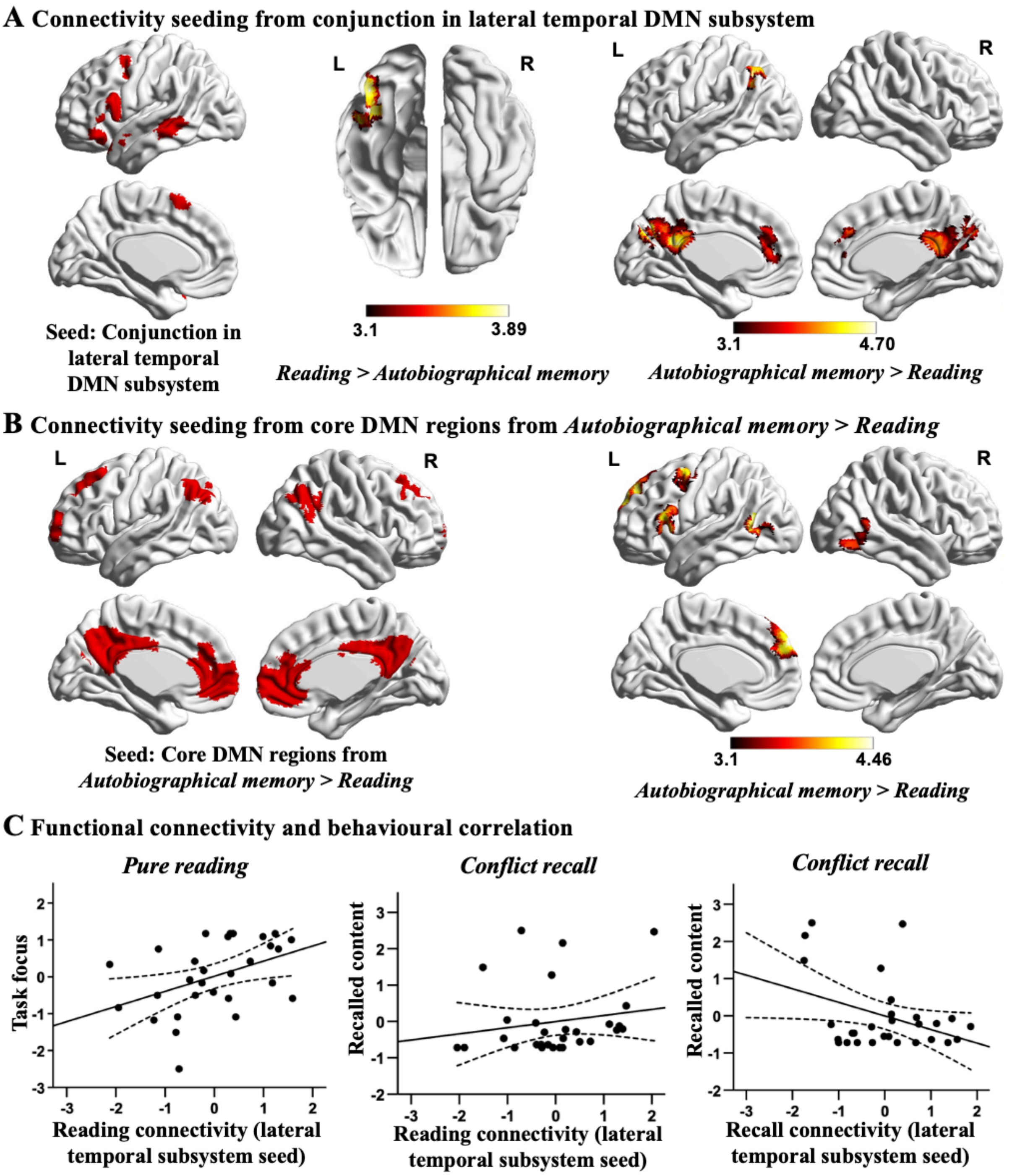


***Figure 3.9.*** **A)** Patterns of significant connectivity between the lateral temporal DMN conjunction seed (in the left panel) and areas that are important for reading comprehension (in the middle panel) and other core DMN regions that are important for autobiographical memory (in the right panel). **B)** Patterns of significant connectivity between the core DMN seed (in the left panel) and areas that largely fell within lateral temporal DMN subsystem (in the right panel) during autobiographical memory recall. **C)** The scatterplots present the correlations between the PPI estimates of identified connectivity and task

performance (i.e., task focus ratings inside the scanner and sentence recall performance outside the scanner) in each experimental condition. The error lines on the scatterplots indicate the 95% confidence estimates of the mean. Each point describes each participant. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

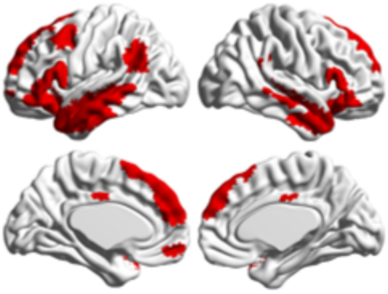
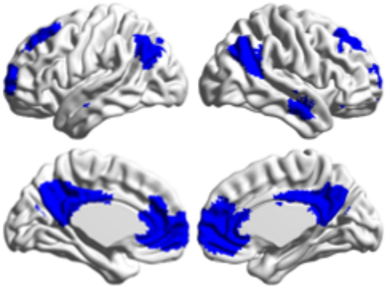
We further tested for relationships between the strength of functional connectivity and behavioural performance (i.e., task focus ratings for reading and autobiographical memory trials and sentence recall outside the scanner). The PPI estimates were extracted from the clusters identified in *Reading* > *Autobiographical memory* and *Autobiographical memory* > *Reading* contrasts for each participant in each experimental condition. We then predicted behavioural performance in each condition with PPI estimates as covariates. Task focus ratings and sentence recall were included as dependent variables in *Pure reading*, *Conflict reading*, and *Conflict recall* conditions. For the *Pure recall* condition, only task focus ratings were relevant. For *Pure reading* and *Pure recall* with no conflict, only reading or recall connectivity were used as covariates, while for the two conflict conditions, both of these connections were included in the model. This analysis revealed that the strength of connectivity from the lateral temporal DMN seed to *Reading* > *Autobiographical memory* regions in the PPI was positively correlated with task focus in the *Pure reading* condition ($t(28) = 2.47$, $r = .41$, $p = .020$) and with sentence recall in the *Conflict recall* condition ($t(28) = 2.14$, $r = .37$, $p = .042$). The strength of connectivity from the lateral temporal DMN seed to regions *Autobiographical memory* > *Reading* regions in the PPI was negatively correlated with sentence recall performance in the *Conflict recall* condition ($t(28) = -2.70$, $r = -.47$, $p = .012$; see Figure 3.9 C). There were no other significant correlations.

### 3.5. Discussion

This study provides a novel characterisation of the neural basis of perceptually-coupled and perceptually-decoupled forms of cognition, and the effects of task focus in these contexts. Reading and autobiographical memory were sometimes set up in opposition, such that irrelevant autobiographical memory cues during reading could elicit the kinds of cognitive states that occur when our minds wander. Participants rated their task focus as it fluctuated across trials. Both reading and autobiographical memory elicited activation in the lateral temporal DMN subsystem, associated with semantic cognition, as well as in visual regions. Analysis of functional connectivity revealed the lateral temporal DMN subsystem was highly flexible, connecting more to visual regions during reading and to core DMN during autobiographical memory, and with these patterns of connectivity predicting performance and task focus. In addition, the tasks produced strikingly different patterns of deactivation relative to a low-level baseline task, with only reading eliciting deactivation within the DMN core subsystem, and neither task deactivating the lateral temporal subsystem. Importantly, there was a task-dependent relationship between core DMN deactivation and task focus: when participants were more focussed on the ongoing task, the core DMN subnetwork showed greater activation in autobiographical memory yet greater deactivation during reading. In contrast, the lateral temporal subsystem did not show effects of task focus and responded to visual inputs even when these were irrelevant to the task.

Despite clear, multi-dimensional differences between core and lateral temporal DMN subsystems, summarised in Table 3.2, the responses in these networks were found to fall at the same point on the principal gradient, which describes a cortical hierarchy from unimodal sensorimotor cortex to heteromodal areas of DMN. This allows us to reject the hypothesis that core DMN regions are nearer the top of the hierarchy by virtue of being more isolated from sensory inputs. Instead, the two DMN subsystems play distinctive and complementary roles in heteromodal cognition, with the lateral temporal subsystem supporting sensory integration and access to conceptual knowledge in both internally- and externally-oriented tasks, and core DMN supporting selective, task-dependent patterns of integration that support internally-oriented cognition.

***Table 3.2.*** Summarisation of multi-dimensional differences between lateral temporal and core DMN subsystems.

| | ***Lateral temporal DMN subsystem*** | ***Core DMN subsystem*** |
|---|---|---|
| ***Dimensional differences*** |  |  |
| **Activation vs. deactivation** | Activates across tasks; responds to task-irrelevant meaningful inputs | Task-specific patterns of activation and deactivation |
| **Effects of task focus** | No modulation of activation with task focus | Greater task focus accentuates task-specific patterns of activation and deactivation |
| **Connectivity** | Acts as a pivot, connecting to visual and core DMN regions | Varying connectivity to lateral temporal DMN regions |
| **Hypothesised role in information integration** | Semantic representation; visual access to heteromodal cortex | Selective integration; sustained internal cognition |

Our finding that the lateral temporal DMN subsystem activates in response to both internal and external tasks that involve semantic cognition (i.e. reading and autobiographical memory) is consistent with prior work implicating lateral temporal cortex and inferior frontal gyrus in the representation and retrieval of heteromodal conceptual knowledge (Badre et al., 2005; Jefferies, 2013; Lambon Ralph et al., 2017; Noonan et al., 2013). The task overlap in this DMN subnetwork was left-lateralised, in line with expectations for a semantic retrieval network (Gonzale Alam, Karapanagiotidis, Smallwood, & Jefferies, 2019; Hurley, Bonakdarpour, Wang, & Mesulam, 2015; Jackson, 2020; Noonan et al., 2013; Rice, Lambon Ralph, & Hoffman, 2015). Previous studies have shown the engagement of lateral temporal cortex in both reading and memory recall (Andrews-Hanna, Saxe, et al., 2014; Ferstl et al., 2008; Lambon Ralph et al., 2017; Summerfield, Hassabis, & Maguire, 2009; Svoboda et al., 2006). Anterior and lateral temporal lobe regions are thought to provide a heteromodal semantic store, not strongly biased towards any one sensory input or feature type (Lambon Ralph et al., 2017; Margulies et al., 2016). This allows lateral temporal cortex to act as a "pivot" within the semantic system, forming distinct functional networks depending on the characteristics of the retrieval context (Chiou & Lambon Ralph, 2019) – specifically, stronger connections to visual cortex when meaning must be extracted from visual inputs, and to core DMN regions when meanings are retrieved in the context of an internally-oriented task.

Other DMN regions in the core as opposed to the lateral temporal subnetwork are equally distant from sensory-motor regions along the principal gradient and yet show differences in their responsiveness to tasks. Chiou et al. (2019) suggested that core DMN regions show deactivation during externally-focussed tasks, while lateral temporal regions show engagement. We show lateral temporal DMN activates in response to meaningful visual inputs (sentences versus letter strings), even when this input is irrelevant to the ongoing task, and irrespective of task focus. Consequently, this subnetwork may be able to detect situations in which meaning emerges in the environment, even when the focus of attention is elsewhere. In contrast, core DMN shows patterns of both increased activation or deactivation as participants report being more focussed, depending on the task. Fluctuating patterns of activation within core DMN may be crucial to our capacity to support both states such as autobiographical memory and mind-wandering, which are divorced from the environment in which they occur, and states such as reading comprehension which involve harnessing overlapping heteromodal regions to understand information in the environment.

DMN regions, across both core and lateral subsystems, are implicated in information integration (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Binney et al., 2012; Bonnici et al., 2016; Horner et al., 2015; Lanzoni et al., 2020; Price et al., 2015; Visser et al., 2012). Consequently, the divergent patterns of connectivity within DMN that we have described for reading and autobiographical memory might support distinct patterns of integration. In reading, a focussed pattern of cognition is required, centred on the meaning of words within their sentence contexts and their integration with long-term knowledge stores. In this context, semantic cognition needs to be partially insulated from other heteromodal codes also linked to DMN, which capture the individual’s recent experiences, long-term episodic memories and current emotional state – all of which are irrelevant to the sentence being comprehended and which contribute to poor comprehension caused by mind-wandering. Deactivation of core DMN regions might achieve this selective pattern of integration. Individual differences in intrinsic connectivity between visual cortex, lateral DMN and core DMN regions have already been shown to relate to the ability to stay on task during reading, and avoid task-unrelated thoughts (Smallwood et al., 2013; Zhang et al., 2019). Greater task focus on reading was also associated with greater deactivation of regions in dorsolateral prefrontal cortex, anterior cingulate cortex, bordering pre-supplementary motor area, and right insula, associated with the ventral attention network. This pattern, although counterintuitive, is associated with participants focussing their thoughts away from their personal goals (Turnbull et al., 2019), potentially allowing attention to the external task.

In contrast, autobiographical retrieval is a multifaceted cognitive process that involves the retrieval of contextual details like sensory features, as well as pertinent semantic information and emotions (Conway, 2001; Greenberg & Rubin, 2003; Inman, James, Vytal, & Hamann, 2018). This task is likely to require a broader pattern of integration across medial and lateral temporal subsystems, which are biased towards episodic and semantic retrieval respectively (Badre & Wagner, 2002; Jackson et al., 2016; Lambon Ralph et al., 2017; Nyberg et al., 1996; Nyberg, Mclntosh, Houle, Nilsson, & Tulving, 1996). Core DMN might play an important role in this integration across domains, since core DMN regions showed greater activation during memory recall when there was no conflict from sentence presentation. Finally, we identified one DMN region in right AG that was negatively correlated with task focus in *both* reading and memory recall tasks. This site might be deactivated when attention is focussed on any specific task (Bzdok et al., 2013; Tyler, Dasgupta, Agosta, Battelli, & Grossman, 2015), given that all tasks necessarily require a more focussed pattern of information integration than unconstrained thought in the absence of an externally-imposed task.

### 3.6. Conclusion

In conclusion, our study reveals distinct roles of lateral temporal and core DMN subsystems within cognition. The lateral temporal subsystem was activated by both internally- and externally-oriented tasks involving semantic retrieval, and as well as by meaningful inputs not relevant to the ongoing task, and this subsystem formed opposing task-specific functional networks. In contrast, core DMN regions showed task-specific patterns of activation and deactivation that were accentuated by increased task focus. We conclude the two DMN subsystems play distinctive and complementary roles in heteromodal cognition, with the lateral temporal subsystem supporting visual to conceptual knowledge, and core DMN supporting selective, task-dependent patterns of integration that support internally-oriented cognition. This division of labour might be key to our capacity to flexibly support different heteromodal mental states, which enables us to understand the world around us and also build internal thoughts that are independent from the immediate environment.

# Chapter 4: Knowing what you need to know in advance: The neural processes underpinning flexible semantic retrieval of thematic and taxonomic relations

**This chapter is adapted from: Zhang, M., Varga, D., Wang, X., Krieger-Redwood, K., Gouws, A., Smallwood, J., & Jefferies, E. (2020). Knowing what you need to know in advance: The neural processes underpinning flexible semantic retrieval of thematic and taxonomic relations. *NeuroImage*, 224, 117405.** [3]

## 4.1. Abstract

Semantic retrieval is flexible, allowing us to focus on subsets of features and associations that are relevant to the current task or context: for example, we use taxonomic relations to locate items in the supermarket (carrots are a vegetable), but thematic associations to decide which tools we need when cooking (carrot goes with peeler). We used fMRI to investigate the neural basis of this form of semantic flexibility; in particular, we asked how retrieval unfolds differently when participants have advanced knowledge of the type of link to retrieve between concepts (taxonomic or thematic). Participants performed a semantic relatedness judgement task: on half the trials, they were cued to search for a taxonomic or thematic link, while on the remaining trials, they judged relatedness without knowing which type of semantic relationship would be relevant. Left inferior frontal gyrus showed greater activation when participants knew the trial type in advance. An overlapping region showed a stronger response when the semantic relationship between the items was weaker, suggesting this structure supports both top-down and bottom-up forms of semantic control. Multivariate pattern analysis further revealed that the neural response in left inferior frontal gyrus reflects goal information related to

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[3] The author, Meichao Zhang, designed the experiment, performed the experiment, analysed the results and wrote the article under the supervision of Prof. Beth Jefferies and Prof. Jonny Smallwood. Dr. Xiuyi Wang and Dr. Katya Krieger-Redwood provided support for data analysis and provided comments on the manuscript. Dr. Andre Gouws and Dominika Varga helped to collect the data.

different conceptual relationships. Top-down control specifically modulated the response in visual cortex: when the goal was unknown, there was greater deactivation to the first word, and greater activation to the second word. We conclude that top-down control of semantic retrieval is primarily achieved through the gating of task-relevant 'spoke' regions.

## 4.2. Introduction

Although meaningful items are often presented in isolation in psychology experiments, in the real world we encounter concepts in rich contexts which allow us to anticipate the type of information we need to retrieve at a given moment. Moment-to-moment flexibility is critical for efficient semantic cognition, since we know many features and associations for any given concept, yet only a subset of this information will be relevant at any given time. For example, we know that carrots are brightly coloured, juicy, crunchy and have a sweet flavour: these physical features are typically shared with other fruits and vegetables; commonalities that contribute to our taxonomic knowledge of hierarchical relations (Hashimoto et al., 2007; Murphy, 2010; Springer & Keil, 1991). We also know that carrots are associated with soup, and are prepared with a peeler; this thematic knowledge is based on temporal, spatial, causal, or functional relations (Estes et al., 2011), and usually involves items which have complementary roles in episodes or events (e.g., *dog* and *leash*; Estes et al., 2011; Goldwater et al., 2011). Contexts can cause one of these types of semantic relation to be prioritised over another: for example, in the supermarket, taxonomic knowledge helps us to organise and locate items on our shopping list (carrots are vegetables), yet while cooking with carrots in the kitchen, we focus on thematic associations relating to recipes and utensils. In these situations, we know something about the kind of knowledge we will need to retrieve, even before we encounter the word "carrot" on the shopping list or in our recipe book.

Semantic retrieval is inextricably linked to the context or current task goals (e.g., Damian et al., 2001; Hsu et al., 2011; Kalénine et al., 2014; Witt et al., 2010), and this influences the extent to which particular conceptual features are activated (Yee et al., 2013). In sentence comprehension and production, context constrains access to relevant semantic information (Damian et al., 2001; Glucksberg et al., 1986; Moss & Marslen-Wilson, 1993) and patients with semantic control deficits benefit from constraining cues but also show negative effects of miscueing contexts (Jefferies et al., 2008; Lanzoni et al., 2019; Noonan et al., 2010). Furthermore, conceptual activation can be influenced by task cues, for example, Rahman and Melinger (2011) found that providing ad hoc contexts for thematic relations (e.g., *fishing trip*) elicited interference amongst a set of thematically-related items to be named, which was otherwise only found for taxonomically-related sets. Yet the neurobiological mechanisms that allow us to flexibly focus retrieval on particular semantic relationships, according to the context, are largely unknown.

Semantic representations are thought to be highly distributed, involving both unimodal 'spoke' regions, such as vision, audition and motor features, as well as heteromodal 'hub' regions, which integrate these diverse features (Buxbaum & Saffran, 2002; Goldberg et al., 2006; Hoffman et al., 2012; Lambon Ralph et al., 2017; Patterson et al., 2007; Reilly, Garcia, & Binney, 2016; Thompson-Schill, Aguirre, Desposito, & Farah, 1999; Visser et al., 2012). By this account, conceptual retrieval occurs when there is interactive-activation between hub and spokes (Clarke & Tyler, 2014; Moss, Rodd, Stamatakis, Bright, & Tyler, 2004; Murphy, Rueschemeyer, Smallwood, & Jefferies, 2019; Tyler et al., 2013). Both ventral anterior temporal lobe (ATL) and angular gyrus (AG) are candidate semantic hubs, well-situated for the convergence of sensorimotor information across modalities, and overlapping with the default mode network (DMN) (Caspers et al., 2011; Margulies et al., 2016; Murphy et al., 2017; Turken & Dronkers, 2011; Uddin et al., 2010; Visser et al., 2012). Some accounts have suggested that ATL is specialised for taxonomic relations, while AG supports thematic relations (de Zubicaray et al., 2013; Geng & Schnur, 2016; Schwartz et al., 2011). However, ATL shows activation for both types of relationships when difficulty is matched (Jackson et al., 2015; Teige et al., 2019). Consequently, ATL might underpin a wide range of semantic decisions, dynamically forming distinct long-range networks with different cortical spoke regions depending on the task (Chiou & Lambon Ralph, 2019; Mollo, Cornelissen, Millman, Ellis, & Jefferies, 2017).

The flexible retrieval of taxonomic and thematic relations might involve interactions between hub and/or spoke regions and control processes. The Controlled Semantic Cognition framework (Lambon Ralph et al., 2017) proposes that retrieval is ‘shaped’ to suit the circumstances by a semantic control network (Badre & Wagner, 2007; Chiou et al., 2018; Davey et al., 2016; Jefferies, 2013; Lambon Ralph et al., 2017; Moss et al., 2005; Thompson-Schill et al., 1997). Recruitment of this network is maximised when non-dominant information or weak associations must be retrieved, or there is competition or ambiguity (Davey, Cornelissen, et al., 2015; Davey et al., 2016; Demb et al., 1995; Noonan et al., 2013; Noppeney & Price, 2004; Wagner et al., 2001; Whitney et al., 2010; Zhang et al., 2004). In these circumstances, a strong left-lateralised response is seen within inferior frontal gyrus (LIFG) and posterior temporal cortex (Badre et al., 2005; Gold & Buckner, 2002; Noonan et al., 2013; Thompson-Schill et al., 1997) – regions which partially overlap with, and yet are distinct from, domain-general executive regions (Davey et al., 2016; Dobbins & Wagner, 2005; Fedorenko et al., 2013; Whitney et al., 2010, 2012). LIFG changes its pattern of connectivity according to the task, connecting more to visual colour regions during demanding colour matching trials, and to ATL during easier globally-related semantic trials (Chiou et al., 2018). Controlled semantic retrieval is also impaired in patients with damage to LIFG (Harvey et al., 2013; Noonan et al., 2010; Robinson et al., 1998; Stampacchia et al., 2018), while inhibitory stimulation of this region disrupts semantic control (Hoffman, Jefferies, & Lambon Ralph, 2010; Whitney et al., 2010, 2012).

Although previous studies have described this semantic control network, we still lack a detailed mechanistic account of how semantic control operates. In many tasks manipulating semantic control (for example, involving ambiguous words, or weak associations), there are few contextual cues and no pre-specified goal for retrieval, so the semantic connection between the items is not known in advance (Davey, Cornelissen, et al., 2015; Hallam, Whitney, Hymers, Gouws, & Jefferies, 2016; Morris, 2006; Moss et al., 2005; Rodd, Johnsrude, & Davis, 2011; Swinney, 1979; Thompson et al., 2017; Wagner et al., 2001). In these circumstances, semantic control cannot be engaged proactively: for example, switching between taxonomic and thematic trials is effortful (Landrigan & Mirman, 2018), presumably because the interaction of semantic hub(s) and spokes must be dynamically altered. In other tasks (particularly feature matching, within the existing literature), there is a pre-specified goal (e.g., to match concepts on colour or shape), and consequently semantic control can be applied in a top-down manner (see Badre et al., 2005)[4]. Since it is not possible to match semantically-unrelated items on a specific feature without being told this feature in advance, proactive and retroactive aspects of semantic control are not easily compared in existing studies – they are tested by different paradigms. We overcame this limitation by manipulating task knowledge within a semantic judgement paradigm: on half of the trials, a cue specified the type of conceptual link (taxonomic or thematic) that would be relevant in the forthcoming trial, while a non-specific cue was presented on the other trials. Using fMRI, we were able to investigate the impact of manipulating prior task knowledge on retrieval within the semantic network, and compare this to the effect of strength of association, which has been shown to modulate responses within semantic control regions in previous studies (Badre et al., 2005; Teige et al., 2019; Wagner et al., 2001).

There are several alternative hypotheses about the neural basis of top-down semantic control that are consistent with previous literature. First, top-down semantic control may draw on the same semantic control mechanisms highlighted by earlier studies (Badre et al., 2005; Davey, Cornelissen, et al., 2015; Teige et al., 2019; Wagner et al., 2001). This view predicts substantial overlap in activation between the effects of task knowledge (allowing top-down control, since the information to focus on is specified in advance) and associative strength (involving stimulus-driven control, in which the information to focus on can only be determined after the concepts are presented). This overlap might be seen in key semantic control regions, such as LIFG, even though manipulations of stimulus-driven control are accompanied by strong differences in task difficulty (e.g., weak associations are harder to retrieve than strong associations), while the provision of task knowledge is not expected to make semantic decisions more difficult. Alternatively, top-down and stimulus-driven semantic control might involve partially-distinct control mechanisms, such as greater reliance on the multiple-demand network for top-down control. This network is implicated in goal-directed behaviour (Crittenden et al., 2016;

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[4] However, these studies often present globally-related concepts as distractors, and consequently, do not fully separate top-down and stimulus-driven control (Krieger-Redwood et al., 2016; Thompson-Schill et al., 1997; Whitney et al., 2012).

Woolgar et al., 2011; Woolgar & Zopf, 2017), and consequently the recruitment of this network might be crucial when a goal for semantic retrieval must be maintained and effortfully implemented.

To allow conceptual retrieval to be shaped to suit the circumstances, it is also necessary for top-down control processes to interact with semantic representations, and there are several hypotheses about how this is achieved. First, it has been suggested that semantic control processes interact with 'spoke' representations in sensory and motor regions (Jackson et al., 2019). This interaction could "gate" conceptual retrieval, for example, by modulating the extent to which visually-presented inputs activate the ventral visual stream; control processes could also shape the flow of activation through the semantic network by regulating the extent to which particular sensorimotor features, such as colour, shape and size, are instantiated during retrieval (via imagery). In addition (or alternatively), semantic control processes may directly modulate the activation of heteromodal conceptual representations in 'hub' regions like ATL.

In light of these alternative accounts, we first asked if top-down semantic control would activate semantic control and domain-general executive regions. In an exploratory analysis, we also asked if this response overlapped with the effect of strength of association (a classic manipulation of semantic control: weak associations require more controlled retrieval than strong associations). Next, we used multivoxel pattern analyses to examine where information about semantic goals could be classified prior to semantic decisions, and characterised the intrinsic connectivity of this region (which fell within LIFG) in an independent dataset. Third, we investigated the level at which control processes are applied to conceptual representations – i.e. whether control is applied to the heteromodal hub (e.g., in ATL), or to the spokes in order to bias the pattern of semantic retrieval in task-appropriate ways. These analyses allowed us to test mechanistic accounts of top-down semantic retrieval.

## 4.3. Methods

### *4.3.1. Participants*

Thirty-two undergraduate students were recruited for this study (age-range 18-23 years, mean age = 20.6 ± 1.52 years, 5 males). All were right-handed native English speakers, and had normal or corrected-to-normal vision. None of them had any history of neurological impairment, diagnosis of learning difficulty or psychiatric illness. All provided written informed consent prior to taking part and received monetary compensation for their time. One participant was excluded from data analysis due to chance-level accuracy on the semantic decision task (*Mean* ± *SD* = 57.5% ± 5.69%). Consequently, 31 participants were included in the final analysis. We also used a separate sample of 211 participants (age-range 18-31 years, mean age = 20.85 ± 2.44 years, 82 males; 5 participants overlapped between the two datasets) who completed resting-state fMRI, to examine the intrinsic connectivity of regions identified in task contrasts. Ethical approval was obtained from the Research Ethics Committees of the Department of Psychology and York Neuroimaging Centre, University of York.

### *4.3.2. Materials*

In the semantic relatedness judgement task, participants decided whether the probe and target were semantically related. Items were linked by one of two different types of semantic relationships – taxonomic (i.e. they judged if the items were in the same category) and thematic (i.e. they judged if the items were commonly found or used together; see Procedure for task instructions). On half of the trials, they were told in advance which relationship would be probed before the presentation of the word pair. For the other half of the trials, there was no specific information about which type of semantic relationship to expect in advance; instead participants decided about semantic relatedness based on the two items presented. Overall, 120 related and 60 unrelated word pairs were included in this task. Our study used a fully-factorial within-subjects design manipulating (i) Task Knowledge (Known Goal vs. Unknown Goal) and (ii) Semantic Relation (Taxonomic relation vs. Thematic relation) to create four conditions, with each experimental condition including 30 related trials. Unrelated word pairs were generated without repeating words from the related pairs (i.e., each of the 180 word-pairs was unique and there was no overlap across conditions). The trials were then evenly divided into two sets corresponding to the Known Goal (30 unrelated, 60 related trials) and Unknown Goal (30 unrelated, 60 related trials) conditions.

Items were selected for taxonomically and thematically-related trials based on existing definitions of these relations. Taxonomic relationships provide hierarchical similarity structures, based primarily on common features shared across same-category items (Hampton, 2006), while thematic relations are largely built around events or scenarios (Estes et al., 2011), which become conventionalized due to the frequent co-occurrence of particular types of objects in real-life situations and in linguistic descriptions of them. We selected a subset of related items used in Teige et al. (2019) study. The words in each pair were related either taxonomically or thematically, but not in both ways: this was confirmed using subjective ratings from an independent sample of 30 participants, who were asked about: (1) Thematic relatedness (Co-occurrence): "*How associated are these items? For example, are they found or used together regularly?*"; (2) Taxonomic relatedness (Physical similarity): "*Do these items share similar physical features?*" and (3) Difficulty: "*How easy overall is it to identify a connection between the words?*". Ratings were made on a 7-point Likert-scale (with a score of 7 indicating strongest agreement). 2-by-2 repeated-measures ANOVAs examined the differences in these ratings between the trials selected for each condition. The results revealed that there were significant main effects of Semantic Relation for *Co-occurrence,* $F(1,29) = 231.67, p < .001, \eta_p^2 = .89$, and *Physical similarity*, $F(1,29) = 318.98, p < .001, \eta_p^2 = .92$. Thematically-related word pairs were rated as having higher co-occurrence compared to taxonomically-related word pairs, while the taxonomically-related word pairs had higher physical similarity than the thematically-related word pairs. Rated difficulty was the same across both the taxonomic and thematic conditions, $F(1,29) = 2.39, p = .13, \eta_p^2 = .08$. Importantly, there were no differences between Known Goal and Unknown Goal trials (*Co-occurrence*: $F(1,29) = .34, p = .56, \eta_p^2 = .01$; *Physical similarity*: $F(1,29) = .54, p = .47, \eta_p^2 = .02$; *Difficulty*: $F(1,29) = .01, p = .93, \eta_p^2 < .001$), and no interactions between Task Knowledge and Semantic Relation for the ratings of thematic relatedness, $F(1,29) = .73, p = .40, \eta_p^2 = .03$, physical similarity, $F(1,29) = .07, p = .79, \eta_p^2 = .002$, and difficulty, $F(1,29) = .01, p = .92, \eta_p^2 < .001$, showing that the trials were well-matched across the Known and Unknown conditions (**see Table 4.1**).

To allow an exploratory analysis of the overall effects of semantic relatedness across both thematic and taxonomic trials, taking into account physical similarity as well as thematic relations, we extracted word2vec values for each trial. Word2vec is a measure of semantic similarity/distance based on the assumption that words with similar meanings occur in similar contexts (Mikolov, Chen, Corrado, & Dean, 2013). In this way, word2vec is able to capture both taxonomic and thematic relationships: for taxonomically related words, items with shared features occur in similar contexts; for example, dog and sheep can be both described in feeding and running contexts, and for thematically related words, items that are frequently found or used together occur in similar contexts; for example, cabbage and bowl both occur in kitchen contexts. Word2vec is correlated with subjective ratings of semantic distance (Wang et al., 2018); however, word2vec may be more sensitive to taxonomic similarity than human volunteers, who tend to be strongly influenced by thematic relationships[5].

Word2vec has been shown to predict human behaviour better than other approaches, like latent semantic analysis (Pereira, Gershman, Ritter, & Botvinick, 2016). We opted to use this metric since previous research has shown that semantic distance, as measured by word2vec, is negatively correlated with the strength of activation in the semantic control network: weakly-related trials require more controlled retrieval to identify a semantic link (e.g., Hoffman, 2018; Teige et al., 2019). Consequently, we included word2vec as a parametric regressor across taxonomic and thematic trials to establish if effects of task knowledge, thought to modulate top-down control processes, occur within the same brain regions as effects of the strength of semantic relations, thought to modulate stimulus-driven control demands. For word2vec, we found a significant main effect of Semantic Relation, $F(1,111) = 31.37$, $p < .001$, $\eta_p^2 = .22$ (taxonomic trials were more related on this metric than thematic trials[5]), but no main effect of Task Knowledge, $F(1,111) = 2.50$, $p = .12$, $\eta_p^2 = .02$, or interaction effect between these two variables, $F(1,111) = .12$, $p = .73$, $\eta_p^2 = .001$ (**see Table 4.1**). In order to avoid any confounding effects from linguistic properties, the probe and target words in the four conditions were also matched for word

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[5] This might explain why taxonomic trials had higher word2vec scores than thematic trials, even though the thematic items were rated by human participants as having higher co-occurrence.

frequency (CELEX database; Baayen et al., 1993), length, and imageability using the N-Watch database (Davis, 2005; $p > .1$, see Table 4.2).

As word order influences semantic processing (Popov, Zhang, Koch, Calloway, & Coutanche, 2019), we analysed the frequency of usage for each word pair, when the words appeared in either order (word 1 → word 2; word 2 → word 1), using the Sketch Engine corpus (Kilgarriff, Rychly, Smrz, & Tugwell, 2004). Paired-samples $t$-tests revealed no differences in the frequency of word use across the two possible word orders in any experimental condition ($t$ values < 1.65, $p$ values > .11). We then analysed the frequency of word pairs in the order in which they were presented in the experiment: there were no main effects of Task Knowledge ($F(1,29) = 2.52$, $p = .12$, $\eta_p^2 = .08$; Known Goal: *Mean* ± *SD* = 185.17 ± 88.81 occurrences; Unknown Goal: *Mean* ± *SD* = 40.03 ± 12.90 occurrences) or Semantic Relation ($F(1,29) = 3.47$, $p = .07$, $\eta_p^2 = .11$; Taxonomic: *Mean* ± *SD* = 27.28 ± 17.69 occurrences; Thematic: *Mean* ± *SD* = 197.92 ± 88.08 occurrences). There was also no interaction, $F(1,29) = 1.44$, $p = .24$, $\eta_p^2 = .05$. These findings indicate that the frequency of the word pairs was well-matched across conditions, irrespective of word order.

**Table 4.1.** *Ratings of Co-occurrence, Physical similarity, Difficulty, and word2vec values for the four Related conditions and the Unrelated trials (*Mean ± SD*).*

| ***Conditions*** | ***Co-occurrence*** | ***Physical similarity*** | ***Difficulty*** | ***Word2vec**** |
|---|---|---|---|---|
| Known Goal Taxonomic Relation | 3.11 ± .84 | 4.94 ± .69 | 4.68 ± .79 | .36 ± .09 |
| Unknown Goal Taxonomic Relation | 3.05 ± .76 | 4.8 ± .99 | 4.69 ± .80 | .33 ± .13 |
| Known Goal Thematic Relation | 5.25 ± .88 | 1.67 ± .75 | 5.03 ± 1.31 | .25 ± .10 |
| Unknown Goal Thematic Relation | 5.48 ± .86 | 1.61 ± .83 | 5 ± 1.28 | .21 ± .11 |
| Known Goal Unrelated Condition | 1.23 ± .17 | 1.07 ± .10 | 6.70 ± .18 | --- |
| Unknown Goal Unrelated Condition | 1.18 ± .27 | 1.08 ± .12 | 6.77 ± .19 | --- |

* The word2vec values were only available for 115 word pairs of the 120 semantic related word pairs, with 1 missing value for Known Goal Taxonomic Relations, Known and Unknown Goal Thematic Relations, and 2 missing values for Unknown Goal Taxonomic Relations.

For the unrelated word pairs, another 12 participants who did not take part in the fMRI experiment were asked to rate each word pair on *Co-occurrence*, *Physical similarity* and *Difficulty*, using a 7-point Likert-scale as described above. However, the *Difficulty* question was adapted to ask: "*How easy is it to decide there is no relationship between the words?*". The unrelated word pairs presented in the Known Goal and Unknown Goal conditions were matched on *Co-occurrence* ($t(29) = .83$, $p = .41$), *Physical similarity* ($t(29) = -.10$, $p = .92$), and *Difficulty* ($t(29) = -1.46$, $p = .16$) as no significant effects were revealed by the paired *t*-tests (**see Table 4.1**). The unrelated probes and targets in Known Goal and Unknown Goal conditions were matched for frequency (CELEX database; Baayen et al., 1993), length and imageability in the N-Watch database (Davis, 2005; $p > .1$, see Table 4.2). Also, the comparisons between related and unrelated words for both probes and targets in each condition did not reveal any significant difference in frequency, length, and imageability ($p > .10$).

**Table 4.2.** *Linguistic properties of the Probe and Target words (*Mean ± SD*).*

| ***Probe*** | ***Frequency*** | ***Length*** | ***Imageability**** |
|---|---|---|---|
| Known Goal Taxonomic Relation | .90 ± .44 | 5.57 ± 1.96 | 579 ± 36.14 |
| Unknown Goal Taxonomic Relation | .94 ± .56 | 5.63 ± 1.52 | 576.98 ± 55.55 |
| Known Goal Thematic Relation | 1.09 ± .63 | 5.77 ± 1.77 | 562 ± 65.82 |
| Unknown Goal Thematic Relation | 1.14 ± .61 | 5.57 ± 1.55 | 571.21 ± 52.73 |
| Known Goal Unrelated Condition | .96 ± .41 | 5.77 ± 1.92 | 570.28 ± 53.54 |
| Unknown Goal Unrelated Condition | .97 ± .50 | 5.80 ± 1.61 | 581.78 ± 49.24 |
| ***Target*** | ***Frequency*** | ***Length*** | ***Imageability**** |
| Known Goal Taxonomic Relation | 1.04 ± .54 | 5.77 ± 1.89 | 578.22 ± 44.64 |
| Unknown Goal Taxonomic Relation | 1.01 ± .38 | 5.3 ± 1.68 | 566.59 ± 89.65 |
| Known Goal Thematic Relation | 1.19 ± .61 | 5.43 ± 2.24 | 567.79 ± 54.11 |
| Unknown Goal Thematic Relation | 1.11 ± .46 | 5.53 ± 1.68 | 561.32 ± 77.29 |
| Known Goal Unrelated Condition | 1.05 ± .66 | 5.70 ± 2.00 | 580.38 ± 53.95 |
| Unknown Goal Unrelated Condition | 1.00 ± .54 | 5.80 ± 1.71 | 578.11 ± 49.87 |

* Imageability ratings were only available for 91 probes and 101 targets of the 120 semantic related word pairs, and 59 probes and 59 targets of the 60 semantic unrelated word pairs.

We also included a non-semantic baseline task which matched the presentation and response format of the semantic task and provided a means of focussing the analysis on the semantic response. Meaningless letter strings were presented on the screen one after another and participants were asked to decide whether the two letter strings contained the same number of letters. There were 30 matching strings and 15 mismatching strings (i.e., different number of letters between the two).

### *4.3.3. Procedure*

We employed a semantic relatedness judgement task in which participants were asked to decide if the words in each pair were related or unrelated. This basic task was unchanged across conditions, but the nature of the semantic relationship changed across semantically-related trials – some words were from the *same category*, while some were *thematically related*. We manipulated the opportunity for top-down controlled semantic retrieval by changing the specificity of the instructions. On half of the trials, a specific task instruction, '*Category?*' or '*Thematic?*', was presented such that participants knew in advance which type of semantic relationship would be relevant on the trial (Known Goal). On the other trials, the semantic decision about the word pair was preceded by a non-specific instruction, '*Category or Thematic?*' (Unknown Goal). This allowed us to compare the brain's response to meaningful items during a semantic task when participants either knew the kind of information that would be relevant to making a subsequent decision, or did not have this information in advance and simply decided based on the words that were presented. As a baseline condition, meaningless letter strings were presented and participants were asked to decide whether the number of letters in the two strings was the same or not. For these trials, a '*Letter number?*' task instruction was presented (See Figure 4.1).

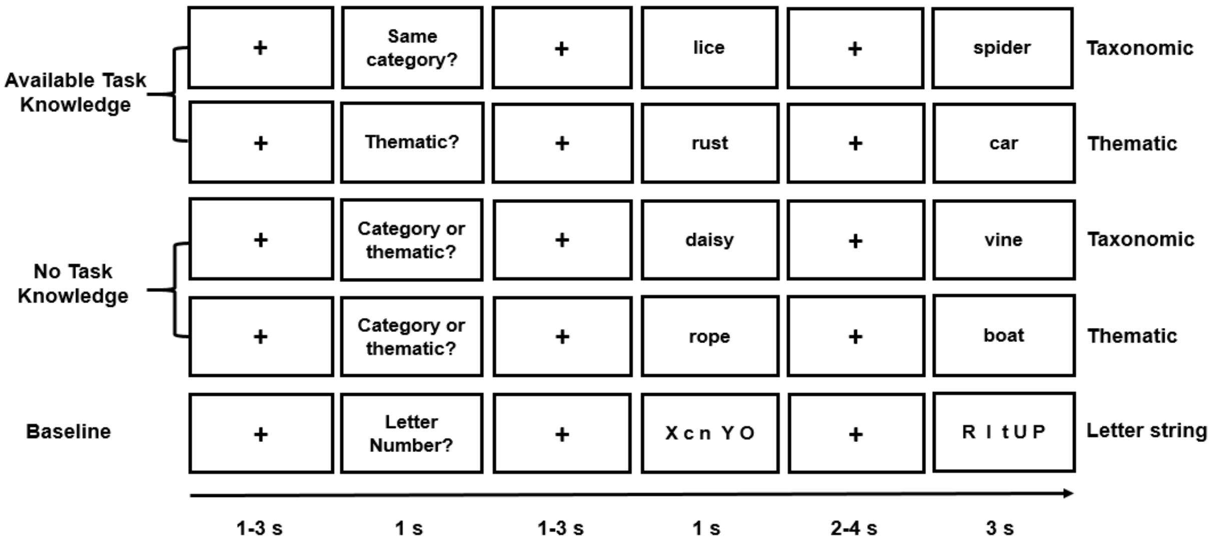


***Figure 4.1.*** Illustration of Known and Unknown Taxonomic, Known and Unknown Thematic, and Letter string trials.

As Figure 4.1 indicates, each trial started with a fixation cross presented for a jittered interval of 1-3s in the centre of the screen. Then the task instruction slide appeared for 1s followed by a jittered inter-stimulus fixation for 1-3s. After that, the probe item was presented on the screen for 1s. After a longer jittered fixation interval lasting 2-4s, the target was presented for 3s. This corresponded to the response period during which participants made their judgments (i.e. decisions about the semantic relationship between the words, or if the number of letters was the same or not) and responded as fast and accurately as possible. They pressed buttons on a response box with their right index and middle fingers to indicate YES and NO responses. The overall likelihood of a YES or NO response was the same across conditions.

Stimuli were presented in five runs each containing 45 trials: 6 related and 3 unrelated trials in each of the four experimental conditions, and 9 letter string trials (6 “same number” and 3 “different number” trials). Each run lasted 9 minutes, and trials were presented in a random order. The runs were separated by a short break and started with a 9-second alerting slide (i.e. Experiment starts soon).

Before entering the scanner, participants received detailed instructions, and the experimenter explained the distinction between taxonomic and thematic relationships. Participants were told that taxonomically-related items are from the same category and share physical features and were given the example of *Kangaroo* and *Hedgehog*. They were told thematically-related items are found or used together and were given the example of *Leaves* and *Hedgehog*. To ensure participants fully understood this distinction, as well as to increase their familiarity with the task format, they completed a 15-trial practice block containing all types of judgements. They were given feedback about their performance and, if accuracy was less than 75%, they repeated the practice trials (this additional training was only needed for one participant who pressed the wrong response buttons).

### *4.3.4. Neuroimaging data acquisition*

Structural and functional data were acquired using a 3T GE HDx Excite Magnetic Resonance Imaging (MRI) scanner utilizing an eight-channel phased array head coil at the York Neuroimaging Centre, University of York. Structural MRI acquisition in all participants was based on a T1-weighted 3D fast spoiled gradient echo sequence (repetition time (TR) = 7.8 s, echo time (TE) = minimum full, flip angle = 20°, matrix size = 256 × 256, 176 slices, voxel size = 1.13 mm × 1.13 mm × 1 mm). The task-based activity was recorded using single-shot 2D gradient-echo-planar imaging sequence with TR = 3 s, TE = minimum full, flip angle = 90°, matrix size = 64 × 64, 60 slices, and voxel size = 3 mm × 3 mm × 3 mm. Data was acquired in a single session. The task was presented across 5 functional runs, each containing 185 volumes.

In a different sample of participants, a 9-minute resting-state fMRI scan was recorded using single-shot 2D gradient-echo-planar imaging (TR = 3 s, TE = minimum full, flip angle = 90°, matrix size = 64 × 64, 60 slices, voxel size = 3 mm × 3 mm × 3 mm, 180 volumes). The participants were instructed to focus on a fixation cross with their eyes open and to keep as still as possible, without thinking about anything in particular. For both the task-based and the resting-state scanning, a fluid-attenuated inversion-recovery (FLAIR) scan with the same orientation as the functional scans was collected to improve co-registration between subject-specific structural and functional scans. The resting-state data were collected alongside task data, with the resting-state sequence presented first, so that measures of intrinsic connectivity could not be influenced by task performance.

### *4.3.5. Pre-processing of task-based fMRI data*

All functional and structural data were pre-processed using a standard pipeline and analysed via the FMRIB Software Library (FSL version 6.0, www.fmrib.ox.ac.uk/fsl). Individual FLAIR and T1-weighted structural brain images were extracted using FSL's Brain Extraction Tool (BET). Structural images were linearly registered to the MNI152 template using FMRIB's Linear Image Registration Tool (FLIRT). The first three volumes (i.e. the presentation of the 9-second-task-reminder 'Experiment starts soon') of each functional scan were removed in order to minimise the effects of magnetic saturation, therefore there was a total of 182 volumes for each functional scan. The functional neuroimaging data were analysed by using FSL's FMRI Expert Analysis Tool (FEAT). We applied motion correction using MCFLIRT (Jenkinson et al., 2002), slice-timing correction using Fourier space time-series phase-shifting (interleaved), spatial smoothing using a Gaussian kernel of FWHM 6 mm (for the univariate analyses only), and high-pass temporal filtering (sigma = 100 s) to remove temporal signal drift. The spatial smoothing step was omitted for multivariate pattern analysis to preserve local voxel information. In addition, motion scrubbing (using the fsl_motion_outliers tool) was applied to exclude volumes that exceeded a framewise displacement threshold of 0.9. One run for two participants showed high head motion values (absolute value > 2 mm) and these runs were excluded from the univariate analysis. These two participants were removed entirely from the multivariate pattern analysis. Mean temporal signal-to-noise ratio (tSNR; ratio of mean signal in each voxel and standard deviation of the residual error time series in that voxel across time) across all the acquisitions is shown in Figure A.2.1 in the appendicies.

### *4.3.6. Univariate analysis of task-based fMRI data*

The analysis examined the controlled retrieval of semantic information at different stages of the task. We differentiated the response to the first word, when participants either knew what type of semantic relationship to retrieve in advance (Specific goal: '*Category?*' or '*Thematic?*') or did not know (Non-specific goal: '*Category* or *Thematic?*'), and the second word when participants linked the words according to the specific instructions or in the absence of a specific instruction about the nature of the semantic relationship. Consequently, the model included three factors: (1) Word Position (First word vs. Second word), (2) Task Knowledge (Known goal vs. Unknown goal), and (3) Semantic Relation (Taxonomic relation vs. Thematic relation).

In addition, in an exploratory analysis, we examined effects of the semantic distance between the probe and target words during semantic decision making. This analysis was designed to establish if the effects of having specific instructions prior to semantic retrieval, seen in LIFG (see below), would overlap with the well-established effect of identifying semantic links between more distantly-related as opposed to closely-related items, which elicits activation within the semantic control network (Davey, Cornelissen, et al., 2015; Noonan et al., 2010; Noonan et al., 2013; Whitney et al., 2010). We included a parametric regressor in the model, across all the taxonomic and thematic trials, to characterise the semantic distance for each trial. This was derived using the word2vec algorithm (Mikolov et al., 2013), which uses word co-occurrence patterns in a large language corpus to derive semantic features for items, which can then be compared to determine their similarity. The inclusion of this analysis allowed us to establish whether the brain regions that support the top-down control of retrieval (i.e. the comparison of Known goal vs. Unknown goal trials) overlap with those sensitive to stimulus-driven control demands. Since the thematic and taxonomic trials were found to differ in word2vec, the inclusion of this additional regressor also statistically controls for differences across these two types of semantic relation – although examining overall effects of semantic relation was not the key aim of the current study.

The pre-processed time-series data were modelled using a general linear model, using FMRIB's Improved Linear Model (FILM) correcting for local autocorrelation (M. W. Woolrich et al., 2001). 10 Explanatory Variables (EV) of interest and 5 of no interest were modelled using a double-Gaussian hemodynamic response gamma function (probe and target were modelled separately; i.e., two EVs for each condition). The 10 EV's of interest were: (1) Probe and (2) Target for Known Goal Taxonomic Relations, (3) Probe and (4) Target for Unknown Goal Taxonomic Relations, (5) Probe and (6) Target for Known Goal Thematic Relations, (7) Probe and (8) Target for Unknown Goal Thematic Relations, (9) Probe and (10) Target for same-number letter string baseline condition. Our EV's of no interest were: (11) Probe and (12) Target unrelated word pairs (when participants should decide that the two words are not semantically linked), (13) Other inputs-of-no-interest (including the instruction slide, the period after the response on each trial when the word was still on the screen, and different-number letter string trials), (14) Fixation (including the inter-stimulus fixations between instructions and first item, as well as between first item and second item when some retrieval or task preparation was likely to be occurring), and (15) Incorrect Responses (including all the incorrect trials across conditions). We also included an EV to model word2vec as a parametric regressor, therefore we had 16 EVs in total. EVs for the first item in each pair commenced at the onset of the word or letter string, with EV duration set as the presentation time (1s). EVs for the second item in each pair commenced at the onset of the word or letter string, and ended with the participants' response (i.e. a variable epoch approach was used to remove effects of time on task). The remainder of the second item presentation time was modelled in the inputs-of-no-interest EV (i.e., word 2 was on screen for 3 seconds, and if a participant responded after 2 seconds, the post-response period lasting 1 second was removed and placed in the inputs-of-no-interest EV). The parametric word2vec EV had the same onset time and duration as the EVs corresponding to the second word in the semantic trials, but in addition included the demeaned word2vec value as a weight. The fixation period between the trials provided the implicit baseline.

In addition to contrasts examining the main effects of Word Position (Word 1 vs. Word 2), Task Knowledge (Known Goal vs. Unknown Goal), and Semantic Relation (Taxonomic Relation vs. Thematic Relation), we included all two-way and three-way interaction terms, and comparisons of each semantic condition with the non-semantic (baseline) letter task. The five sequential runs were combined using fixed-effects analyses for each participant. In the higher-level analysis at the group level, the combined contrasts were analysed using FMRIB's Local Analysis of Mixed Effects (FLAME1), with automatic outlier de-weighting (Woolrich, 2008). A 50% probabilistic grey-matter mask was applied. Clusters were thresholded using Gaussian random-field theory, with a cluster-forming threshold of $z = 3.1$ and a familywise-error-corrected significance level of $p = .05$.

### *4.3.7. ROI-based multivariate pattern analysis*

To examine whether regions in the semantic control network (Noonan et al., 2013) contained information about the semantic goal specified by the instructions, we performed ROI-based MVPA using the PyMVPA toolbox (Hanke et al., 2009). This network, including LIFG, posterior middle temporal gyrus, dorsal angular gyrus, and pre-supplementary cortex, was defined by a formal meta-analysis of 53 studies that contrasted semantic tasks with high over low executive control demands (Noonan et al., 2013). We examined the neural response to the first word, as this allowed us to capture the process of tailoring ongoing retrieval to suit the task demands, before the presentation of different semantic relationships could elicit different neural patterns. We used a linear support vector machine (SVM) classifier (Linear CSVMC, Chang & Lin, 2011) to separately decode the neural patterns elicited for Known Goals vs. Unknown Goals. We also examined decoding of different types of semantic relationship: Known Goal Taxonomic Relation vs. Known Goal Thematic Relation, when semantic control regions might reflect the distinction between these trial types, and Unknown Goal Taxonomic Relation vs. Unknown Goal Thematic Relation, as a control analysis, since semantic control regions should not be able to decode Unknown trial types.

To derive condition-specific beta estimates, we repeated the univariate first-level GLM analysis on spatially unsmoothed fMRI data. The resulting beta images pertaining to each condition were estimated in each of the five runs and only trials with correct responses were included. Consequently, the spatial pattern information entered for classification analysis represented the average neural pattern for each condition and each run. This approach is consistent with previous studies investigating of semantic and goal representations (Murphy et al., 2017; Peelen & Caramazza, 2012; van Loon, Olmos-Solis, Fahrenfort, & Olivers, 2018). We employed a searchlight method (Kriegeskorte, Goebel, & Bandettini, 2006) to reveal local activity patterns within the semantic control network that carry goal information using a spherical searchlight with a radius of 3 voxels, within a leave-one-run-out cross-validation scheme across all 5 runs (i.e., five training-testing iterations). Each run acted in turn as the testing set, and the remaining 4 runs were used for training the SVM. Z-scored normalization of each voxel per run and per condition was performed in order to control for global variations of the hemodynamic response across runs and subjects, and remove any contributions of mean activation and retain only pattern information.

Classifiers were trained and tested on individual subject data transformed into MNI standard space. Leave-one-run-out cross-validation was carried out for Known vs. Unknown Goal, and Known

Goal Thematic vs. Known Goal Taxonomic relations separately, with classification accuracy (i.e., proportion of the correctly classified testing samples that have the same predicted label as the target label) calculated within each fold. Since the classifier was tested on two samples corresponding to each condition in each fold, for example Known Goal Taxonomic Relation and Known Goal Thematic Relation, the performance for each iteration could be 0% (i.e., no correct prediction), 50% (i.e., only correctly classified one of the two conditions), 100% (i.e., all correctly classified). Classification accuracies were then averaged across folds and assigned to the central ROI voxel to produce participant-specific information maps, with the accuracies at individual level widely ranging from 0 to 1 (i.e., 0/0.1/0.2/0.3/0.4/0.5/0.6/0.7/0.8/0.9/1). To identify whether any region within the ROI contained significant pattern information (i.e., above chance level = 50%), individual information maps from all participants were submitted to a nonparametric one-sample *t*-test on each voxel based on permutation methods implemented using the Randomize tool in FSL (5000 permutations). Threshold-free cluster enhancement (TFCE; Smith & Nichols, 2009) was used to identify significant clusters from the permutation tests. The final results were thresholded at a TFCE cluster-corrected $p$-value $< 0.05$ after controlling for family-wise error rate.

### *4.3.8. Resting-state neuroimaging data analysis*

Resting-state functional connectivity analyses in an independent dataset were used to establish patterns of intrinsic connectivity for the clusters we derived from the task contrasts. First, we looked to see if the identified LIFG clusters linked to task knowledge (derived from the contrast of *Known > Unknown Goal*), effects of word2vec, and classification of specific goal information would show connectivity with the broader semantic control network, described by Noonan et al. (2013). Secondly, we assessed patterns of intrinsic connectivity for sites sensitive to the type of semantic relationship, to establish whether these brain regions showed relatively strong connectivity with each other and to other default mode network regions. Lastly, we characterised the intrinsic connectivity of a site implicated in the application of semantic control (a site in visual cortex which showed an interaction between task knowledge and word position). This resting-state, from more than 200 healthy students at the University of York, has been used in multiple previous publications (e.g., Sormaz et al., 2018; Vatansever et al., 2017; Vatansever, Karapanagiotidis, Margulies, Jefferies, & Smallwood, 2019; Wang et al., 2018).

Resting-state functional connectivity analyses were conducted using CONN-fMRI functional connectivity toolbox, version 18a (http://www.nitrc.org/projects/conn) (Whitfield-Gabrieli & Nieto-Castanon, 2012), based on Statistical Parametric Mapping 12 (http://www.fil.ion.ucl.ac.uk/spm/). First, we performed spatial pre-processing of functional and structural images. This included slice-timing correction (bottom-up, interleaved), motion realignment, skull-stripped, co-registration to the high-resolution structural image, functional indirect segmentation, spatially normalisation to Montreal Neurological Institute (MNI) space and smoothing with a 8-mm FWHM-Gaussian filter. In addition, a temporal filter in the range 0.009-0.08 Hz was applied to constrain analyses to low-frequency fluctuations. A strict nuisance regression method included motion artifacts, scrubbing, a linear detrending term, and CompCor components attributable to the signal from white matter and cerebrospinal fluid (Behzadi, Restom, Liau, & Liu, 2007), eliminating the need for global signal normalisation (Chai, Castañón, Öngür, & Whitfield-Gabrieli, 2012; Murphy, Birn, Handwerker, Jones, & Bandettini, 2009). ROIs were taken from the task-based fMRI results (see Results section), and binarised using fslmaths. In the first-level analysis, we extracted the time series from these seeds and used these data as explanatory variables in whole-brain connectivity analyses at the single-subject level. For group-level analysis, a whole-brain analysis was conducted to identify the functional connectivity of each ROI with a cluster-forming threshold of $z = 3.1$ correcting for multiple comparisons ($p < .05$, FDR corrected). Connectivity maps were uploaded to Neurovault (Gorgolewski et al., 2015, https://neurovault.org/collections/3509/).

### *4.3.9. ROI selection for "Hub" and "Spoke" analysis*

Additional ROI analysis for heteromodal hub and spoke sites were conducted to further characterise the effects of semantic relation and task knowledge. We identified coordinates for hub ROIs from meta-analyses of neuroimaging studies on semantic cognition. We examined (i) left ventral ATL (MNI coordinates −41, −15, −31) from an average of peaks across eight studies that included a semantic > non-semantic contrast (Rice, Hoffman, Binney, & Lambon Ralph, 2018), (ii) left lateral ATL (MNI coordinates −54, 6, −28) from an activation likelihood estimation (ALE) meta-analysis of 97 studies (Rice et al., 2015), and (iii) left AG (MNI coordinates −48, −68, 28) from an ALE meta-analysis of 386 studies (Binder et al., 2009; Humphreys & Lambon Ralph, 2014). We created these

ROIs by placing a binarised spherical mask with a radius of 3 mm, centred on the MNI coordinates in each site. For spoke ROIs, masks corresponding to primary auditory, motor and visual cortex were generated from Juelich histological atlas in standard space in FSLview, with each mask thresholded at 25% probability and binarized using fslmaths.

## 4.4. Results

### *4.4.1 Results outline*

First, we describe the behavioural results. Second, we report univariate analyses which identified brain regions showing effects of (i) Word Position – i.e. differences in the response to the first and second words of each pair, (ii) Task Knowledge – i.e. differences in semantic retrieval when the relationship was known or not known in advance, and (iii) Semantic Relation – i.e. sensitivity to different types of conceptual relationships, supported by taxonomic or thematic links, and (iv) any interactions between these three factors. To anticipate our key results, we found that a region in LIFG showed a stronger response for trials with a known goal. Regions of the temporal lobe were sensitive to the type of conceptual relationship, but these areas did not show an effect of task knowledge. Instead, a region of visual cortex showed an interaction between task knowledge and word position, consistent with the modulation of spoke-related activity to allow proactive control of semantic retrieval. We then conducted resting-state functional connectivity analyses in a separate dataset, to examine the intrinsic connectivity of these regions and to characterise their overlap with established brain networks. Third, we compared effects of Task Knowledge (i.e. top-down control) with the parametric effect of semantic distance between the words in each pair, using word2vec scores to characterise this well-established semantic control manipulation, in line with previous studies (e.g., Badre et al., 2005; Teige et al., 2019; Wagner et al., 2001). This analysis tested whether a shared region of LIFG supported semantic control when retrieval could be controlled in a top-down fashion and when the inputs themselves determined the control demands. Next, we performed multivariate pattern analysis of the task-based fMRI data to establish how goal information is maintained within the semantic control network. We tested the hypothesis that the semantic control site in LIFG would be able to distinguish between different kinds of semantic relation following the task instructions, and prior to these relations being presented. Finally, we employed an ROI approach to check further effects of control demands in both "Hub" and "Spoke" regions, to test hypotheses about which aspects of conceptual knowledge might be modulated by control processes.

### *4.4.2. Behavioural results*

We obtained behavioural data from a total of 54 participants (31 tested in the scanner and 23 tested in the lab, with data from the scanner presented separately Section A.2.2 in the appendicies). Figure 4.2 shows task accuracy (left panel) and reaction time (RT; right panel). Trials with incorrect responses were excluded from the RT analysis (16.3%). We performed repeated-measures ANOVAs on both RT and accuracy, examining the effects of Task Knowledge (Known Goal vs. Unknown Goal) and Semantic Relation (Taxonomic relation vs. Thematic relation). For both accuracy and RT, there was a main effect of Semantic Relation (Accuracy: $F(1,53) = 7.19$, $p = .01$, $\eta_p^2 = .12$; RT: $F(1,53) = 15.82$, $p < .001$, $\eta_p^2 = .23$), as the thematic trials were more difficult than the taxonomic trials. There was no main effect of Task Knowledge (Accuracy: $F(1,53) = .05$, $p = .82$, $\eta_p^2 = .001$; RT: $F(1,53) = .07$, $p = .79$, $\eta_p^2 = .001$), and no interaction (Accuracy: $F(1,53) = .27$, $p = .61$, $\eta_p^2 = .005$; RT: $F(1,53) = 1.00$, $p = .32$, $\eta_p^2 = .02$).

We also performed paired-samples *t*-tests (Bonferroni-corrected for four comparisons) comparing each semantic condition with the letter string baseline (Mean RT = 1.16 s; Mean Accuracy = 92.0%). For RT, there were no significant differences (Known Taxonomic vs. Letter Baseline: $t(53) = -2.28$, $p = .10$; Unknown Taxonomic vs. Letter Baseline: $t(53) = -2.06$, $p = .18$; Known Thematic vs. Letter Baseline: $t(53) < 1$; Unknown Thematic vs. Letter Baseline: $t(53) < 1$). Accuracy on the letter string task was higher than in the semantic conditions (Known Taxonomic vs. Letter Baseline: $t(53) = -3.09$, $p = .012$; Unknown Taxonomic vs. Letter Baseline: $t(53) = -4.29$, $p < .004$; Known Thematic vs. Letter Baseline: $t(53) = -6.06$, $p < .004$; Unknown Thematic vs. Letter Baseline: $t(53) = -5.87$, $p < .004$).

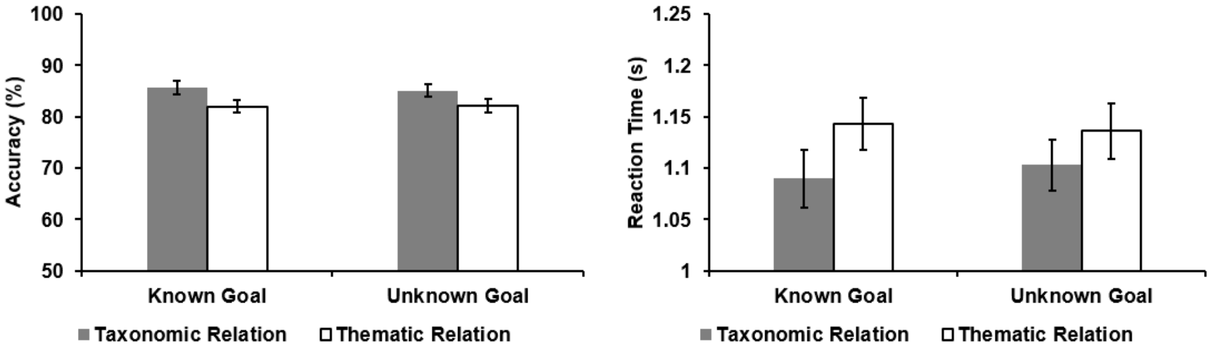


***Figure 4.2.*** **Behavioural results**. Accuracy (percentage correct, left panel) and reaction times (in seconds, right panel) for the target words in each semantic condition (*Known Goal Taxonomic Relation*, *Unknown Goal Taxonomic Relation*, *Known Goal Thematic Relation*, and *Unknown Goal Thematic Relation*). Error bars represent the standard error.

### *4.4.3. Univariate analysis*

#### *4.4.3.1. Main effects in task-based fMRI*

**Effects of word position**: First, we examined the brain regions involved in different stages of the task in a whole-brain analysis. This analysis characterised the baseline effects of task structure prior to investigating how task knowledge might interact with these effects. We compared each experimental condition with the letter string baseline at each word position (providing a basic level of control for visual input and button presses), before performing contrasts between different word positions. Brain regions showing a stronger response to the first than second word included left superior temporal gyrus and right central opercular cortex (see Figure 4.3 A). In contrast, left inferior frontal gyrus, bilateral lateral occipital cortex, bilateral inferior/middle temporal gyrus, paracingulate/cingulate gyrus, parahippocampal gyrus and primary visual areas showed a stronger response to the second word (i.e., when the semantic decision was made; see Figure 4.3 B). Similar effects were observed when Word 1 and Word 2 were contrasted directly, without the subtraction of the letter string baseline (see Figure A.2.4 in the appendicies).

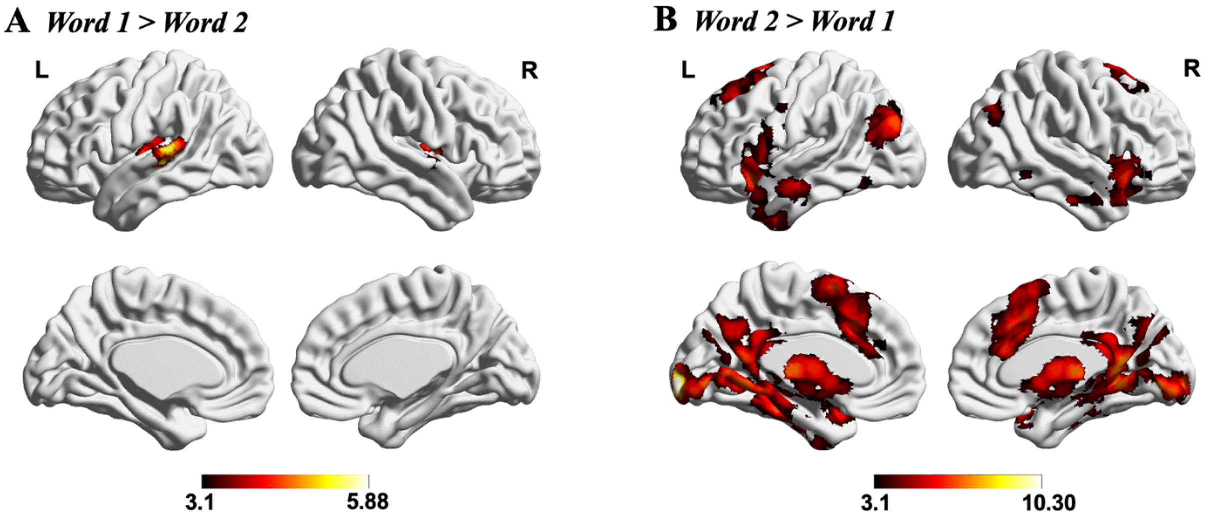


***Figure 4.3. Effects of word position.*** **(A)** ***Word 1 (experimental conditions - letter string baseline) > Word 2 (experimental conditions - letter string baseline).*** **(B)** ***Word 2 (experimental conditions - letter string baseline) > Word 1 (experimental conditions - letter string baseline).*** Both maps were cluster-corrected with a voxel inclusion threshold of $z > 3.1$ and family-wise error rate using random field theory set at $p < .05$. L = Left hemisphere; R = Right hemisphere.

**Effects of task knowledge**: The next stage of our analysis sought to capture activation relating to the effect of task knowledge, regardless of semantic relation, comparing all of the Known Goal trials with Unknown Goal trials. Activation of LIFG was stronger when the goal was known compared to when the goal was not known (see Figure 4.4 A). This cluster largely fell within the semantic control network defined by Noonan et al. (2013) in a formal meta-analysis of 53 studies that manipulated executive semantic demands (in green with overlap in yellow at the top right-hand corner of Figure 4.4 A). This semantic control network partially overlaps with the default mode network (DMN; blue regions at the bottom left-hand of Figure 4.4 A) as defined by Yeo et al. (2011) in a 7-network parcellation of whole-brain functional connectivity, particularly in the anterior and ventral parts of LIFG (cyan regions). There is also partial overlap with the multiple demand network (MDN; in red), as defined by the response to difficulty across a diverse set of demanding cognitive tasks (Fedorenko et al., 2013), particularly in the posterior and dorsal parts of LIFG (yellow regions at the bottom left-hand of Figure 4.4 A). In this way, the semantic control network is intermediate between DMN and MDN (Davey et al., 2016). Of those voxels within this identified LIFG cluster, 66.85% fell within the semantic control network, 25.7% were within the DMN, and 25.0% were within the MDN (some voxels fell in more than one of these networks).To understand the intrinsic connectivity of this region, we seeded it in an independent resting-state fMRI dataset, revealing a pattern of strong connectivity with posterior temporal cortex, intraparietal sulcus and anterior cingulate cortex/pre-supplementary motor area (see Figure 4.4 B), including the key regions of the semantic control network (see Figure 4.4 C; Chiou et al., 2018; Noonan et al., 2013; Whitney et al., 2010). This analysis confirmed that the LIFG cluster responding to task knowledge forms a network at rest with other brain areas associated with semantic control.

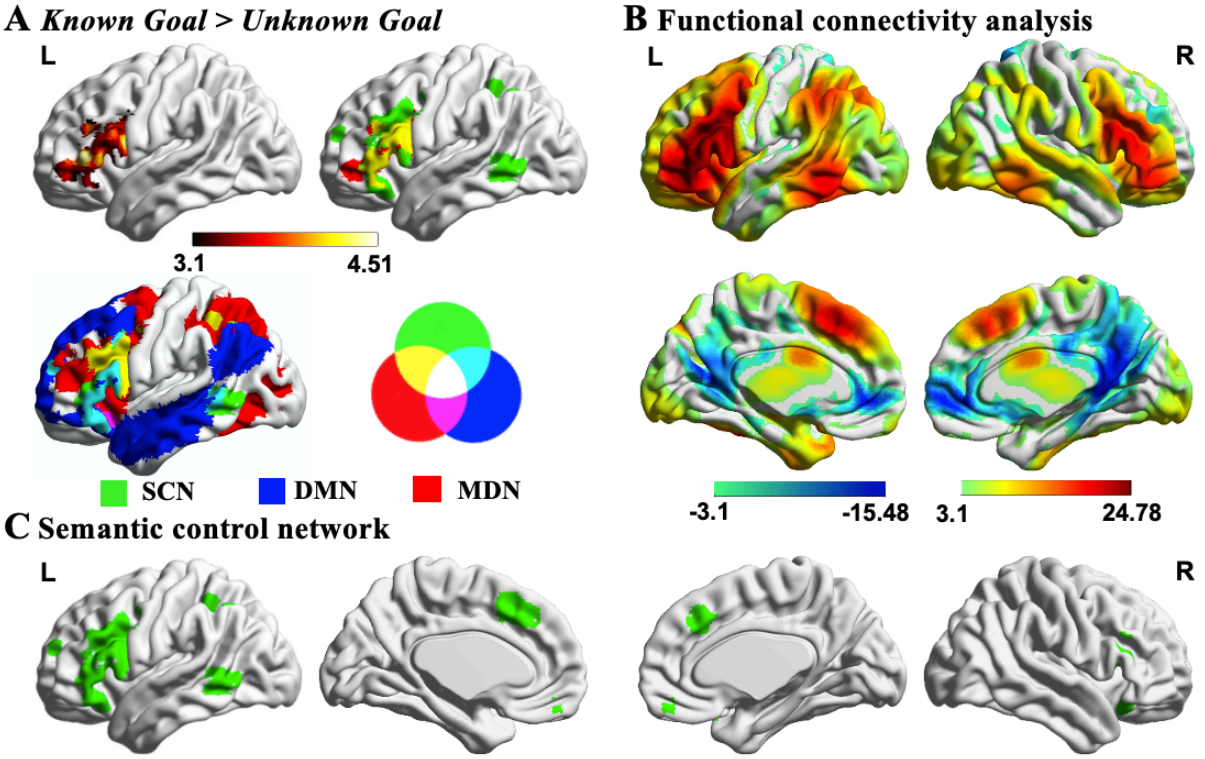


***Figure 4.4*. Effects of task knowledge. A)** Significant activation in left inferior frontal gyrus defined using the contrast *Known Goal* > *Unknown Goal*. This cluster overlapped with the semantic control network (SCN; in green) from Noonan et al. (2013; overlap in yellow). This semantic control network is intermediate between default mode network (DMN; in blue with overlap in cyan with SCN) and multiple demand network (MDN; in red with overlap in yellow with SCN). The network maps are fully saturated to emphasize the regions of overlap. **B-C)** The functional connectivity of this region with the

rest of the brain revealed a large-scale brain network commonly associated with regions of the semantic control network. All maps are thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere.

**Effects of Semantic Relation:** We characterised the main effect of semantic relation (Thematic vs. Taxonomic) across both Known and Unknown trials, to identify brain regions responding to semantic task demands as opposed to task knowledge. Anterior middle temporal gyrus (aMTG) and hippocampus showed a stronger response to thematic than taxonomic relations (see Figure 4.5 A). Of those voxels within these sites, 77.9% of aMTG and 12.7% of hippocampus fell within the DMN defined by Yeo et al.'s (2011) 7-network parcellation (in blue in Figure 4.5 B with overlap in pink). These clusters, showing effects of type of semantic relation, were used as seeds in an analysis of intrinsic connectivity in an independent sample – this revealed a similar pattern across the two sites, with relatively high connectivity with angular gyrus, medial prefrontal cortex, posterior cingulate and anterior temporal regions (see Figure 4.5 C-D). In summary, this analysis revealed sites that respond to type of semantic relation are distinct from those that respond to task knowledge. There were no regions that were more active for taxonomic than thematic trials.

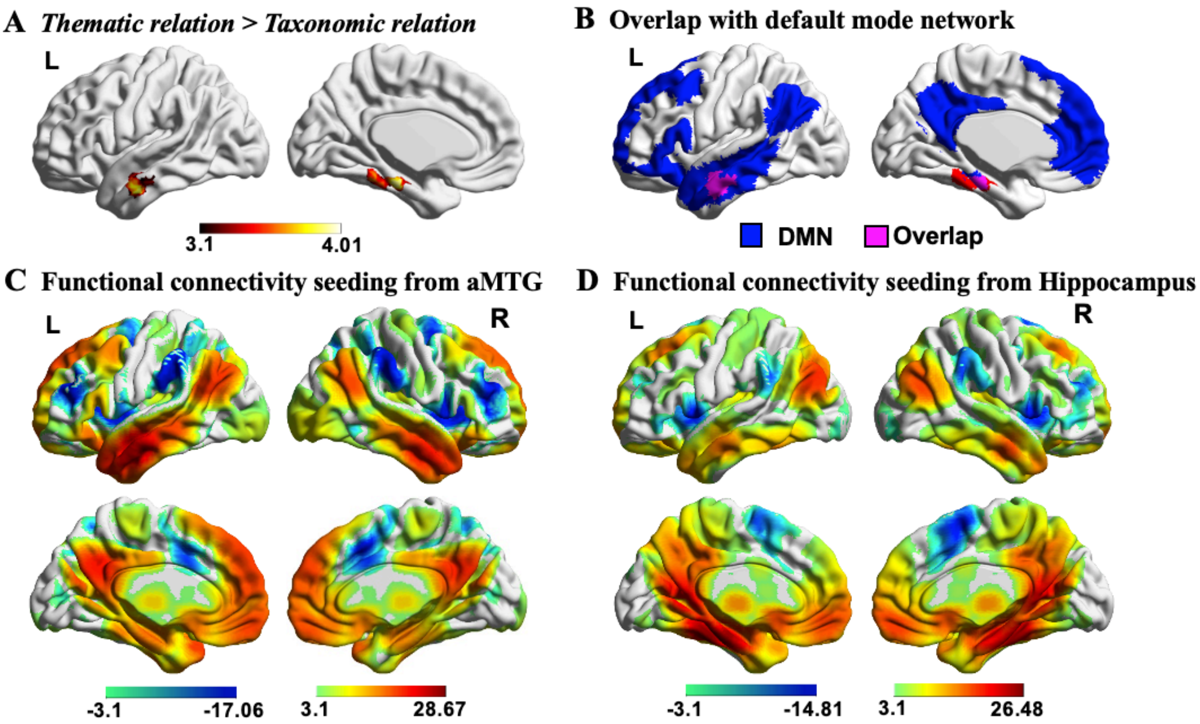
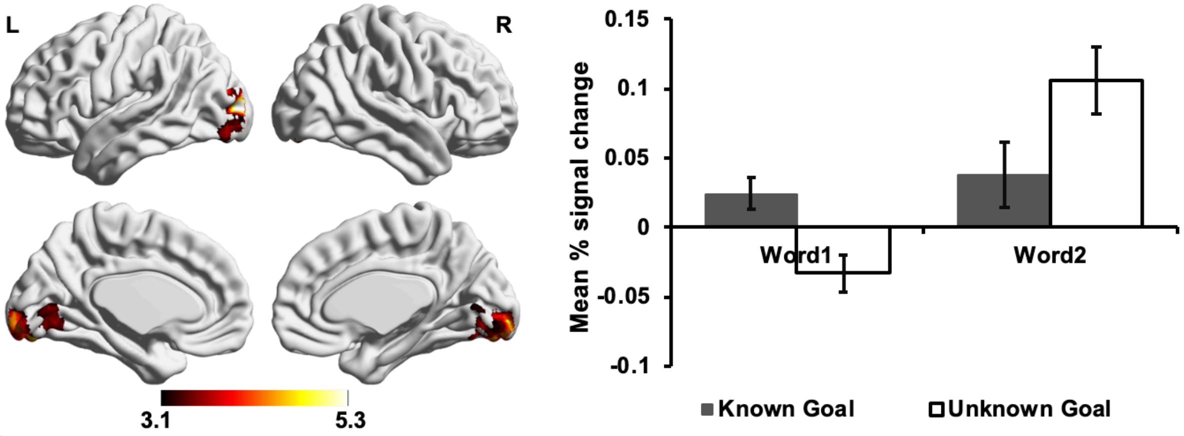


***Figure 4.5*. Effects of Semantic Relation. A)** Significant activation in aMTG and hippocampal gyrus defined using the contrast of *Thematic relation* > *Taxonomic relation*. **B)** These clusters overlapped with the default mode network (in blue) defined by Yeo et al. (2011; overlap in pink). The maps are fully saturated to emphasize the regions of overlap. **C-D)** The functional connectivity of these regions with the rest of the brain revealed a large-scale brain network commonly associated with regions of the default mode network. All maps were thresholded at $z > 3.1$ ($p < .05$). L = Left hemisphere; R = Right hemisphere; aMTG = anterior middle temporal gyrus.

#### *4.4.3.2. Interaction between Task Knowledge and Word Position*

Next, we examined the interaction between task knowledge (Known Goal vs. Unknown Goal) and word position (Word 1 vs. Word 2). An interaction effect was observed in visual regions, including lingual gyrus, occipital pole, occipital fusiform gyrus, and lateral occipital cortex. To understand the nature of this effect, we extracted parameter estimates for each condition (see Figure 4.6 A). When the goal for semantic retrieval was unknown, this region showed deactivation to the first word and stronger activation to the second word, compared with when the goal was known – the responsiveness of visual cortex to written words was modulated by goal information. The findings are consistent with the gating of visual processing by task knowledge, such that the engagement of visual ‘spoke’ regions is suppressed when the required pattern of retrieval is not yet known, preventing the unfolding of a semantic response which might not be appropriate to the pattern of retrieval required by the task. This visual site was used as a seed region in an analysis of intrinsic connectivity in an independent dataset, revealing high levels of connectivity with other visual regions, moderate connectivity with motor and auditory sites, and low levels of connectivity with angular gyrus and posterior cingulate cortex (see Figure 4.6 B).

**A Activation showing an interaction between Word Position and Task Knowledge**



**B Functional connectivity analysis**

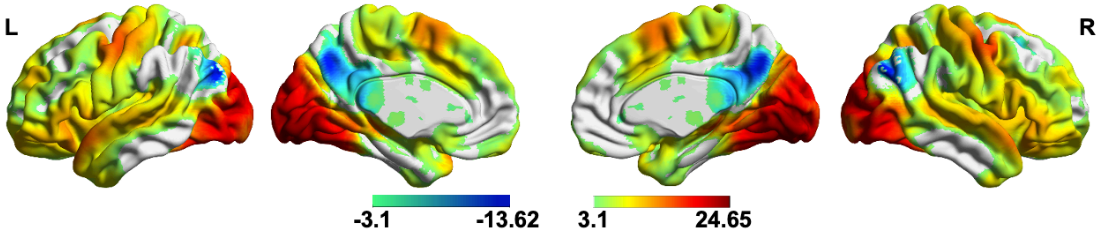


*Figure 4.6. Interaction effects.* **A) Activation showing an interaction between Word Position (Word 1 vs. Word 2) and Task Knowledge (Known Goal vs. Unknown Goal).** The bar charts plot the mean percentage (%) change in the visual cluster for each condition relative to implicit baseline (i.e., the first fixation interval), revealing differences in activity between Known Goal and Unknown Goal at the first and the second words. Error bars depict the standard error of the mean. **B)** The functional connectivity of this region with the rest of the brain revealed a large-scale brain network commonly associated with the processing of visual input. All maps are cluster-corrected with a voxel

inclusion threshold of $z > 3.1$ and family-wise error rate using random field theory set at $p < .05$. L = Left hemisphere; R = Right hemisphere.

### *4.4.3.3. Effects of the strength of semantic relations*

In order to establish if the LIFG cluster that responded to Task Knowledge also responded to a commonly-used manipulation of semantic control demands, in an exploratory analysis, we examined the parametric effect of the strength of the conceptual relationship between the two words, across thematic and taxonomic trials[6]. The whole-brain parametric modelling revealed that word2vec – a measure of the strength of the semantic connection between words – was correlated with activation in right middle frontal gyrus (MFG) when the words were easier to link (i.e., high word2vec score), and with anterior LIFG when the words were harder to link (i.e., low word2vec score; see Figure 4.7 A). We computed a formal conjunction of word2vec modulation effects associated with harder trials and the *Known* > *Unknown* contrast and established that these two independently-derived maps overlapped in anterior LIFG (see Figure 4.7 B). These results indicate that anterior LIFG is involved in both (i) goal-directed semantic retrieval (top-down semantic control) and (ii) the retrieval of weak semantic links between distantly related word pairs, even when there are no specific task instructions and so the semantic information itself must establish which aspects of meaning should be focussed on (bottom-up semantic control). Given that word2vec was not matched between taxonomic and thematic trials, we also extracted the parameter estimates from the LIFG cluster modulated by word2vec, to examine if the effects of this variable were similar across these conditions. Paired sample *t*-tests revealed no significant differences between taxonomic (*Mean* ± *SD* = 120.94 ± 304.34) and thematic trials (*Mean* ± *SD* = 141.88 ± 264.46; $t(30) = -.30$, $p = .77$).

To investigate the intrinsic connectivity of these regions at rest, we seeded them in an independent dataset. Right MFG showed connectivity to default mode network regions that typically

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[6] Follow-up analyses contrasting separate estimates of word2vec effects for thematic and taxonomic trials, and for known and unknown trials, revealed no clusters showing a stronger BOLD response for semantically-distant items.

show a stronger response during more automatic memory retrieval (Philippi, Tranel, Duff, & Rudrauf, 2014; Spreng et al., 2009), including medial and inferolateral temporal regions, middle frontal gyrus, medial prefrontal cortex, angular gyrus and posterior cingulate cortex (red regions in Figure 4.7 C). In contrast, anterior LIFG showed stronger intrinsic connectivity with regions in the semantic control network, implicated in shaping semantic retrieval when dominant aspects of meaning are not suited to the current goal or context (Chiou et al., 2018; Noonan et al., 2013; Whitney et al., 2010); these sites included inferior frontal gyrus, posterior middle temporal gyrus, anterior cingulate cortex, and dorsal angular gyrus (red regions in Figure 4.7 D), alongside anterior temporal lobe and primary visual areas.

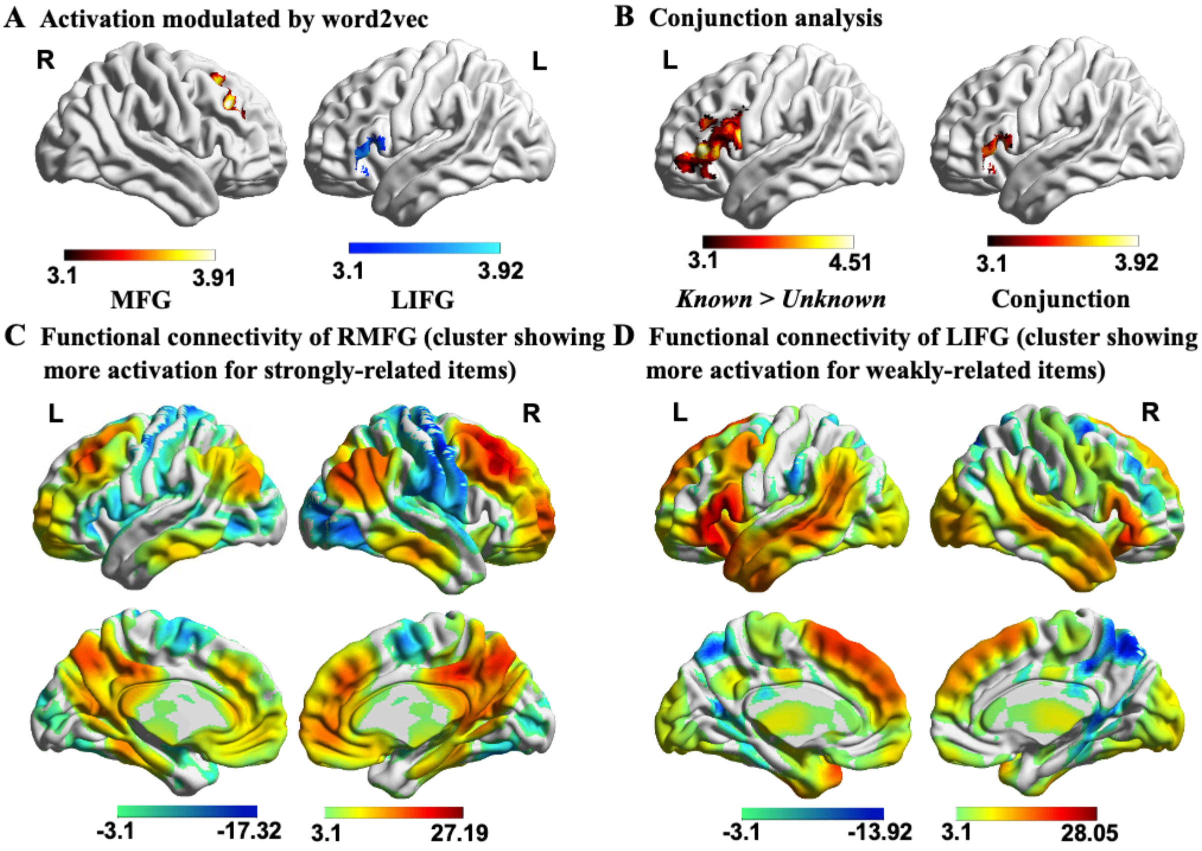

*Figure 4.7.* **Brain activation modulated by semantic distance between words (measured by word2vec). A)** Right MFG in red showed stronger responses to the word pairs with higher word2vec values, while anterior LIFG in blue showed greater activation for the word pairs with lower word2vec values. **B)** The anterior LIFG site which is sensitive to word2vec fully overlapped with the LIFG cluster identified in the contrast *Known Goal* > *Unknown Goal*, with this conjunction identified using FSL's ‘easythresh_conj’ tool. **C-D)** The functional connectivity of right MFG and anterior LIFG (identified

from the parametric effects of word2vec) with the rest of the brain. These analyses revealed large-scale brain networks associated with the default mode network and semantic control network, respectively. All maps are cluster corrected at a threshold of $z > 3.1$ ($p < .05$). LIFG = Left inferior frontal gyrus; RMFG = Right middle frontal gyrus; L = Left hemisphere; R = Right hemisphere.

### *4.4.4. Multivariate pattern analysis*

Next, we investigated whether the pattern of activation across voxels within the semantic control network (Noonan et al., 2013) maintained information about the type of semantic information to be retrieved. Specifically, we examined whether regions within this network could discriminate between taxonomic and thematic trials when the goal for retrieval was known. We predicted that brain regions supporting proactive aspects of semantic control should be able to distinguish the type of semantic relation being probed even during the presentation of the first word, before a specific taxonomic or thematic link was presented[7]. Consequently, we focussed this analysis on the neural response to the first word in the pair. The classification analysis revealed a cluster within LIFG that could decode taxonomic and thematic relations when the goal was known (decoding accuracy: *Mean* ± *SD* = 60 ± 10 %, FWE-corrected $p < .05$; see Figure 4.8 A). We performed an additional MVPA analysis examining the classification of taxonomic and thematic relations when the goal was *not* known in advance, and found no significant effects. This provides a useful control analysis, as no classification effects are expected under these circumstances, when there is no known goal to maintain. The LIFG site able to classify current goal showed high intrinsic connectivity with other areas of the semantic control network, implicated in shaping semantic retrieval (Chiou et al., 2018; Noonan et al., 2013; Whitney et al., 2010), including posterior middle temporal gyrus, dorsal angular gyrus, and anterior cingulate/pre-supplementary motor area (red regions in Figure 4.8 B).

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[7] We also examined the distinction between Known and Unknown trials. We could distinguish these conditions within middle frontal gyrus (6 voxels) and LIFG (1 voxel), overlapping with the Known Thematic vs. Known Taxonomic classification effect.

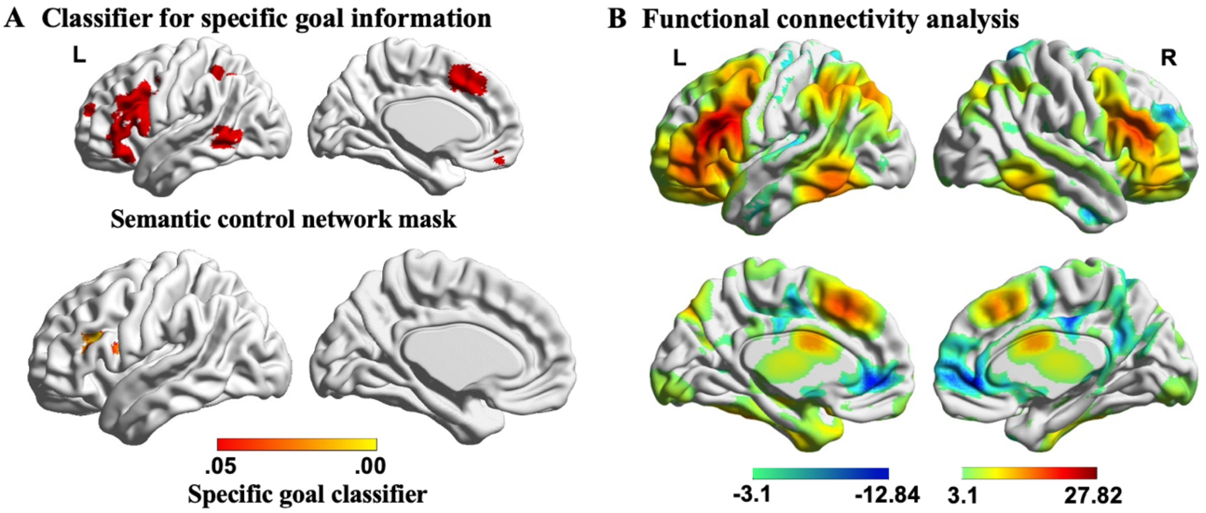


***Figure 4.8.*** **A)** Semantic control network which supports semantic control, used as mask for classification analysis, in the upper left panel. Results of group-level searchlight analysis for specific goal classification shown in the bottom left panel (*Known Taxonomic* vs. *Known Thematic* at the first word; FWE-corrected $p < .05$). Colour bar indicates $p$ value. **B)** The functional connectivity of this region with the rest of the brain revealed a large-scale brain network commonly associated with the regions of semantic control network. L = Left hemisphere; R = Right hemisphere.

#### *4.4.5. Additional analysis to characterise effects of control demands in "Hub" and "Spoke" regions*

The findings so far suggest that an interaction between LIFG and visual cortex may underpin proactive semantic control. In the final analysis, we used an ROI approach to check for further effects of theoretical significance, to guard against Type II errors. We examined both clusters that emerged from the main analysis for additional effects of interest, and spherical ROIs defined according to meta-analyses (for hub sites) and atlases (for spoke sites) for effects that may have been missed in whole-brain analyses.

First, we checked for any potential effects of top-down and bottom-up control demands in clusters found to be sensitive to the type of semantic relation. Next, we report results for several putative heteromodal hub sites (i.e., lateral ATL, ventral ATL, and left AG; see Figure 4.9 A) to establish whether brain regions linked to heteromodal conceptual representation can show effects of control demands similar to those seen in visual cortex, or if the effects of top-down control are restricted to 'spoke' regions in this dataset. Then, we examined whether the cluster in visual cortex that showed an interaction between Task Knowledge and Word Position in the whole-brain analysis was also influenced by bottom-up control demands (word2vec), to establish if this cluster was specifically sensitive to prior knowledge of goals for semantic retrieval, or more generally supported semantic control processes. Finally, we examined additional spoke sites (primary visual/auditory/motor cortex; see Figure 4.9 B) to establish if there was any evidence of further interactions between Task Knowledge and Word Position, beyond visual cortex. These analyses established whether effects of top-down control are restricted to visual regions in our data.

#### *4.4.5.1. Heteromodal hub sites*

First, we considered whether there were effects of semantic control in the left aMTG and hippocampus clusters showing effects of semantic relation in the whole-brain analysis. Uncorrected one-sample *t*-tests suggested that neither left aMTG or hippocampus were sensitive to control demands. In these hub regions, there was no effect of Task Knowledge (aMTG: *Mean* ± *SD* = .005 ± .08, $t(30) < 1$; Hippocampus: *Mean* ± *SD* = .003 ± .07, $t(30) < 1$), no interaction between Task Knowledge and Word Position (aMTG: *Mean* ± *SD* = -.007 ± .07, $t(30) < 1$; Hippocampus: *Mean* ± *SD* = .01 ± .06, $t(30) < 1$) and no significant effect of strength of semantic relation (i.e. word2vec; aMTG: *Mean* ± *SD* = .03 ± .11, $t(30) = 1.28$, $p = .21$; Hippocampus: *Mean* ± *SD* = -.05 ± .12, $t(30) = -2.07$, $p = .048$), although this latter effect was significant for the hippocampus.

Next, we examined spherical ROIs centred on heteromodal hub sites defined by the literature. We performed a 2 (Word 1 vs. Word 2) by 2 (Known Goal vs. Unknown Goal) by 2 (Taxonomic vs. Thematic) repeated-measures ANOVA for each hub site, revealing that the main effect of Semantic Relation was significant for both ventral ATL ($F(1,30) = 12.46$, $p = .001$, $\eta_p^2 = .29$) and lateral ATL ($F(1,30) = 7.09$, $p = .012$, $\eta_p^2 = .19$), with thematic trials eliciting greater activation relative to taxonomic trials. This effect was not significant in left AG ($F(1,30) = 2.60$, $p = .12$, $\eta_p^2 = .08$). The interaction effect between Task Knowledge and Word Position was not significant for any of the hub sites (ventral ATL: $F(1,30) = .08$, $p = .78$, $\eta_p^2 = .003$; lateral ATL: $F(1,30) = .37$, $p = .55$, $\eta_p^2 = .01$; left AG: $F(1,30)$

= 1.45, $p$ = .24, $\eta_p^2$ = .05). In addition, we found a significant interaction effect between Semantic Relation and Task Knowledge in left AG, $F(1,30) = 5.92$, $p = .021$, $\eta_p^2 = .17$. Tests of simple effects revealed that this region showed a stronger response to thematic trials relative to taxonomic trials when the goal was known, $F(1,30) = 6.53$, $p = .016$, $\eta_p^2 = .18$, while the activation in this region was comparable between these conditions when the goal was unknown, $F(1,30) = .013$, $p = .91$, $\eta_p^2 < .001$. These results are presented in Figure 4.9 A.

#### ***4.4.5.2. Unimodal spoke sites***

The visual cortex cluster defined by the interaction term between Word Position and Task Knowledge showed no effects of word2vec in a one-sample $t$-test (mean signal change: $Mean \pm SD$ = .02 ± .13, $t(30) < 1$), indicating that this visual area is not strongly modulated by bottom-up control demands.

For the spoke regions, a series of 2 (Word 1 vs. Word 2) by 2 (Known Goal vs. Unknown Goal) by 2 (Taxonomic vs. Thematic) repeated-measures ANOVAs at each site revealed that the interaction effect between Word Position and Task Knowledge was only significant in visual cortex, $F(1,30) = 11.93$, $p = .002$, $\eta_p^2 = .29$. There was no effect for auditory cortex, $F(1,30) = .04$, $p = .84$, $\eta_p^2 = .001$, or motor cortex, $F(1,30) = .10$, $p = .76$, $\eta_p^2 = .003$. This interaction effect was also significantly greater in the visual cortex than that in the other two spokes as indicated by a significant three-way interaction effect between Spoke, Word Position, and Task Knowledge, $F(2,60) = 9.17$, $p < .001$, $\eta_p^2 = .23$. The results are summarized in Figure 4.9 B.

Taken together, these results suggest that heteromodal hub regions, especially in ATL, are sensitive to the type of semantic relation, while semantic goal information primarily modulates activation in visual cortex.

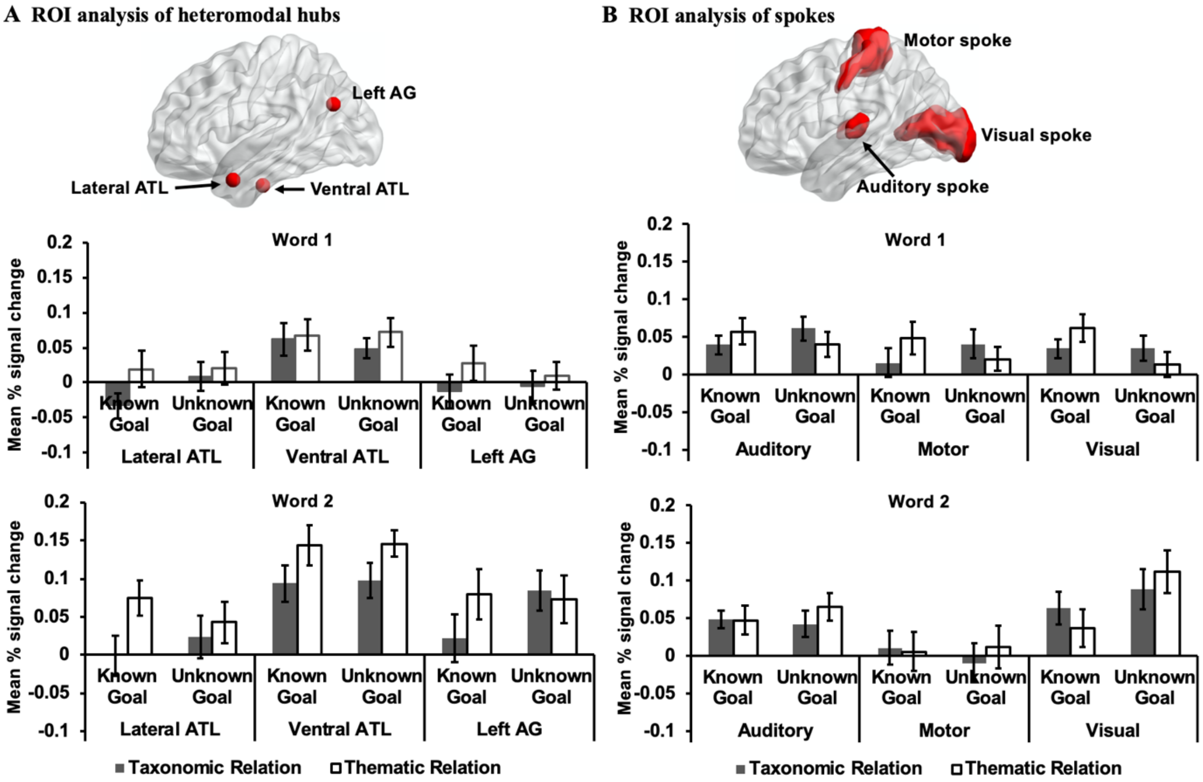


*Figure 4.9.* **A) ROI analysis of heteromodal hubs and B) spokes.** The bar charts plot the mean percentage (%) change extracted from these ROIs for each experimental condition compared to implicit baseline (i.e., the first fixation interval) at the first and the second words. Error bars depict the standard error of the mean. ATL = anterior temporal lobes; AG = angular gyrus.

## 4.5. Discussion

We examined how control is applied to conceptual representations within the hub and spoke framework. The Controlled Semantic Cognition account (Lambon Ralph et al., 2017) proposes that concepts emerge from interaction of a heteromodal hub in ATL with modality-specific ‘spoke’ regions such as visual cortex. Consequently, semantic control processes can be thought of as biasing activation in the hub and/or spoke regions. A key semantic control site, LIFG, showed greater activation when participants knew what aspect of semantic knowledge they should retrieve in advance (top-down control), and also when they identified links between weakly-related words (bottom-up control in the absence of a goal). MVPA analysis revealed that LIFG could classify specific goal information related to different semantic relationships (i.e., taxonomic and thematic relations) during the presentation of the first word in the pair (and therefore before the association indicated by the words could be retrieved). Heteromodal hub sites linked to memory representation were also sensitive to the type of semantic relationship but did not show an effect of control demands. In addition, goal information modulated the activation of visual cortex, in a way that suggested task knowledge could gate the recruitment of visual 'spoke' regions. When the goal was unknown, and therefore extensive semantic retrieval to the first item was of little benefit to task performance (and potentially a hindrance), there was deactivation to the first word and strong activation to the second word. When the goal was known in advance, visual cortex showed an increased response to the first word, while the response to the second word was greatly reduced. These findings are consistent with the view that LIFG proactively controls semantic retrieval to written words based on current goals, and the consequences of this top-down control manipulation can be seen in visual regions. In this paradigm, semantic control processes appear to be applied to spoke and not hub representations. A computational model of top-down semantic control recently made this prediction: efficient semantic cognition was achieved in a model in which control processes were applied to peripheral (e.g., unimodal spoke regions) rather than deep layers (e.g., heteromodal semantic regions) of a semantic network (Jackson et al., 2019).

Our results confirmed that LIFG supports both goal-directed semantic retrieval (i.e. top-down control) and stimuli-driven controlled retrieval processes (i.e. bottom-up control), since we found overlapping responses for the proactive application of task knowledge and for the retrieval of weak semantic relationships (as assessed by word2vec). LIFG is widely found to be involved in the controlled retrieval of semantic knowledge across paradigms – including bottom-up manipulations of control demands, for example, weak vs. strong associations and trials with strong vs. weak distractors (Badre et al., 2005; Krieger-Redwood, Teige, Davey, Hymers, & Jefferies, 2015; Noonan et al., 2013; Thompson-Schill et al., 1997; Wagner et al., 2001; Whitney et al., 2010), and top-down manipulations that instruct participants to focus on specific features, such as colour, shape or size, as opposed to global semantic relationships (Badre et al., 2005; Chiou et al., 2018; Davey et al., 2016). However, the feature and global matching tasks used in previous studies required retrieval to be focussed on different types of information. We separated the capacity for proactive control from the type of semantic retrieval required by the task, by informing participants about the nature of the semantic relationship on half of the trials. Our results confirm that LIFG shapes semantic retrieval in a top-down way, even when there is no difference in difficulty between trials that can be controlled and trials that lack prior task knowledge.

LIFG is not functionally homogeneous – different subdivisions within LIFG are thought to have dissociable functions in supporting controlled semantic retrieval: specifically, anterior-to-mid LIFG has been implicated in "controlled retrieval", needed when the subset of knowledge required by a task cannot be brought to the fore through automatic retrieval processes; in contrast, posterior LIFG is thought to support selection, by resolving competition among active representations (Badre et al., 2005; Badre & Wagner, 2007). Our task manipulations were not designed to investigate functional distinctions within LIFG, and differences in the locations of responses we observed in this region might result from differences in methodology. However, our findings are broadly consistent with previous studies: activation in anterior LIFG was modulated by semantic distance, with increased engagement for weakly-linked word pairs, which is similar to the controlled retrieval induced by the contrast of weak and strong associations used by Badre et al. (2005), while MVPA revealed that dorsal and posterior portions of LIFG contained information about the semantic relationship needed on the current trial. This site might support the selection of goal-relevant information by prioritising particular aspects of conceptual knowledge during retrieval. Since the connections of taxonomic and thematic relations are thought to be based on different organisational principles (Estes et al., 2011; Rogers & McClelland, 2004), with taxonomic relations relying on perceptual similarity, and thematic relations activating visuo-motor regions involved in action and space processing (Kalénine et al., 2009), LIFG might shape semantic retrieval to suit the task by influencing the kind of information that is prioritised. The ability of posterior regions in LIFG to decode the distinction between thematic and taxonomic trials even at the first word (before taxonomic and thematic relations were actually presented) suggests that participants may have been able to selectively focus their retrieval on task-relevant features.

Our key finding was that visual processing was modulated by semantic goal information to support flexible semantic retrieval. Visual cortex is critical to our ability to recognise objects or words

(Goodale & Milner, 1992; Patterson et al., 2007) – visual cortex can gate meaning retrieval, since word and object recognition have both been shown to involve interactive-activation between the heteromodal hub in ATL and visual 'spoke' representations (Carreiras et al., 2014; Clarke & Tyler, 2014; Nobre et al., 1994; Pammer et al., 2004; Tyler et al., 2013). Visual cortex also plays a role in representing the perceptual features of concepts, and consequently allows the fully instantiated retrieval of a concept through visual imagery (Bannert & Bartels, 2013; Bergmann, Genç, Kohler, Singer, & Pearson, 2016; Borghesani et al., 2016; Dijkstra, Zeidman, Ondobaka, van Gerven, & Friston, 2017; Kan, Barsalou, Olseth Solomon, Minor, & Thompson-Schill, 2003; Mellet, Tzourio, Denis, & Mazoyer, 1998; Murphy, Rueschemeyer, et al., 2019; Peelen & Caramazza, 2012). These observations give rise to at least two potential explanations for the modulation of visual activation according to task knowledge. (1) First, semantic control processes might act to gate the extent to which sensory inputs can drive conceptual retrieval. As visual cortex allows access to meaning for visually-presented inputs, the Task Knowledge by Word Position interaction we observed could reflect modulation of input processing, with suppression of feed-forward visual processing preventing patterns of semantic retrieval that might be irrelevant to the task, or even compete with the required conceptual knowledge once this is known. For example, in the trial ROPE – BOAT, rich conceptual retrieval to the item ROPE, focussed on similarity to the items WOOL and STRING, could be disadvantageous in efficiently retrieving the link to the subsequent word. (2) Alternatively, semantic control might modulate the richness of semantic retrieval, such that before it is possible to know what to focus on, sensory-motor features pertaining to possible relationships are not instantiated and conceptual retrieval remains relatively abstract. This might facilitate later retrieval by reducing the need to inhibit specific irrelevant features. Imagery might be expected to be particularly important for taxonomic relations (which are largely defined in terms of shared physical features) – but we did not observe differences between taxonomic and thematic trials in the effect of Task Knowledge in the current dataset. Imagery might also be expected to affect multiple spoke regions in a similar way, while input gating should be sensitive to the input modality being used in a task, and there was no discernible modulation of auditory/motor spoke regions in our data. The key differences between these accounts concern the timing and direction of connectivity between heteromodal ATL and visual cortex, and consequently, they are not readily separated using our fMRI data. Future research employing magnetoencephalography could potentially establish *how* visual responses are modulated by task knowledge.

Intriguingly, we found deactivation in visual cortex to the first word (relative to the implicit baseline), followed by increased activation to the second word in the pair when the type of semantic retrieval needed on the trial was not known in advance. Similar BOLD suppression in visual cortex has been found in studies of spatial attention, with lateralised BOLD deactivation associated with lateralised attention (Gouws et al., 2014). Deactivation of visual cortex during visual imagery correlates with better decoding of the imagined content (Vetter, Smith, & Muckli, 2014). In the current study, when the goal was unknown, deactivation of visual cortex may have supported the maintenance of minimal conceptual knowledge about the first word before the semantic retrieval demands of the task became clear. This surprising observation of BOLD deactivation in response to visual input during semantic retrieval adds to the existing literature by showing that the suppression of visual cortex is sensitive to task knowledge.

Overall, the results of the current study suggest that flexible semantic retrieval is supported by dynamic interactions between goal information within brain regions implicated in semantic control (LIFG) and primary visual areas. Our findings are consistent with Chiou et al. (2018) who found that LIFG showed different patterns of connectivity across different tasks – with stronger connectivity to semantic sites during easier global semantic judgements and to visual sites during harder visual feature matching decisions. The current findings advance this understanding by demonstrating that visual cortex supports *proactive* forms of semantic control, even when the task was unchanged between conditions (i.e. our participants performed semantic relatedness judgements on every trial) and even when difficulty was matched across conditions. One possibility is that in both the current study, and in Chiou et al.'s task, an explicit instruction to focus on particular aspects of knowledge was achieved by modulating processing within the visual 'spoke' system, consequently altering the dynamic interaction between hub and spokes.

In contrast to visual cortex, heteromodal ATL itself did not show any effects of the ability to proactively control retrieval. The hub and spoke architecture anticipates that conceptual representations within the heteromodal hub are updated slowly – and since we retain an understanding of conceptual commonalities across tasks and contexts with differing control demands, control processes might not be integrated with the most heteromodal parts of the semantic system. Of course, the nature of the task or the modality of presentation might influence the way in which semantic retrieval is controlled. Since we used visually presented words, input gating in this experiment would be expected to be primarily visual. Moreover, the form of top-down control we employed might have made it relatively easy to shape conceptual retrieval by constraining the visual spokes: participants knew what kinds of visual features were pertinent in known goal trials, and could control the timing of semantic retrieval. In other manipulations of semantic control demands, such as during the retrieval of weak semantic relationships, there are no explicit goals for retrieval provided by the task instructions, and consequently semantic control might be supported by different processes. We found no evidence that semantic distance (as measured by word2vec) modulated the visual region that responded to top-down control, even though this manipulation elicited a significant response in LIFG. Consequently, the question of how semantic control is achieved in these circumstances remains unresolved.

We found that brain regions linked to heteromodal aspects of long-term memory were sensitive to the nature of the semantic relationship, showing a stronger response overall to thematic than taxonomic relations, rather than effects of control demands (effects of task knowledge and semantic relatedness). Although the hippocampus is not commonly thought of as a semantic region, it often shows sensitivity to semantic variables in fMRI studies (Addis & McAndrews, 2006; Hoscheidt, Nadel, Payne, & Ryan, 2010; Ryan, Cox, Hayes, & Nadel, 2008). Moreover, the hippocampus might support global scene processing (Burgess, Maguire, & O'Keefe, 2002; Nielson, Smith, Sreekumar, Dennis, & Sederberg, 2015), relevant to thematic knowledge (Lin & Murphy, 2001). The lateral ATL site identified in our whole-brain analysis is anatomically distinct from the ventral ATL site which is thought to be the centre-point of the hub in the hub-and-spoke framework (Lambon Ralph et al., 2017). However, both these ATL sites can classify the meaning of words but not their presentation modality (Murphy et al., 2017; Visser et al., 2010).

Our findings are at odds with the claim that ATL is a taxonomic hub (Geng & Schnur, 2016; Lewis et al., 2015; Schwartz et al., 2011), although consistent with some previous studies; for example, Sass et al. (2009) found stronger left lateral temporal activation for thematically-related words using a similar paradigm to ours (see also Peelen & Caramazza, 2012). Both lateral ATL and hippocampus are allied with the default mode network as shown by their functional connectivity profile, and regions within this network are typically sensitive to more automatic aspects of semantic retrieval (Davey, Cornelissen, et al., 2015; Spreng et al., 2009; Teige et al., 2019). For example, ATL has been found to show a stronger response to easier trials when the associative strength between word pairs is higher (Teige et al., 2019). In opposition to this commonly-observed effect, we found stronger responses in lateral ATL and hippocampus for the more difficult thematic condition (associated with poorer behavioural performance and lower word2vec scores). Consequently, differences in difficulty across taxonomic and thematic trials in the current experiment seem unlikely to explain the effects of semantic relation that we observed. While we are not able to fully explain this pattern, the thematic word pairs might have elicited more specific semantic retrieval: for example, the trial ROPE – BOAT (thematic pair) might encourage participants to think about specific types of boat, while the items BUGGY – BOAT (taxonomic pair) share only general features of vehicles, such as movement and being ridden. ATL is thought to show a stronger response to more specific patterns of semantic retrieval (Patterson et al., 2007; Rogers et al., 2006).

Several limitations of our study should be mentioned. First, our decision to exclude unrelated word pairs and incorrect trials from our main task regressors means that the contrast of task over implicit baseline will not identify *all* semantic activation during the task. Instead, our analysis is optimised to characterise the effects of task knowledge on semantic retrieval. Furthermore, since the word2vec variable was not originally considered in our design, these values were not well-matched between different types of semantic relationships. This difference in difficulty is also reflected by behavioural performance, with lower accuracy and slower responses to thematic trials compared to taxonomic trials. Our motivation for an exploratory analysis of word2vec was to establish if the same regions within LIFG respond to task knowledge and semantic relatedness, since this latter variable has been shown many times to modulate responses within the semantic control network (e.g., Badre et al., 2005; Teige et al., 2019; Wagner et al., 2001). In this way, we could establish if a common region supports goal-directed semantic retrieval and stimuli-driven controlled retrieval. It also should be noted that the current investigation cannot provide evidence of a causal link between LIFG and visual responsiveness; future studies employing inhibitory transcranial magnetic stimulation may be able to provide this evidence.

## 4.6. Conclusion

In conclusion, our study reveals that LIFG in the semantic control network proactively constrains semantic retrieval based on current goals (provided in a top-down fashion by the task instructions), by modulating the responsiveness of visual 'spoke' regions. As such, this study starts to address the question of how semantic control processes are applied to conceptual representations to shape retrieval to suit the circumstances – with control applied to spoke as opposed to hub regions within the hub and spoke model of conceptual representation.

# Chapter 5: Thesis Summary and Discussion

## 5.1. Summary of research questions

Semantic cognition plays a critical role in supporting our flexible behaviour and thoughts across diverse and novel circumstances (Estefan et al., 2019; Jefferies, 2013; Lambon Ralph et al., 2017; Patterson et al., 2007; Smallwood et al., 2016; Svoboda et al., 2006). This thesis investigated the neural basis of flexible semantic retrieval, with a focus on the contributions of large-scale networks underpinning semantic cognition. The empirical work examined distinct modes of semantic retrieval – namely perceptually-coupled situations driven by external events and perceptually-decoupled retrieval (i.e., internally-generated thoughts that are independent from the environment). The thesis also considered different mechanisms that underpin semantic flexibility: the information to focus on was either specified in advance, allowing goal-directed retrieval, or it was determined by features of the concepts themselves.

Most previous research has focussed on *where* semantic knowledge is represented in the brain (Binder & Desai, 2011; Chao et al., 1999; Hauk et al., 2004; Lambon Ralph et al., 2017; Patterson et al., 2007; Pobric et al., 2010a, 2010b). Little is known about *how* stable semantic representations in long-term memory, associated with heteromodal regions such as the anterior temporal lobes (ATL) and modality-specific spokes, support different patterns of semantic retrieval flexibly to suit the circumstances. This thesis addresses this gap in understanding.

The work was motivated by two potential mechanisms proposed to support flexible semantic retrieval. One hypothesis is that ***different patterns of functional connectivity from regions implicated in semantic cognition are pivotal in supporting our diverse behaviour and thoughts.*** Default mode network (DMN) is thought to be a heteromodal network that is relevant to long-term memory (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Humphreys et al., 2015; Margulies et al., 2016). The function of this network is not homogeneous (Andrews-Hanna, Reidler, Huang, et al., 2010; Andrews-Hanna, Smallwood, et al., 2014): the lateral temporal DMN subsystem and medial temporal DMN subsystem are implicated in semantic memory and episodic memory respectively, while the core DMN regions act as functional hubs allowing information to be integrated and transferred across subsystems. It has been shown that the lateral temporal DMN regions, implicated in semantic representations, connect to both primary visual cortex and other DMN regions at rest (Jackson et al., 2016; Murphy et al., 2017). These different patterns of functional connectivity from the lateral temporal regions (e.g., ATL) might serve different modes of conceptual processing, with semantic regions coupling to input systems (e.g., visual areas) to make sense of incoming perceptual information while coupling at other times to other DMN regions (e.g., medial temporal regions) linked to internally-generated thoughts. Another possibility is that ***semantic retrieval may flexibly recruit different networks in different modes of semantic retrieval.*** Contemporary accounts have proposed that semantic cognition relies upon two principal interacting neural systems, the semantic representation system and control processes (Lambon Ralph et al., 2017). Prior research shows the importance of distributed sites within the semantic control network in shaping semantic retrieval (Badre et al., 2005; Badre & Wagner, 2002; Davey, Cornelissen, et al., 2015; Noonan et al., 2013; Thompson-Schill et al., 1997; Thompson et al., 2018). One recent study provided some evidence of the interaction between these two systems by showing that a control site in left inferior frontal gyrus could connect with both the spoke and hub site to retrieve semantic information required by a task (Chiou et al., 2018). Therefore, this dynamic interaction between control processes and long-term semantic representations according to goal or context information might be key to the flexibility of semantic cognition. In this way, the networks implicated in control (i.e., the semantic control network and multiple-demand network) and semantic representation (e.g., heteromodal semantic regions within the default mode network or spoke regions) might be flexibly recruited in different modes of semantic retrieval, such as when the semantic retrieval is directed by a specific goal or driven by the presented stimuli. In light of these possibilities, the specific aims of this thesis were:

- To explore if distinct patterns of functional connectivity from common regions implicated in semantic cognition support perceptually-coupled and decoupled mental states. Using functional connectivity analysis, Chapter 2 explored whether different patterns of functional connectivity from semantic sites at rest could predict individual differences in reading performance and off-task thoughts while reading. Using psychophysiological interaction analysis (PPI analysis), Chapter 3 explored if different patterns of task-based functional coupling from semantic regions could support reading comprehension and autobiographical memory recall, given that both of these tasks involve semantic information.

- To further explore the neurocognitive architecture underpinning the flexibility of semantic cognition in supporting perceptually-coupled and decoupled retrieval. Chapter 3 used task-based fMRI to investigate the contributions of DMN subsystems to these different aspects of conceptual processing. Chapter 3 identified both activation and deactivation in reading and memory recall tasks relative to a letter string baseline, and compared them along the principal gradient of functional connectivity which captures the separation between heteromodal DMN regions and sensorimotor regions described by Margulies et al. (2016). The identification of similarities and differences in brain activation elicited by tasks allowed us to characterise the common activation in regions within lateral temporal DMN subsystem and distinct activation in core DMN subsystem. Also, this study manipulated potential conflict between these tasks (e.g., recalling personal memory during the presentation of meaningful sentences) and collected task focus ratings. Both of these manipulations could establish (i) if DMN subsystems related to semantic cognition and memory recall are still activated even when this response is task-irrelevant, and (ii) whether DMN regions always deactivate when people are more focussed on a task or if this pattern varies across externally- and internally-oriented tasks.
- To examine how we tailor semantic retrieval to suit the task demands in a top-down way, according to task knowledge, Chapter 4 (i) identified the control regions that play a role in *proactive* semantic control when people knew what aspect of conceptual knowledge (taxonomic knowledge vs. thematic knowledge) to retrieve in advance, and (ii) examined whether this task knowledge would modulate semantic responses within the heteromodal "hub" in anterior temporal lobes (ATL) or alternatively unimodal "spoke" regions (e.g., visual cortex), which are thought to interact to compute concepts.

## 5.2. Main findings

### *5.2.1. Chapter 2*

This study examined the association between diverse patterns of connectivity and individual differences in comprehension and mind-wandering while reading. In this study, we used a combination of task-based fMRI (i.e., responses to a semantic localiser task, in which meaningful sentences or nonwords were presented visually one at a time) and resting-state fMRI in the same cohort. Individual variations in reading comprehension and off-task thoughts while reading were assessed outside the scanner. Behaviourally, there was a strong negative correlation between these measures: people who mind-wandered more often during reading comprehended the text less well. In sentence localiser task, we found people with good comprehension showed stronger activation in middle temporal gyrus (MTG) for meaningless orthographic inputs. This activation intersected default mode network, dorsal attention, and frontoparietal networks. Functional connectivity seeding from voxels falling within each network revealed that the intrinsic connectivity of this DMN region at rest (i) had a pattern of relatively weak connectivity with visual regions in participants who reported more frequent mind-wandering during reading, and (ii) showed greater connectivity with another region in DMN, in medial prefrontal cortex, for individuals with better comprehension.

These findings show that DMN connectivity is associated with good as well as poor comprehension, and that relatively-low level visual processes contribute to higher-order cognitive states. Our individual differences analysis complements task-based studies of comprehension in the ventral visual stream by showing that activation in heteromodal semantic regions is necessary but not sufficient for good comprehension. In people with strong connectivity between MTG and visual cortex, semantic cognition tends to be perceptually-coupled, while perceptually-decoupled semantic retrieval is associated with poor comprehension and frequent mind-wandering. Thus, the opposing roles of DMN in different mental states may reflect flexible connectivity to task-relevant or irrelevant information to supporting reading comprehension or off-task thoughts.

### *5.2.2. Chapter 3*

Having found that individual differences in reading and off-task thoughts were associated with different patterns of intrinsic connectivity from an MTG site within DMN in Chapter 2, the next study performed an online task-based fMRI investigation to further examine the neural basis of different forms of semantic retrieval. Participants were asked to either comprehend sentences presented word-by-word, or recall their generated autobiographical memories. The potential competition between tasks was manipulated by presenting a memory recall cue before the presentation of sentences for comprehension or presenting an irrelevant sentence while recalling personal memories. Task focus ratings were recorded for each reading and memory recall trial. To identify the similarities and differences in task activation, each experimental condition was contrasted with a low-level baseline condition (i.e., passively viewing meaningless letter strings). We also characterised the distributions of each task's activation and deactivation patterns in terms of their positions on the principal gradient of functional connectivity from unimodal to heteromodal cortex described by Margulies et al. (2016). This chapter also characterised the whole-brain activity of conflict effects and the parametric effect of task focus in each task. To understand how different semantic functional networks are flexibly formed to support reading and autobiographical memory recall, PPI analyses examined patterns of functional coupling of common semantic regions identified across tasks. The findings revealed:

a. Relative to a low-level baseline task, both tasks elicited greater activation in lateral temporal cortex and left inferior frontal gyrus, which are associated with semantic cognition and fall within the lateral temporal DMN subsystem.
b. These tasks differed in patterns of deactivation, with reading evoking greater deactivation in the DMN core subsystem, especially in medial prefrontal cortex, precuneus cortex, and posterior cingulate cortex.
c. The DMN subsystems were linked to different task functions: regions within lateral temporal DMN, especially lateral temporal cortex, were strongly activated by reading comprehension while core DMN regions showed greater activation to autobiographical memory recall.

d. Importantly, the activity of DMN varied with the magnitude of how well people focussed on the task, with greater activation in medial temporal and core DMN regions corresponding to more focus on memory recall and greater deactivation in the DMN core during more focussed reading.

e. The lateral temporal DMN region showing common activation could form diverse patterns of functional coupling during different task performance: it strongly coupled with inferior temporal gyrus and visual area when comprehending sentence and showed greater connectivity with DMN cores when recalling personal memories.

These findings suggest that regions within the lateral temporal DMN subsystem, implicated in semantic cognition, can be activated by both external perceptual input and the retrieval of information in an internally-oriented task. Its diverse patterns of functional connectivity with visual areas and other DMN sites support different mental states. Importantly, the core DMN subsystem contributes to on-task states for both perceptually-coupled and decoupled aspects of cognition. The lateral temporal DMN subsystem might be a fundamental component of semantic cognition, supporting both perceptually-coupled and decoupled states through flexible patterns of connectivity to visual cortex and other DMN regions, while the core DMN regions provide functional hubs that are important for supporting memory-based internal thoughts requiring broad integration of diverse information.

### *5.2.3. Chapter 4*

The findings from both Chapter 2 and Chapter 3 provide evidence that the regions implicated in semantic cognition form diverse patterns of functional connectivity to support perceptually-coupled and decoupled aspects of cognition. In particular, these empirical studies highlight the distinct roles of DMN subsystems in supporting these different mental states. The last empirical study examined another possibility - namely that control processes modulate the activation of semantic representations based on task knowledge that enables flexible semantic retrieval. In this study, on half of the trials, participants were told in advance whether to search for a taxonomic or thematic relationship, while on other trials, there were no explicit instructions. The words forming taxonomically and thematically related pairs were presented one at a time, and we examined how the response to the first and second words of the pair changed as a function of the opportunity to engage in top-down semantic control. The key findings were that:

a. Left inferior frontal gyrus (LIFG), largely within the semantic control network, showed greater activation when participants knew the trial type in advance. An overlapping region in anterior LIFG showed a stronger response when the semantic relationship between the items was weaker, suggesting this structure supports both top-down and bottom-up forms of semantic control.
b. Multivariate pattern analysis (MVPA) revealed that the neural response in a posterior part of LIFG reflects goal information related to different conceptual relationships.
c. ATL and hippocampus, that fell within DMN, were sensitive to the type of relationship with greater responses to thematic trials, yet they showed no effect of task knowledge.
d. Instead, top-down control modulated the response in visual cortex: when the goal was unknown, there was greater deactivation to the first word, and greater activation to the second word.

This study revealed that LIFG in the semantic control network proactively constrains semantic retrieval based on current goals, by gating the inputs from visual ‘spoke’ regions. The posterior part of LIFG within the multiple demand network was relevant to the representation of goal information, while the anterior part of LIFG within semantic control network was implicated in “controlled retrieval” required when semantic information could not be brought to mind automatically. This functional dissociation of LIFG is in line with the view of previous studies (Badre et al., 2005; Badre & Wagner, 2007). Notably, this study starts to address the question of how semantic control processes are applied to conceptual representations to shape retrieval to suit the circumstances; our findings suggest that these control processes are primarily applied to spoke as opposed to hub regions within the hub and spoke model of conceptual representation.

## 5.3. Linking data to theory

### *5.3.1. Default mode network (DMN)*

#### *5.3.1.1. DMN supports both perceptually-coupled and decoupled mental states*

An established body of work has shown the involvement of DMN in opposing cognitive states. It contributes to aspects of cognition that are decoupled from the perceptual information in the environment – including autobiographical and episodic memory recollection (Andrews-Hanna, 2012; Buckner et al., 2008; Spreng et al., 2009; Svoboda et al., 2006), spontaneous thoughts (Christoff et al., 2009; Mason et al., 2007; Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011), creativity (Beaty et al., 2014; Kühn et al., 2014) and imagination (Østby et al., 2012), and it also actively supports externally-focused, goal-directed tasks that are driven by perceptual inputs – including semantic processing (Binder et al., 2009; Humphreys et al., 2015; Smallwood et al., 2013), and demanding working memory tasks (Krieger-Redwood et al., 2016; Murphy et al., 2018; Vatansever et al., 2015). The thesis adds evidence showing how DMN supports both perceptually-coupled and decoupled mental states and allows us to reject several accounts of DMN function: (i) the data goes against the historical view that DMN is a "task-negative network", since activation was shown to be positively correlated with task focus in some circumstances (Chapter 3); (ii) we show that DMN is not only involved in perceptually-decoupled tasks; instead the lateral DMN subsystem supports meaning-based tasks that are perceptually-driven as well as decoupled (Chapter 3); (iii) the data show that while there are some functional distinctions within the DMN, parts of the lateral subsystem support *both* perceptually-coupled and decoupled mental states (Chapters 2 and 3). This is in line with findings that DMN regions show echoes of multiple other brain networks in their patterns of intrinsic connectivity, including visual as well as memory systems (Leech et al., 2012; Leech et al., 2011).

The capacity of DMN in supporting these opposing mental states might arise from its topographical organisation. Margulies et al. (2016) described a principal gradient of functional connectivity with regions supporting primary sensory/motor functions at one end and transmodal DMN at the other end. These DMN sites are maximally distant (and equidistant) in both functional and structural space from sensory-motor regions. This location suggests that DMN regions are situated at the top of an information-processing hierarchy, allowing the integration of multiple types of features (Bullmore & Sporns, 2009; Margulies et al., 2016). Such regions are therefore important for supporting episodic and semantic memory, which draw together diverse features from multiple modality-specific regions (Binder et al., 2009; Horner et al., 2015; Lambon Ralph et al., 2017; Schacter & Addis, 2007). When we need to make sense of the perceptual inputs from the external world, access to heteromodal semantic representations in DMN enables us to capture their meaning. When our cognition is perceptually-decoupled, such as when we recall personal memories that include multiple elements, i.e. places, people, and objects that are not in the environment, the distance of DMN from sensorimotor regions might enable processing that is insulated from perceiving and acting. In this way, our cognition can escape from the immediate environment to focus on internally-oriented mental states. In conclusion, the location of DMN at the apex of the principal gradient might allow this system to support both heteromodal yet perceptually coupled states and perceptually-decoupled states, since responses that are independent from primary systems are necessary in both cases.

Importantly, the findings in this thesis also reveal that the DMN contributes to on-task states when cognition is both perceptually-coupled and decoupled (Chapter 3). Previous studies have shown that the DMN becomes inactive when we focus on a specific cognitive task, and often shows reduced activity during demanding or difficult tasks (Gilbert, Bird, Frith, & Burgess, 2012; Leech et al., 2011; Mckiernan, Kaufman, Kucera-Thompson, & Binder, 2003; Raichle et al., 2001; Singh & Fawcett, 2008). Activity of this network, especially midline structures, has been linked to different high-level processes that involved internalized experience, such as self-referential processing (Spreng et al., 2009; Spreng et al., 2010), which frequently occur when our mind wanders during tasks. Nevertheless, the thesis confirms that the DMN is not only involved in off-task states (although activation is reversely correlated with task focus during an externally-focussed task, reading, in core DMN). Instead, greater activation in medial temporal and core DMN regions is linked to better focus on memory recall (Chapter 3).

The activity pattern of DMN in supporting task focus depends on the task context. The findings from Chapter 3 suggest that greater task focus corresponded with a task-specific activity pattern of the core DMN regions, with greater activation for autobiographical memory recall and greater deactivation for reading comprehension. Previous studies have shown that the neural activity pattern in DMN is linked to off-task thought (Konu et al., 2020; Sormaz et al., 2018), for example, increased activation in ventromedial prefrontal cortex is associated with patterns of ongoing thoughts, particularly those with episodic and social features (Konu et al., 2020). The data from this thesis provides more direct evidence for the role of DMN in task focus during internally-oriented mental states. The greater involvement of midline DMN structures in focussed autobiographical memory might reflect the manipulation and integration of retrieved information. By contrast, DMN shows an opposing activity pattern during reading comprehension, which might allow cognition to better focus on perceptually driven semantic processes, since reading mainly involves interaction between the lateral temporal regions (e.g., ATL) and unimodal cortex (e.g., visual spoke; Clarke et al., 2013; Spitsyna et al., 2006).

In addition, the contribution of DMN to task focus might also depend on the DMN sites. It can be seen that the same DMN site can play opposing roles in task focus in different task contexts, like medial prefrontal cortex which showed greater activation during better memory recall and greater deactivation during better reading performance (Chapter 3). However, the same DMN site can also show the same pattern in supporting "on-task" states across tasks: the magnitude of deactivation in right AG showed negative correlation with task focus in both reading and memory recall tasks (Chapter 3). A previous study also found that this region showed deactivation in both semantic and non-semantic task performance (Humphreys et al., 2015), however the current findings revealed that it showed greater activation when recalling personal memories during the presentation of meaningful visual inputs (Chapter 3). This right AG site might act as a multimodal buffer for information that comes from both internal representation and external perceptual inputs, but play a less specialized role in task focus. When cognition is focussed on a specific task state, its deactivation might be critical to shut off the buffering of task-irrelevant inputs during the ongoing task. While the specific roles of these DMN sites in supporting task focus remain speculative, the findings from this thesis suggest that the function of DMN in supporting task focus is distinctive and variable across subnetworks.

***Take home message***: Instead of DMN being "task-negative" or "perceptually-decoupled", the findings from this thesis show that portions of DMN support both perceptually-coupled and decoupled aspects of cognition. Lateral DMN is found to support both external and internal semantic states, which require information integration, while medial DMN supports perceptually-decoupled states. DMN regions can show opposing responses across contexts (e.g., mPFC), or play a common role across tasks (e.g., right AG).

#### ***5.3.1.2. Lateral temporal DMN subsystem***

Contemporary accounts of semantic cognition have suggested that regions within the lateral temporal DMN subsystem play a critical role in heteromodal representation and the retrieval of conceptual knowledge (Badre et al., 2005; Jefferies, 2013; Lambon Ralph et al., 2017; Murphy et al., 2017; Patterson et al., 2007; Visser et al., 2012). It has been proposed that this subnetwork prefers mental activities "*interfacing with*" perceptible events (Chiou et al., 2019). In line with this view, we found lateral temporal DMN regions were activated by meaningful visual inputs (compared with letter strings), even when this visual information was task-irrelevant (Chapter 3). Yet inconsistent with this view, the current findings suggest that the activation in this subnetwork can be elicited by both perceptual inputs and internal task demands (Chapters 2 and 3). This lateral temporal DMN subsystem, associated with semantic cognition, might play a fundamental role in supporting both perceptually-coupled and decoupled mental states that involve access to conceptual knowledge (Estefan et al., 2019; Lambon Ralph et al., 2017; Smallwood et al., 2016; Svoboda et al., 2006). In addition, the lateral temporal sites identified in this thesis (see Figure 5.1) are anatomically distinct from the ventral ATL site thought to be a semantic representation hub in the hub-and-spoke view (Lambon Ralph et al., 2017). However, previous studies have shown that lateral temporal DMN sites, such as anterior MTG, can also integrate features across input modalities and classify the meaning of concepts instead of the modality of presentation, like ventral ATL (Murphy et al., 2017; Visser et al., 2012). The data in this thesis provide evidence for the role these heteromodal semantic sites, that are allied to DMN, in supporting different aspects of cognition.

Furthermore, the current data adds to previous studies by revealing how these different mental states emerge from the same semantic representation system. While previous studies have shown that the lateral temporal cortex can connect to both input modalities and other DMN regions (Binney et al., 2010; Jackson et al., 2016; Murphy et al., 2017; Visser et al., 2012), the current findings further establish the relationship between these different patterns of connectivity with the lateral temporal DMN subsystem and their functional outcomes. The data in Chapters 2 and 3 suggest that the same regions within the lateral temporal DMN subsystem, implicated in semantic cognition, support both internally-oriented and externally-oriented mental states by forming diverse patterns of connectivity with both input systems and other DMN regions. Particularly, functional coupling of the lateral temporal DMN subsystem with the perception systems is critical for us to understand incoming perceptual inputs, since we need to map these perceptual inputs onto their heteromodal meanings stored in long-term memory (Caramazza & Mahon, 2003; Friederici et al., 2003; James et al., 2003; Lambon Ralph et al., 2017). However, this coupling between input and conceptual systems might be critical, but not sufficient, for higher-order cognitive states, since we identified that connectivity within DMN, between MTG and medial prefrontal cortex (mPFC), is also associated with better reading performance. Conversely, it has been argued that decoupling from immediate inputs is necessary for self-generated thoughts since this allows our cognition to escape from the events in the environment (Smallwood, 2013). In line with this view, the current findings showed that a heteromodal semantic region, MTG, was less coupled to primary visual cortex for individuals with frequent off-task thoughts while reading. This functional decoupling of semantic regions from input processes might be a prerequisite for the occurrence and integrity of self-generated thoughts. Moreover, the connectivity of the lateral temporal DMN subsystem with other DMN regions is also essential for supporting the processes of internally-generated thoughts, since the DMN, especially core DMN regions, support perceptually-decoupled states (Andrews-Hanna, Reidler, Huang, et al., 2010; Christoff et al., 2009; Spreng et al., 2009). By forming these distinct patterns of functional networks, semantic cognition can flexibly support both perceptually-coupled and decoupled aspects of cognition. Figure 5.1 summarises the functional connectivity findings of regions within the lateral temporal DMN subsystem across the experimental chapters.

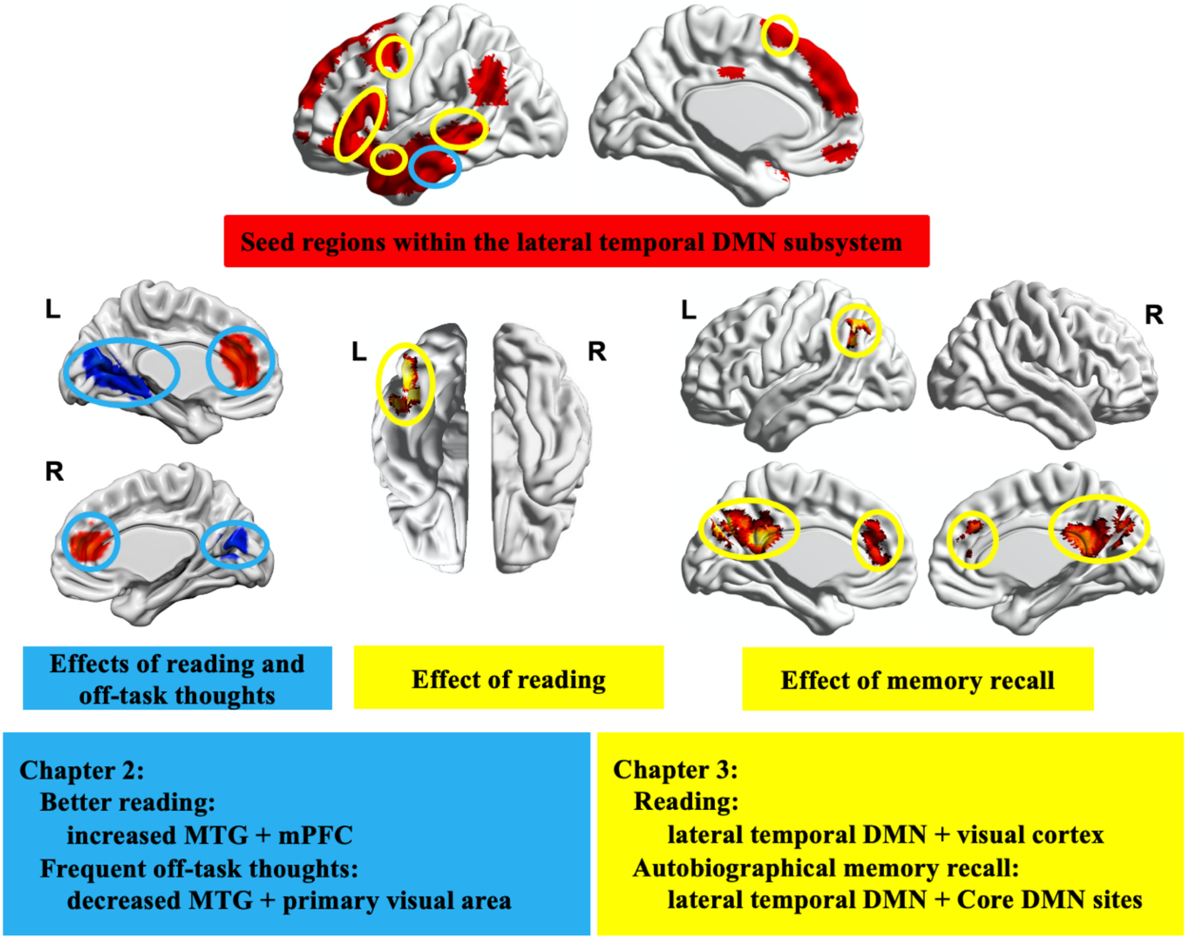


***Figure 5.1.*** Summarised results of functional connectivity seeding from regions within lateral temporal DMN subsystem across the experimental chapters. Functional connectivity results of reading and off-task thoughts from Chapter 2 in blue circle, and functional connectivity results of reading comprehension and autobiographical memory recall from Chapter 3 in yellow circle. DMN = default mode network; MTG = middle temporal gyrus; mPFC = medial prefrontal gyrus; L = left hemisphere; R = right hemisphere.

However, sometimes these opposing mental states can be in competition (Smallwood et al., 2013; Smallwood, McSpadden, et al., 2008) – for example, when you are attempting to perform an externally-oriented task and internally-motivated thoughts occur. These diverse patterns of connectivity from the lateral temporal DMN subsystem might also explain why semantic processing can be both a benefit and a cost to an ongoing task. Take mind-wandering during reading as an example; the negative influence of mind-wandering on reading comprehension is well-documented (Franklin et al., 2011;

Sanders et al., 2017; Smallwood et al., 2013; Smallwood, McSpadden, et al., 2008). Frequent off-task thoughts are linked to stronger functional decoupling between regions within the lateral temporal DMN subsystem and visual system (Chapter 2), while greater functional coupling between lateral temporal and medial temporal/core DMN subsystems is beneficial for memory-based task but detrimental to external engagement (Poerio et al., 2017; Chapter 3). The balance between these two patterns of functional connectivity might influence the extent to which semantic cognition is perceptually-coupled or decoupled to support ongoing tasks. The perceptually-coupled semantic processing supports better understanding of visually-presented texts, while decoupled semantic processing disrupts making sense of external information.

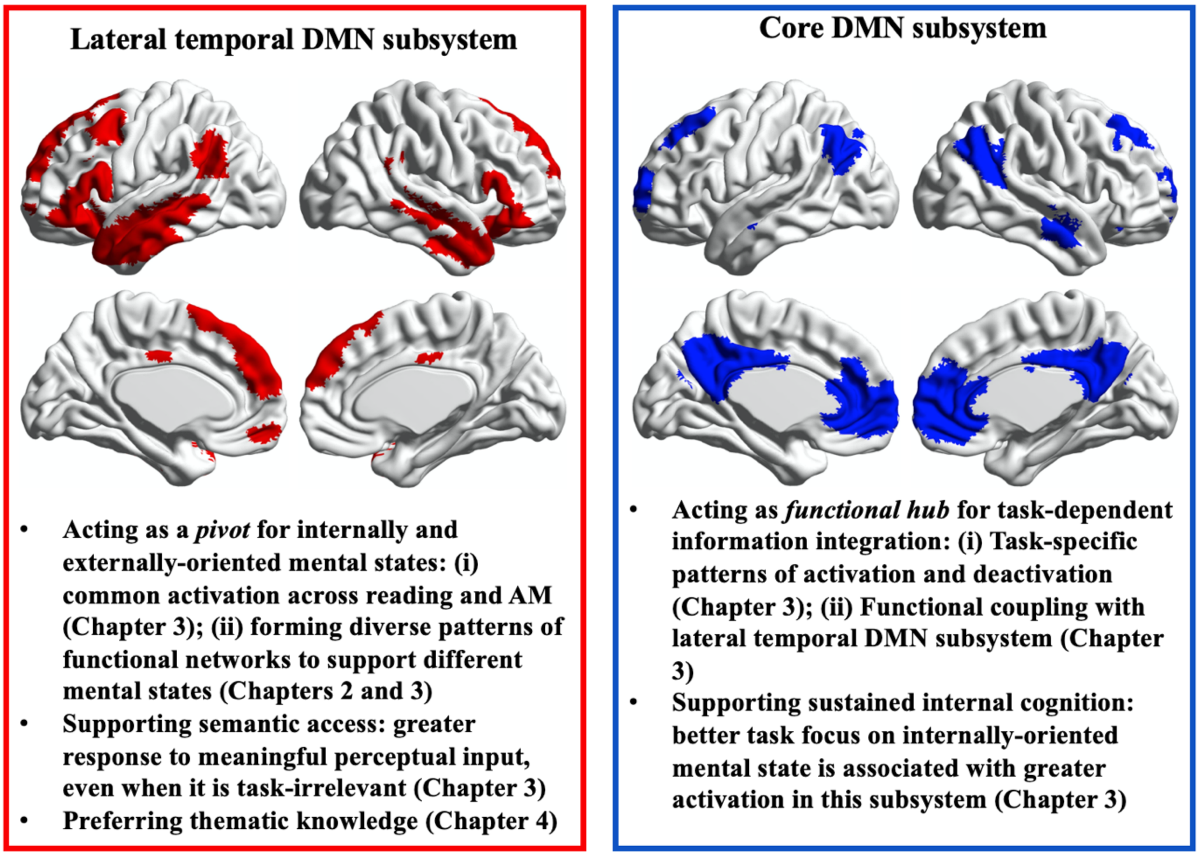
Interestingly, the findings from Chapters 2 and 3 suggest that the functional connectivity between the lateral temporal DMN subsystem and mPFC, another region within DMN, is associated with better reading performance, yet mPFC still deactivates during reading. Smallwood et al. (2013) also found that increasing task focus on reading is associated with stronger functional connectivity between temporal cortex and anterior mPFC. The mPFC is thought to be a functional hub that integrates diverse elements of cognition (Margulies et al., 2016; Rossell et al., 2001; Visser et al., 2012; Zhao et al., 2017). The functional connectivity from mPFC shows wide connections with sensory and motor cortices (Margulies et al., 2007). Despite reading selectively activating regions within the lateral temporal DMN subsystem and deactivating core DMN regions (Chapter 3), the functional connectivity between DMN core and lateral temporal DMN regions might be essential for the integration of semantic information, which allows comprehension of what is being read. This functional coupling between the lateral temporal and core DMN subsystems (including mPFC, within DMN core) is also identified during perceptually-decoupled mental states (Chapter 3). The core DMN regions might play an important role in supporting the integration of semantic information in both aspects of cognition.

***Take home message***: Collectively, results from the first two experimental studies provide converging evidence about the role of the lateral temporal DMN subsystem in flexible semantic cognition. This subsystem, implicated in the representation and retrieval of conceptual knowledge, supports access to heteromodal semantic representations in both perceptually-coupled and decoupled mental states. Furthermore, regions within this subnetwork form diverse patterns of functional connectivity with both input modality and other DMN regions, which allows our semantic cognition to flexibly support different aspects of cognition.

#### ***5.3.1.3. Functional subdivisions of DMN subsystems***

As previously mentioned, DMN consists of multiple subsystems implicated in different aspects of cognition (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Yeo et al., 2011). The findings in this thesis also shed light on functional subdivisions of DMN subsystems. As the *Section 5.3.1.2* mentioned, the lateral temporal DMN subsystem responds to both perceptually-coupled and decoupled mental states (Chapter 3), and can form distinct patterns of functional connectivity to support these mental states (Chapters 2 and 3). During perceptually coupled states, these diverse patterns of functional coupling between semantic regions within this subsystem and unimodal regions can not only support the perceptual-to-meaning mappings (Chapters 2 and 3), but also support the retrieval of particular aspects of conceptual knowledge, such as action or place (Chiou & Lambon Ralph, 2019). Therefore, this lateral temporal DMN subsystem, implicated in semantic cognition, acts as a *pivot* within the semantic system, supporting both the sensory integration and access to heteromodal/particular aspect of conceptual knowledge in different mental states. Particularly, this subsystem might be strongly sensitive to meaningful perceptual inputs appeared in the external environment, even when our attention is focussed on elsewhere. This view is supported by the finding that this subnetwork is still activated by meaningful visual input, even when it is task-irrelevant (Chapter 3). This subnetwork might be able to detect the meaningful external input and allow its access to heteromodal semantic representations. In addition, this thesis work also found this subsystem also shows a preference for thematic knowledge, even though this type of trial is harder than taxonomic decisions (Chapter 2). This is inconsistent with the dual hub account which claims that ATL specifically supports taxonomic knowledge (de Zubicaray et al., 2013; Schwartz et al., 2011). Task difficulty seems unlikely to explain it since regions within this subsystem contribute to link strong associations irrespective of the type of semantic relationship (Lau et al., 2013; Teige et al., 2019; Teige et al., 2018). Instead, it might be that ATL supports both types of semantic relations, in line with previous studies (Jackson et al., 2015; Teige et al., 2019). This preference to thematic knowledge might be explained by the functional role of the DMN since this network is associated with habitual, memory-based, and meaningful aspects of cognition (Chen et al., 2017; Philippi et al., 2014; Spreng et al., 2010). Compared to taxonomic knowledge, the establishment of thematic relations might depend more on our personal experiences particularly when the association is weak, since this type of semantic knowledge is based on the co-occurrence of objects in the same events or episodes (Estes et al., 2011; Mirman & Graziano, 2012a), and consequently elicits greater activation in this network.

Differing from the lateral temporal DMN subsystem, the core DMN subsystem shows a task-specific pattern of activity, with activation during memory recall and deactivation during reading comprehension (Chapter 3). This is in line with a recent study that proposed the core DMN is more perceptually-decoupled (Chiou et al., 2019). These opposing activity patterns within core DMN subsystem might be essential for our capacity to focus on both perceptually-coupled and decoupled aspects of cognition. Moreover, this subsystem also forms distinct patterns of functional connectivity with other DMN subsystems which is associated with both internally and externally-oriented mental states. Not only have previous studies showed functional connectivity between DMN core regions and other DMN regions, including regions associated with episodic and semantic memory, during a wide range of internal-generated mental states (Smallwood et al., 2016; Spreng et al., 2009), but the current results find functional coupling between the core DMN and lateral temporal DMN subsystems during both reading and memory recall (Chapters 2 and 3). These findings might suggest that this core DMN structure, acting as a *functional hub*, plays an important role in supporting the integration of diverse information in these mental states. This role might be particular important for internally-oriented mental states since these states require a broad pattern of information integration (Conway, 2001; Greenberg & Rubin, 2003; Horner et al., 2015; Inman et al., 2018; Smallwood et al., 2016), for example, recalling personal memory involves re-experiencing of personally relevant events and retrieval of contextual details like sensory features (Conway, 2001; Greenberg & Rubin, 2003; Inman et al., 2018). In addition, this core DMN subsystem might also play a role in maintaining sustained internal cognition since the increased activation in this subnetwork is associated with better focus on recalling personal memories (Chapter 3). This pattern of activity in core DMN subsystem might be an important support of integration of diverse information during ongoing thought, with better internally-focussed cognition evoking greater activation in these *functional hub*s. These functional subdivisions of DMN subsystems are summarized in Figure 5.2.



**Lateral temporal DMN subsystem**

- **Acting as a *pivot* for internally and externally-oriented mental states: (i) common activation across reading and AM (Chapter 3); (ii) forming diverse patterns of functional networks to support different mental states (Chapters 2 and 3)**
- **Supporting semantic access: greater response to meaningful perceptual input, even when it is task-irrelevant (Chapter 3)**
- **Preferring thematic knowledge (Chapter 4)**

**Core DMN subsystem**

- **Acting as *functional hub* for task-dependent information integration: (i) Task-specific patterns of activation and deactivation (Chapter 3); (ii) Functional coupling with lateral temporal DMN subsystem (Chapter 3)**
- **Supporting sustained internal cognition: better task focus on internally-oriented mental state is associated with greater activation in this subsystem (Chapter 3)**

***Figure 5.2.*** Summarisation of functional subdivisions of lateral temporal DMN subsystem and Core DMN subsystem.

In addition to the different patterns of connectivity seen for the DMN subsystems, the thesis work examined similarities and differences in task-evoked activation/deactivation along the principal gradient of functional connectivity described by Margulies et al. (2016), and asked whether it is possible to explain the functional dichotomy of DMN subsystems based on their position on the principal gradient. For example, Chiou et al. (2019) claimed that the principal gradient increases its representational complexity, from primitive sensory-motoric processing, through lexical-semantic representations, to elaborated self-generated thoughts, and argued that core DMN should be higher on the principal gradient than lateral DMN in line with this hierarchy. Inconsistent with this claim, the findings from Chapter 3 revealed that the activation elicited by both tasks are comparable at the top of principal gradient, suggesting that the activation in lateral temporal DMN regions driven by external sensory inputs does not mean these sites would be lower down the gradient. Moreover, the activation and deactivation elicited by reading are equally high on the gradient and showed the same gradient location, even though these sites fell in different subsystems. Therefore, we cannot simply use the position along the principal gradient to explain the functional subdivision of DMN subsystems. Instead, at the top of the gradient, these DMN subsystems play distinct functions in different modes of mental states.

***Take home message***: The findings from this thesis suggest that the lateral temporal DMN and core DMN subsystems play distinctive, yet complementary, roles in different aspects of heteromodal cognition. The lateral temporal subsystem, acting as a "*pivot*" within the semantic system, is important for supporting semantically-relevant mental states. This subsystem not only supports visual-to-semantic mapping processes, which enables us to make sense of incoming perceptual information, but also supports internal semantically-relevant mental states, such as autobiographical memory recall. In addition, this subnetwork also shows a preference for thematic knowledge compared to taxonomic knowledge. The core DMN sites, acting as a *functional hub*, supports selective, task-dependent patterns of information integration. Its functional role in integration might be more important for supporting internally-oriented cognition which requires broad integration of diverse information. Moreover, this network also supports sustained internally-oriented mental states, which might allow cognition to be better internally-focussed on thoughts that are decoupled from external environment.

### 5.3.2. Semantic control processes

#### 5.3.2.1. Left inferior frontal gyrus (LIFG)

Contemporary accounts of semantic cognition, such as the controlled semantic cognition framework, have proposed that flexible semantic retrieval relies on control processes that interact with the semantic representation system (Lambon Ralph et al., 2017). Converging evidence from neuroimaging, neuropsychological, and TMS has revealed a largely distributed left-lateralised network in supporting controlled aspects of semantic cognition (Badre et al., 2005; Badre & Wagner, 2002;

Davey, Cornelissen, et al., 2015; Jefferies, 2013; Noonan et al., 2013; Thompson-Schill et al., 1997). The regions within this semantic control network show greater engagement when there is a need to suppress the strongest/irrelevant aspects of semantic information or to solve competition/ambiguity (Davey, Cornelissen, et al., 2015; Davey et al., 2016; Teige et al., 2019; Wagner et al., 2001; Zempleni et al., 2007). These control processes are thought to shape semantic retrieval to suit the current context or goal, which could flexibly heighten its connectivity with the hub or spoke components within the semantic representation system in a way that is appropriate for the task context (Chiou et al., 2018). This allows us to selectively focus retrieval on a particular aspect of conceptual knowledge that is appropriate to the circumstances. The results of this thesis help to further elucidate the role of left inferior frontal gyrus, a key semantic control site, in supporting different modes of semantic retrieval.

The data from this thesis reveal that LIFG not only supports perceptually-coupled and decoupled semantic retrieval (Chapters 3; see Figure 5.3), but also goal-directed and context-driven semantic retrieval (Chapter 4). The involvement of LIFG in the retrieval of semantic knowledge has been widely reported (Badre et al., 2005; Badre & Wagner, 2007; Noonan et al., 2010; Noonan et al., 2013; Thompson-Schill et al., 1997). Most studies of LIFG function have focused on its role in semantic control by manipulating the specificity of the required conceptual knowledge (e.g., colour feature vs. global association; Badre et al., 2005; Thompson-Schill et al., 1997), the strength of association (Badre et al., 2005; Teige et al., 2019; Wagner et al., 2001; Whitney et al., 2010), or the potency of semantically-related distractors (Thompson-Schill et al., 1997). Even though LIFG is thought to support goal-directed semantic retrieval, for example retrieving colour features when the task requires this information, it is hard to distinguish the specific role of LIFG in top-down semantic control, since the greater activation in this region seen during semantic feature matching over global association matching might reflect different difficulties or control demands of these tasks, or just the different kinds of information required by the tasks. The current results show greater recruitment of LIFG on trials in which the goal for retrieval is known in advance, relative to when the goal is not known, even when difficulty is well-matched, and the type of conceptual knowledge required by task is consistent across these two conditions. These findings demonstrate a specific role of LIFG in shaping semantic retrieval in a top-down fashion. In addition, in line with previous studies, the results from parametric analysis also revealed that the anterior portion of LIFG supports the retrieval of weak semantic associations, irrespective of prior knowledge of the pattern of retrieval required to make the conceptual link. In this way, the current findings add to previous studies by showing that LIFG is not only important for shaping semantic retrieval when there are high demands on control processes, but also that LIFG plays a more proactive role in semantic retrieval, allowing the semantic network to be constrained based on the current goal information.

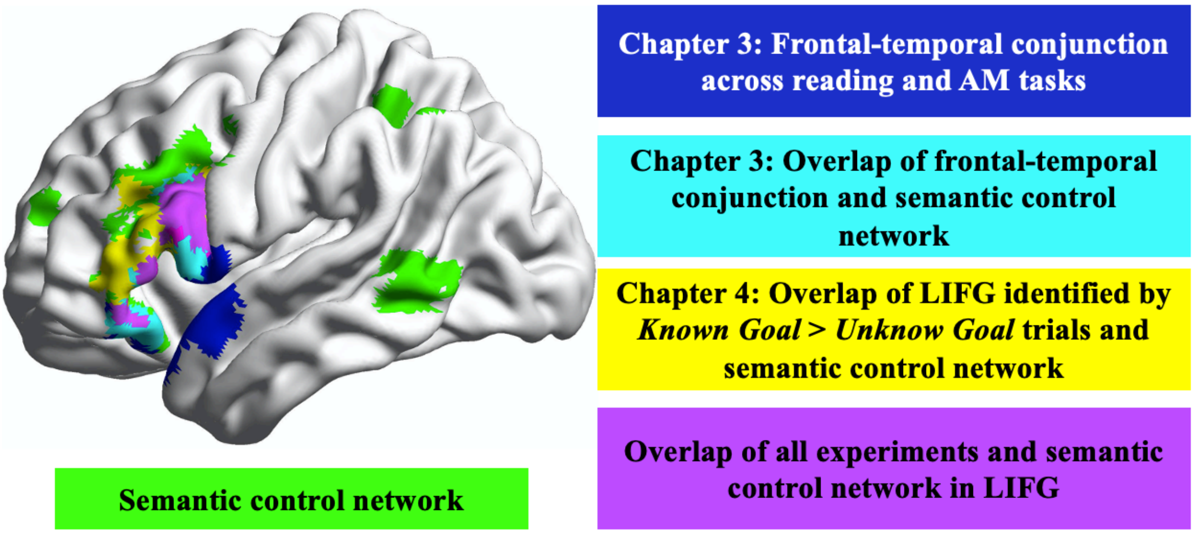


***Figure 5.3.*** Overlap of LIFG findings across the experimental chapters with the semantic control network. Frontal-temporal conjunction across reading and autobiographical memory (AM) tasks identified by formal conjunction analysis in Chapter 3 projected in blue, and its overlap with semantic control network (in green) in cyan. Overlap of semantic control network and LIFG identified by *Known Goal* > *Unknown Goal* contrast in Chapter 4 projected in yellow. Overlap of all these experimental chapters and semantic control network in LIFG projected in purple.

Furthermore, MVPA analysis revealed that a posterior portion of LIFG represented goal information about the aspect of conceptual information to be retrieved on that trial (i.e., taxonomic semantics vs. thematic semantics). This effect was found for *Known* trials, but not when the goal for retrieval was *Unknown*. This LIFG site is within both the semantic control network and multiple demand network (MDN). Beyond semantic cognition, it has been shown that the inferior frontal and intraparietal sulcus represent task features that relate to goal-directed behaviour (Crittenden et al., 2016; Woolgar et al., 2011; Woolgar & Zopf, 2017). A recent study also showed that MDN regions, including inferior frontal gyrus, can represent information about currently-relevant conceptual features (Wang, Gao, Smallwood, & Jefferies, 2020). The represented task features in LIFG might allow the semantic system to prioritise the retrieval of goal-relevant aspects of conceptual knowledge.

The current findings are also consistent with the view that sub-regions within LIFG have dissociable functions in supporting semantic retrieval, although the results in this thesis do not show formal statistical dissociations within LIFG within the same study, and the functions of these regions may be more similar than they are different. Anterior LIFG is thought to support controlled access to stored conceptual representations, whereas middle/posterior LIFG are proposed to support the selection of goal-relevant products of retrieval, operating post-retrieval to resolve competition among active representations (Badre et al., 2005; Badre & Wagner, 2007). The thesis findings are potentially compatible with this framework, as Chapter 4 shows that the anterior part of LIFG responds to the demands of controlled semantic retrieval, while posterior part of LIFG supports (the selection of) goal-relevant semantic information (see Figure 5.4). The *controlled retrieval* function of anterior LIFG might be more necessary for bottom-up semantic retrieval, since the presented stimuli determine the way in which control processes must be applied. When the required knowledge cannot be automatically activated, the demands on this region are thought to increase to allow appropriate semantic information to be retrieved. The *goal-relevant selection* function of mid-to-posterior LIFG might be more critical for goal-directed semantic retrieval, since there is a need to select a particular subset of conceptual knowledge based on current goal information. The engagement of this site might represent the maintenance of relevant goal information to shape semantic retrieval that aligns with these goals. Accordingly, both of these aspects of LIFG function are critical for us to flexibly shape our semantic retrieval to suit variable circumstances.

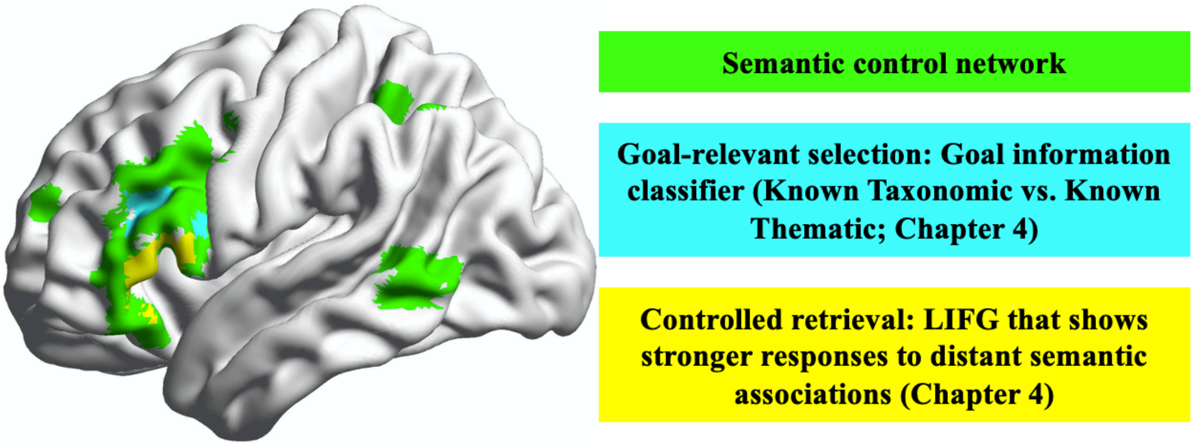


***Figure 5.4.*** Illustration of dissociable functions of LIFG identified in this thesis.

***Take home message***: The results from this thesis suggest that LIFG within the semantic control network not only supports retrieval of conceptual knowledge in less constrained contexts (i.e., without specific goal information), like linking distant semantic associations or generating internal thoughts, but also plays an important role in supporting *proactive* semantic retrieval. In line with the view that the functional role of this site is not homogeneous, our findings are consistent with the view that the anterior part of LIFG supports controlled semantic retrieval and the posterior part of this site is more related to goal-directed semantic retrieval. This evidence for a role of LIFG in both *proactive* and *retroactive* semantic retrieval adds to knowledge about the neural basis of flexible semantic cognition.

#### *5.3.2.2. Top-down control over spoke regions*

Semantic representations are underpinned by distributed brain areas including both heteromodal semantic hubs (i.e., ATL) and multiple modality-specific spokes (Binder et al., 2016; Lambon Ralph et al., 2017; Martin, 2016; Patterson et al., 2007). The control processes applied to these semantic representations enable us to tailor our retrieval in a way that is appropriate for each specific task context (Chiou et al., 2018; Jefferies, 2013; Lambon Ralph & Patterson, 2008). This view is supported by findings that semantic control sites can flexibly form different patterns of connectivity with distinct elements within the semantic representation system based on task contexts (Chiou et al., 2018). However, this past research does not reveal how control processes actually constrain semantic retrieval, and whether it is hub or spoke representations that interact with control regions like LIFG.

The data presented in this thesis advances this understanding by revealing the role of spoke regions in supporting *proactive* forms of semantic retrieval (Chapter 4). The finding that goal information modulated the response to the written words in primary visual cortex supports the view proposed by Jackson and her colleagues (2019) that control processes exert a greater influence over spoke regions rather than heteromodal hub representations. This work was based on a computational model of controlled semantic cognition, in which semantic control processes were allowed to interact with representations at different layers of a deep neural network, in which surface layers represented modality-specific regions, while 'deep' layers supported semantic representations that were more abstracted away from these sensory-motor features (representing heteromodal ATL). Only in this way could the hub be sufficiently insulated from contextual information to acquire more context-invariant conceptual representations (Jackson et al., 2019). In this view, the semantic hub is more insensitive to contextual information; instead, the spokes regions acting as the input systems are more sensitive to the task or context information. Usually, different contexts require retrieval of different aspects of conceptual knowledge, like retrieving colour or action knowledge. The ATL can form different connections with spoke regions to retrieve content-specific representations within modality-specific representation systems according to task contexts (Chiou & Lambon Ralph, 2019). This suggest semantic retrieval also relies on the dynamic interplay between the hub and spokes within the semantic representation system. This top-down manipulation of perceptual processing might enable the flexibly altering the interaction between hub and spoke regions to tailor semantic retrieval.

The current findings also demonstrate the role of spoke regions in supporting flexible semantic retrieval. These sensory and motor spokes are important for both perceptual level processing and semantic representations (Clarke et al., 2013; Lambon Ralph et al., 2017; Patterson et al., 2007). The perceptual inputs are initiated by modality-specific systems, and eventually elaborated in ATL (Marinkovic et al., 2003). Making sense of these perceptual inputs involves interactive-activation between sensory input regions and ATL (Carreiras et al., 2014; Clarke & Tyler, 2014; Tyler et al., 2013). Primary sensory regions can gate the degree to which conceptual processing can be driven by sensory input. In this way, context information could facilitate different modes of semantic retrieval by reducing the need to inhibit pre-activated task- or goal-irrelevant semantic information. For example, when the nature of the semantic link to be retrieved is not clear in advance, full conceptual retrieval driven by inputs may be supressed. Moreover, modality-specific spokes also play an important role in representing modality-specific semantic knowledge (Lambon Ralph et al., 2017; Patterson et al., 2007; Pulvermüller, 2005), and consequently the activity of these sites would also influence the semantic retrieval of featural knowledge represented in these spokes. Deactivation in input systems would lead to more impoverished and abstract semantic retrieval, while greater activation in these sites would allow richer semantic retrieval to emerge. In this way, control processes might support efficient flexible semantic retrieval, by gating the amount and nature of conceptual retrieval driven by an input.

***Take home message***: The data presented in this thesis is aligned with the view that control processes are applied to shallower elements (nearer primary sensory-motor systems), rather than deep heteromodal layers, of the semantic network (Jackson et al., 2019). Effects of top-down control were seen in the visual spoke, instead of heteromodal hub regions, within the semantic representation system. This manipulation of perceptual level processing might allow semantic retrieval to be efficiently and easily shaped based on current goal information.

### 5.4. Limitations and future directions

This thesis provides evidence about how flexibility within semantic cognition comes about. Although these findings advance understanding of the neural basis of flexible semantic retrieval, there still are questions that remain to be answered in view of the data presented here. An important first step might be to further characterise the functional outcomes of different patterns of connectivity from regions that support flexible semantic retrieval. The findings from this thesis show that the lateral DMN subsystem, implicated in semantic cognition, acts as a “pivot”, forming distinct connections with both input systems and other DMN regions to support internally and externally-oriented mental states. These diverse patterns of functional coupling might predict behavioural performance related to these different mental states. The lateral temporal DMN subsystem might form strong connections with medial temporal and core DMN during memory-based performance, like memory recall or mind-wandering; for perceptually coupled semantic tasks, this subsystem might exhibit strong connections with perceptual input systems. Also, it was found that LIFG could form different connections with both the

ATL semantic hub and specific spoke regions, based on the task context (Chiou et al., 2018). The results from this thesis showed that this site supports both *retroactive* and *proactive* semantic control. In line with the previous view that different regions of left IFG have dissociable roles (Badre & Wagner, 2007), the findings from Chapter 4 also suggest that different subregions within LIFG support distinct cognitive functions, with anterior LIFG more important for linking weak associations and posterior LIFG supporting the representation of goal information. These LIFG subregions might form distinct patterns of functional connectivity to support goal-directed and stimuli-driven semantic retrieval. However, more work is needed to formally establish these functional subdivisions, to explore their distinct patterns of connectivity, and to understand their association to functional gradients explored in Chapter 3. One possibility is that anterior LIFG shows strong functional connectivity with lateral temporal cortex regions to support stimuli-driven semantic retrieval, since these regions are implicated in heteromodal semantic representation. In contrast, the posterior LIFG might exhibit greater connectivity with spoke regions to support goal-directed semantic retrieval. The results in this thesis show that visual spoke regions support proactive forms of semantic retrieval, with functional coupling between posterior LIFG and this visual spoke relevant to goal-directed semantic retrieval.

Another major line of investigation concerns how external perceptual information and internal representations are integrated in the core DMN regions. The core DMN regions have been argued to act as functional hubs to allow diverse information to be transferred and integrated (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Andrews-Hanna, Smallwood, et al., 2014), which might be critical for supporting information integration in perceptually-coupled and decoupled aspects of cognition. In particular, the data in this thesis suggest that medial prefrontal cortex (mPFC), a core DMN region, showed greater connections with lateral temporal DMN subsystem, which could predict reading performance and support autobiographical memory recall. Better memory recall performance is also linked to greater activation in both medial temporal and core DMN regions, including mPFC. The mPFC is thought to be a functional hub that integrates diverse information (Margulies et al., 2016; Rossell et al., 2001; Visser et al., 2012; Zhao et al., 2017). This site might play a specific role in supporting the integration of semantic information driven by both perceptual inputs and internal task demands. For semantic tasks, this site might show strong connections with lateral temporal DMN subsystem to support semantic integration. In addition, for episodic memory, the core DMN regions might also exhibit greater functional coupling with medial temporal DMN subsystem, allowing the integration of greater inputs of internal representations from this subsystem. Further studies may explore the contributions of core DMN regions in these different types of information integration.

Further elucidating the interaction between DMN and other networks would also be a beneficial avenue for investigation to understand the flexibility of semantic cognition, given the lateral temporal DMN subsystem is implicated in the representation and retrieval of conceptual knowledge (Badre & Wagner, 2002; Humphreys et al., 2015; Jackson et al., 2016). (i) One direction is its interaction with control networks. Both the multiple demand network (MDN) and semantic control network are important for control processes, MDN is thought to be important for goal maintenance during goal-directed behaviour (Crittenden et al., 2016; Duncan, 2010). In contrast, the semantic control network is important for shaping semantic retrieval to suit the context (Davey et al., 2016; Jefferies, 2013). When semantic retrieval is goal-directed, like retrieving particular semantic features of conceptual knowledge, the DMN might show greater connectivity with MDN at these moments; when semantic retrieval is driven by weak contexts, like linking distantly related word pairs, the DMN might exhibit greater connectivity with semantic control network. Another direction is its interaction with attention networks. There are two key attention networks; the dorsal attention network (DAN) is linked to the orientation of attention in the external environment in a top-down fashion, and the ventral attention network (VAN) is important in maintaining task sets and acting as an altering mechanism or “circuit-breaker” for the dorsal attention system (Corbetta & Shulman, 2002; Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Sestieri, Shulman, & Corbetta, 2012). It has been shown that dorsolateral prefrontal cortex (DLPFC) within the ventral attention network supports both on-task states in demanding task contexts and “off-task thought” during non-demanding task contexts; this site is also involved in prioritising off-task thoughts, and individuals who increase off-task thoughts when external demands decrease show lower correlation between the lateral temporal DMN subnetwork and dorsal attention network within this site (Turnbull et al., 2019). The findings from Chapter 3 revealed that greater task focus on reading was also associated with greater deactivation of regions associated with the VAN. This pattern might be important to reduce the propensity to re-orient attention to off-task thoughts and consequently allow a better focus on external task. It might be useful to investigate network interactions within VAN regions. High connectivity between lateral temporal DMN and DAN within VAN regions might be associated with better externally-oriented semantic task performance. While high correlation between lateral temporal DMN subsystem with the other two DMN subsystems might link to better internal-generated thoughts within VAN regions. Also, it might also be interesting to explore if other aspects of factors could modulate these networks connections, like individual differences in trait rumination which is the tendency to focus on negative aspects of one's self or negative interpretations of one's life. People with greater score on this trait might show lower DMN and DAN correlation within VAN regions. Therefore, further studies could investigate the contributions of control and attention networks to flexible semantic retrieval.

## 5.5. Conclusions

This thesis sought out to examine the neural basis underpinning flexible semantic cognition by employing different modes of semantic retrieval, with a focus on the contribution of large-scale networks. By using convergent methods of task-based fMRI and functional connectivity analyses, the empirical work in this thesis revealed that the lateral temporal DMN subsystem that associated with semantic cognition, could form diverse patterns of functional coupling with both input systems and other DMN subsystems to support perceptually-coupled and decoupled aspects of cognition, acting as a *pivot*. Moreover, the data suggest functional subdivisions of DMN subsystems, with the lateral temporal DMN subsystem supporting both visual and internal task demands access to heteromodal semantic representation stored within this subnetwork, and core DMN regions supporting selective, task-dependent patterns of information integration that support perceptually-decoupled mental states. Furthermore, the thesis found that LIFG within the semantic control network supports both *retroactive* and *proactive* semantic control, importantly, top-down control was primarily applied to the visual spoke to support goal-directed semantic retrieval. Based on these findings, we conclude that flexibility within semantic cognition is achieved by (i) forming distinct patterns of functional connectivity from semantic regions with input systems and other DMN subsystems to support internally-oriented and externally-oriented mental states, and (ii) gating the input of task-relevant spoke regions according to goal information. In these ways, our semantic cognition can not only enable us to make sense of the external world and travel in our internal world, but also enable us to efficiently retrieve appropriate aspect of conceptual knowledge to suit the current circumstances.

# Appendicies

## A.1. Supplementary analyses of Chapter 3

### *A.1.1. Task activation*

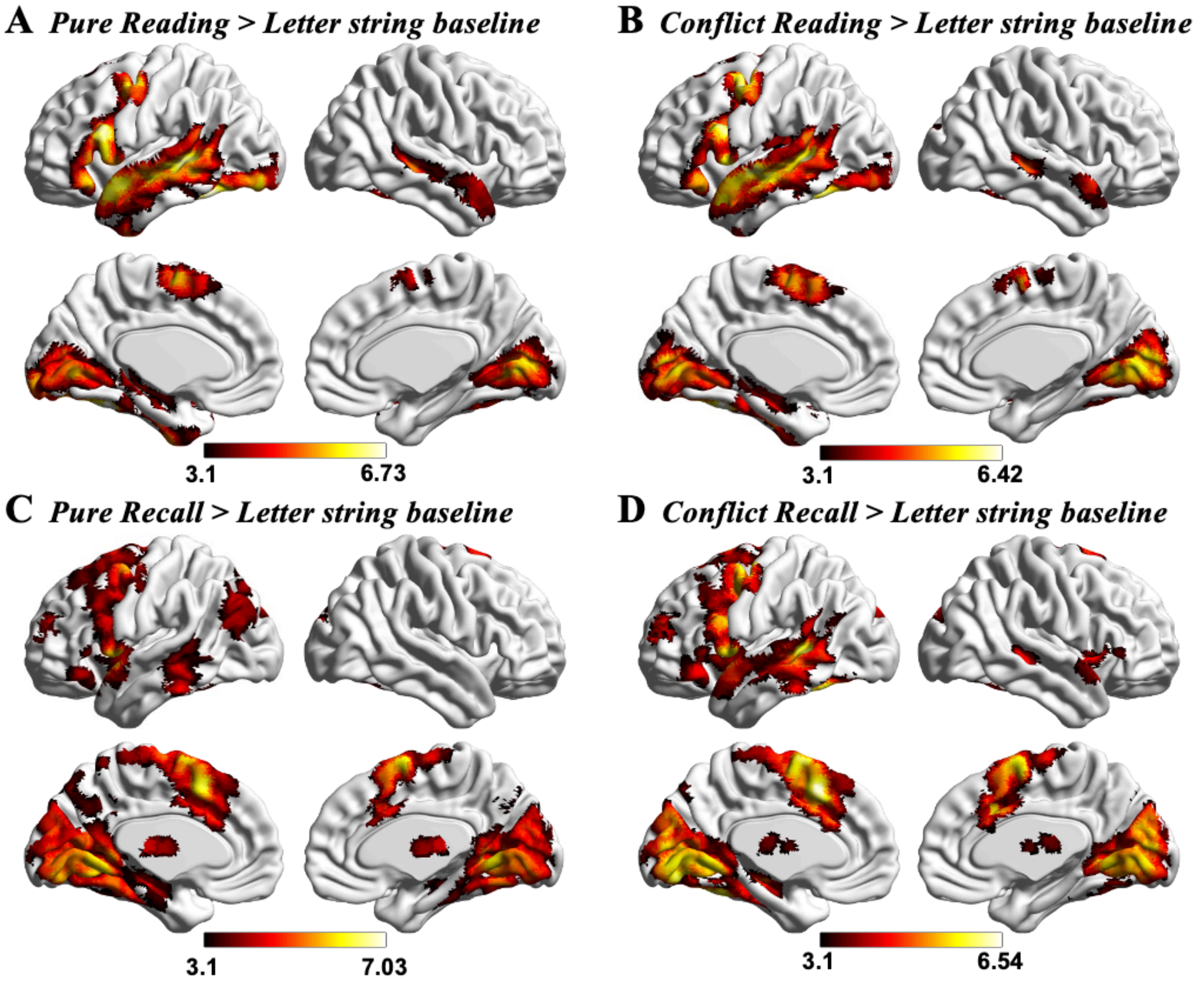


*Figure A.1.1.* **Comparisons between each experimental condition and meaningless letter string stimuli processing.** All maps were cluster-corrected with a voxel inclusion threshold of $z > 3.1$ and family-wise error rate using random field theory set at $p < .05$. L = Left hemisphere; R = Right hemisphere.

### *A.1.2. Gradient bin-by-bin analysis at threshold 2.3*

A 2 (Activity: *Activation* vs. *Deactivation*) by 2 (Task: *Reading* vs. *Autobiographical memory*) by 10 (Bins) repeated-measures ANOVAs was conducted to examine the effect of Task in each bin at each state of activity. This three-way interaction effect was significant, $F(9,252) = 8.40$, $p < .001$, $\eta_p^2 =$

.23, and separate ANOVAs analysis revealed that the interaction between Task and Bins was significant for both states of activity, with greater interaction effect in deactivation, $F(9,252) = 13.33$, $p < .001$, $\eta_p^2 = .32$, compared to activation, $F(9,252) = 2.90$, $p = .003$, $\eta_p^2 = .09$. Simple effects tests of the effect of Task in each bin at each state of activity revealed that the pattern of activation was similar between reading and autobiographical memory recall along the principal gradient ($p$ values > .06 across all the bins: see Figure A.1.2). However, reading elicited greater deactivation at the top of gradient relative to autobiographical memory (Bin 2, 4, 5, 6, 7, 8, 9, 10, $p$ values < .004; see Figure A.1.2), while comparable deactivation at the bottom of gradient (Bin 1and 3; $p$ values > .06). We observed the same patterns when replacing 0s with mean.

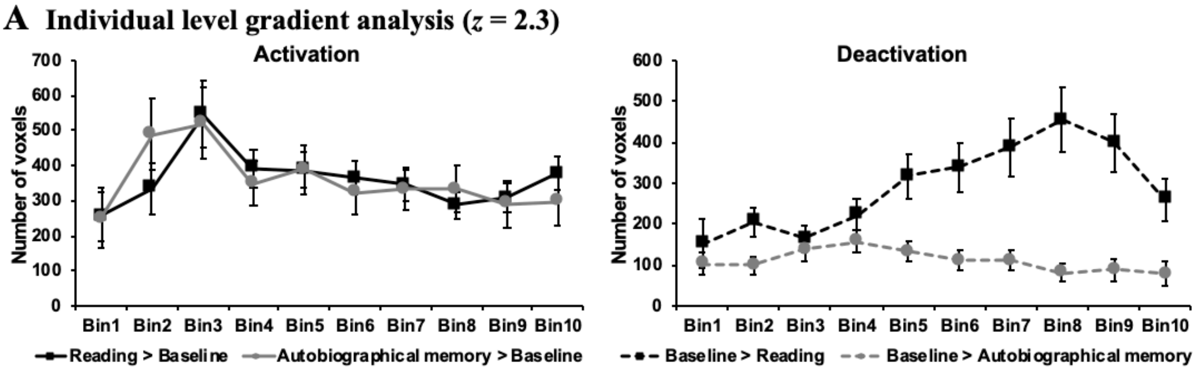


***Figure A.1.2.*** **Individual level gradient analysis at threshold 2.3.** The whole-brain map was evenly divided into 10 bins from the bottom to the top of the gradient. The line charts present the activation and deactivation in each bin at each activity state relative to the letter string baseline. Error bars represent the standard error.

## A.2. Supplementary analyses of Chapter 4

### *A.2.1. Temporal signal-to-noise ratio (tSNR)*

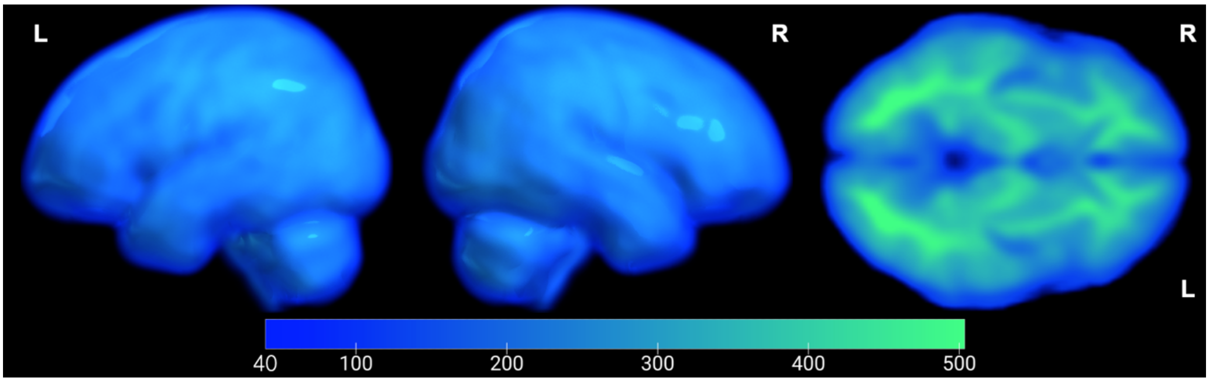


***Figure A.2.1.*** **Temporal signal-to-noise ratio.** Average temporal signal-to-noise ratio (tSNR; ratio of mean signal in each voxel and standard deviation of the residual error time series in that voxel across time) across all acquisitions. tSNR was computed independently from motion-corrected and linearly detrended BOLD fMRI time series for each scan. The resulting statistics were projected into group space for averaging across scans (i.e., 5 runs for each participant) and participants (n = 31). Mean tSNR values for lateral ATL and ventral ATL (i.e., the generated ROIs of hubs) were 271.25 and 221.59, respectively. These tSNR values are considered to demonstrate "good" signal in a 3T scanner (Binder et al., 2011).

### *A.2.2. Analysis of behavioural data recorded inside the scanner*

Task accuracy (left panel) and reaction time (RT; right panel) only for the participants included in the fMRI investigation are presented in Figure A.2.2. Trials with incorrect responses were excluded from the RT analysis (16.6%). We performed repeated-measures ANOVAs on both RT and accuracy, examining the effects of Task Knowledge (Known Goal vs. Unknown Goal) and Semantic Relation (Taxonomic relation vs. Thematic relation). For accuracy, there were no main effects of Semantic Relation, $F(1,30) = 2.11$, $p = .16$, $\eta_p^2 = .07$, or Task Knowledge, $F(1,30) = .20$, $p = .66$, $\eta_p^2 = .01$, and no interaction, $F(1,30) = 1.16$, $p = .29$, $\eta_p^2 = .04$. For RT, there was no main effect of Task Knowledge, $F(1,30) = .01$, $p = .91$, $\eta_p^2 < .001$, but responses were faster overall on taxonomic than thematic trials,

$F(1,30) = 15.40$, $p < .001$, $\eta_p^2 = .34$. There was no significant interaction between Task Knowledge and Semantic Relation, $F(1,30) = 3.46$, $p = .073$, $\eta_p^2 = .10$, but this marginal result prompted us to examine a larger behavioural dataset (see main text) to establish if this was likely to be a type II error. There was no evidence of an interaction in this larger dataset.

We also performed paired-samples t-tests, Bonferroni-corrected for multiple comparisons, to compare each semantic condition with the letter string baseline (Mean RT = 1.18 s; Mean Accuracy = 92.4%). For RT, there were no significant differences ($p > .0125$). Accuracy on the letter string task did not differ from the Known Goal Taxonomic condition ($p = .015$), but this task was more accurate than the other semantic conditions ($p < .005$).

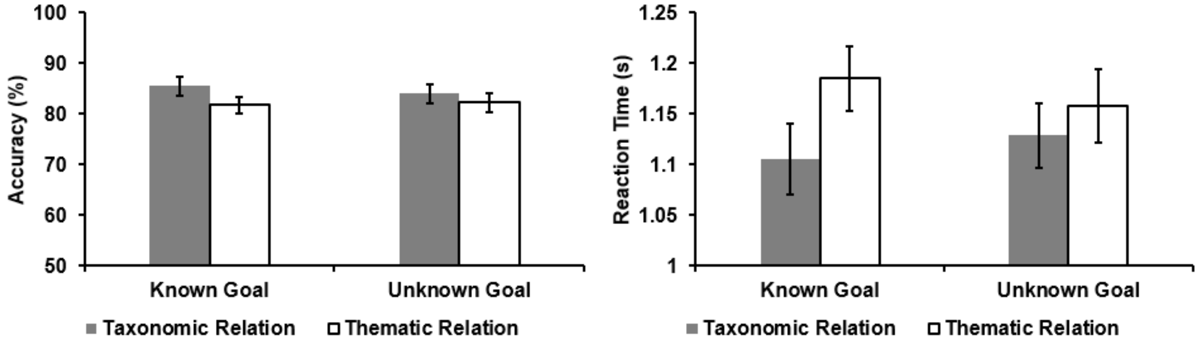


***Figure A.2.2.*** **Results of behavioural data recorded inside the scanner**. Accuracy (percentage correct, left panel) and reaction times (in seconds, right panel) for the target words in each semantic condition (Known Goal Taxonomic Relation, Unknown Goal Taxonomic Relation, Known Goal Thematic Relation, and Unknown Goal Thematic Relation). Error bars represent the standard error.

### *A.2.3. Semantic task activation*

We contrasted the meaningless letter string condition with each semantic condition. Semantic processing across the four conditions showed a common engagement of the semantic control network, including activation in left inferior frontal gyrus, posterior middle temporal gyrus, lateral occipital cortex, precuneus cortex and paracingulate gyrus.

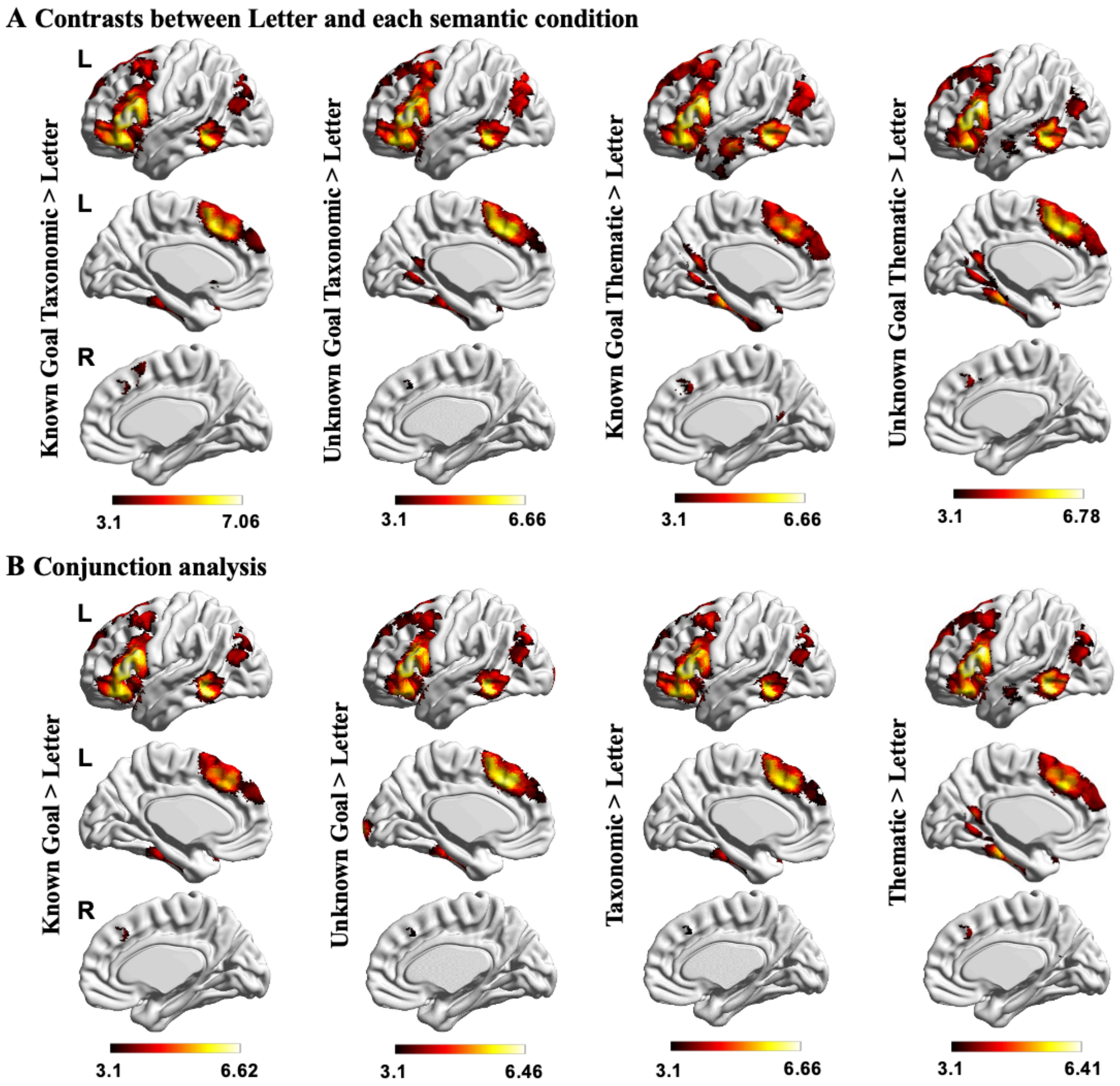


*Figure A.2.3*. **Semantic task activation. A) Comparisons between semantic and meaningless letter string stimuli processing.** Each column indicates the activated regions for Known Goal Taxonomic, Unknown Goal Taxonomic, Known Goal Thematic, and Unknown Goal Thematic versus letter string stimuli, respectively. **B) The conjunction analysis across the semantic and letter string contrasts.** The comparisons of *Known Goal Taxonomic* > *Letter* contrast and *Known Goal Thematic* > *Letter* contrast, *Unknown Goal Taxonomic* > *Letter* contrast and *Unknown Goal Thematic* > *Letter* contrast, *Known Goal Taxonomic* > *Letter* contrast and *Unknown Goal Taxonomic* > *Letter* contrast, and *Known Goal Thematic* > *Letter* contrast and *Unknown Goal Thematic* > *Letter* contrast revealed the overlapping regions for Known Goal, Unknown Goal, Taxonomic relation, and Thematic relation. Their conjunction was identified using FSL's 'easy thresh_conj' tool. All maps were cluster-corrected with a voxel inclusion threshold of $z > 3.1$ and family-wise error rate using random field theory set at $p < .05$. L = Left hemisphere; R = Right hemisphere.

### *A.2.4. Effects of Word Position without the subtraction of the letter string baseline*

Brain regions showing a stronger response to the first than second word included left superior temporal gyrus, lateral occipital cortex, and postcentral gyrus (see Figure A.2.4 A). In contrast, bilateral inferior frontal gyrus, left posterior middle temporal gyrus, postcentral gyrus, right anterior temporal gyrus, anterior paracingulate/cingulate cortex, parahippocampal gyrus and primary visual areas showed a stronger response to the second word (i.e., when the semantic decision was made; see Figure A.2.4 B).

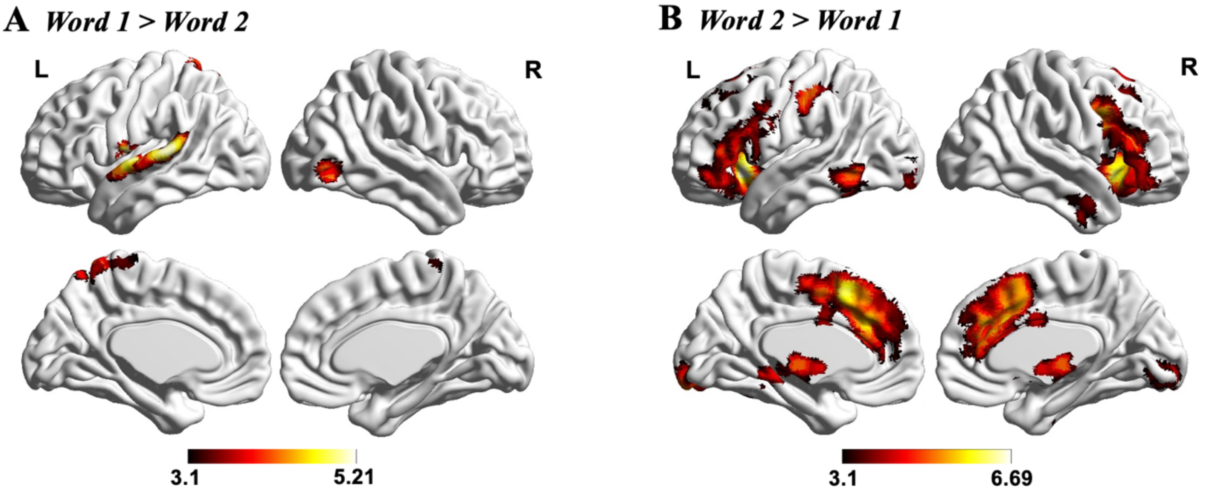


***Figure A.2.4*. Effects of Word Position.** Both **(A)** ***Word 1 > Word 2*** and **(B)** ***Word 2 > Word 1*** maps were cluster-corrected with a voxel inclusion threshold of $z > 3.1$ and family-wise error rate using random field theory set at $p < .05$. L = Left hemisphere; R = Right hemisphere.

# References

Abdel Rahman, R., & Melinger, A. (2011). The dynamic microstructure of speech production: Semantic interference built on the fly. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(1), 149-161.

Addis, D. R., & McAndrews, M. P. (2006). Prefrontal and hippocampal contributions to the generation and binding of semantic associations during successful encoding. *NeuroImage, 33*(4), 1194-1206.

Andrews-Hanna, J. R. (2012). The brain's default network and its adaptive role in internal mentation. *The Neuroscientist, 18*(3), 251-270.

Andrews-Hanna, J. R., Reidler, J. S., Huang, C., & Buckner, R. L. (2010). Evidence for the default network's role in spontaneous cognition. *Journal of Neurophysiology, 104*(1), 322-335. doi:10.1152/jn.00830.2009

Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron, 65*(4), 550-562.

Andrews-Hanna, J. R., Saxe, R., & Yarkoni, T. (2014). Contributions of episodic retrieval and mentalizing to autobiographical thought: evidence from functional neuroimaging, resting-state connectivity, and fMRI meta-analyses. *Neuroimage, 91*, 324-335.

Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences, 1316*(1), 29-52.

Anticevic, A., Cole, M. W., Murray, J. D., Corlett, P. R., Wang, X.-J., & Krystal, J. H. (2012). The role of default network deactivation in cognition and disease. *Trends in cognitive sciences, 16*(12), 584-592.

Arias-Trejo, N., & Plunkett, K. (2013). What's in a link: Associative and taxonomic priming effects in the infant lexicon. *Cognition, 128*(2), 214-227. doi:10.1016/j.cognition.2013.03.008

Arrington, C. N., Kulesz, P. A., Francis, D. J., Fletcher, J. M., & Barnes, M. A. (2014). The contribution of attentional control and working memory to reading comprehension and decoding. *Scientific Studies of Reading, 18*(5), 325-346. doi:org/10.1080/10888438.2014.902461

Baayen, R. H., Piepenbrock, R., & Van Rijn, H. (1993). The CELEX lexical database (CD-ROM). Linguistic data consortium. *Philadelphia, PA: University of Pennsylvania*.

Baddeley, A. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology Section A, 49*(1), 5-28.

Badre, D., Poldrack, R. A., Paré-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable controlled retrieval and generalized selection mechanisms in ventrolateral prefrontal cortex. *Neuron, 47*(6), 907-918. doi:10.1016/j.neuron.2005.07.023

Badre, D., & Wagner, A. D. (2002). Semantic retrieval, mnemonic control, and prefrontal cortex. *Behavioral and Cognitive Neuroscience Reviews, 1*(3), 206-218. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/17715593

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia, 45*(13), 2883-2901.

Bannert, M. M., & Bartels, A. (2013). Decoding the yellow of a gray banana. *Current Biology, 23*(22), 2268-2272.

Barnett, A., Marty-Dugas, J., & McAndrews, M. P. (2014). Advantages of sentence-level fMRI language tasks in presurgical language mapping for temporal lobe epilepsy. *Epilepsy & Behavior, 32*, 114-120.

Barredo, J., Verstynen, T. D., & Badre, D. (2016). Organization of cortico-cortical pathways supporting memory retrieval across subregions of the left ventrolateral prefrontal cortex. *Journal of Neurophysiology, 116*(3), 920-937. doi:10.1152/jn.00157.2016

Barron, E., Riby, L. M., Greer, J., & Smallwood, J. (2011). Absorbed in thought: The effect of mind wandering on the processing of relevant and irrelevant events. *Psychological Science, 22*(5), 596-601. doi:10.1177/0956797611404083

Barsalou, L. W. (1999). Perceptions of perceptual symbols. *Behavioral and Brain Sciences, 22*(4), 637-660. doi:Doi 10.1017/S0140525x99532147

Beaty, R. E., Benedek, M., Wilkins, R. W., Jauk, E., Fink, A., Silvia, P. J., . . . Neubauer, A. C. (2014). Creativity and the default network: A functional connectivity analysis of the creative brain at rest. *Neuropsychologia, 64*, 92-98. doi:10.1016/j.neuropsychologia.2014.09.019

Bedny, M., Caramazza, A., Grossman, E., Pascual-Leone, A., & Saxe, R. (2008). Concepts are more than percepts: the case of action verbs. *Journal of Neuroscience, 28*(44), 11347-11353. doi:10.1523/Jneurosci.3039-08.2008

Bedny, M., Dravida, S., & Saxe, R. (2014). Shindigs, brunches, and rodeos: The neural basis of event words. *Cognitive, Affective, & Behavioral Neuroscience, 14*(3), 891-901. doi:10.3758/s13415-013-0217-z

Behzadi, Y., Restom, K., Liau, J., & Liu, T. (2007). A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *NeuroImage, 37*(1), 90-101.

Bemis, D. K., & Pylkkänen, L. (2013). Basic linguistic composition recruits the left anterior temporal lobe and left angular gyrus during both listening and reading. *Cerebral Cortex, 23*(8), 1859-1873.

Bergmann, J., Genç, E., Kohler, A., Singer, W., & Pearson, J. (2016). Smaller primary visual cortex is associated with stronger, but less precise mental imagery. *Cerebral Cortex, 26*(9), 3838-3850.

Binder, J. R., Conant, L. L., Humphries, C. J., Fernandino, L., Simons, S. B., Aguilar, M., & Desai, R. H. (2016). Toward a brain-based componential semantic representation. *Cognitive Neuropsychology, 33*(3-4), 130-174. doi:10.1080/02643294.2016.1147426

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. *Cerebral Cortex, 19*(12), 2767-2796.

Binder, J. R., Gross, W. L., Allendorfer, J. B., Bonilha, L., Chapin, J., Edwards, J. C., . . . Lowe, M. J. (2011). Mapping anterior temporal lobe language areas with fMRI: a multicenter normative study. *Neuroimage, 54*(2), 1465-1475.

Binney, R. J., Embleton, K. V., Jefferies, E., Parker, G. J., & Lambon Ralph, M. A. (2010). The ventral and inferolateral aspects of the anterior temporal lobe are crucial in semantic memory: evidence from a novel direct comparison of distortion-corrected fMRI, rTMS, and semantic dementia. *Cerebral Cortex, 20*(11), 2728-2738. doi:10.1093/cercor/bhq019

Binney, R. J., Parker, G. J., & Lambon Ralph, M. A. (2012). Convergent connectivity and graded specialization in the rostral human temporal lobe as revealed by diffusion-weighted imaging probabilistic tractography. *Journal of Cognitive Neuroscience, 24*(10), 1998-2014. doi:DOI 10.1162/jocn_a_00263

Bird, C. M., & Burgess, N. (2008). The hippocampus and memory: insights from spatial processing. *Nature Reviews Neuroscience, 9*(3), 182-194.

Bird, C. M., Keidel, J. L., Ing, L. P., Horner, A. J., & Burgess, N. (2015). Consolidation of complex events via reinstatement in posterior cingulate cortex. *Journal of Neuroscience, 35*(43), 14426-14434.

Bonner, M. F., & Grossman, M. (2012). Gray matter density of auditory association cortex relates to knowledge of sound concepts in primary progressive aphasia. *Journal of Neuroscience, 32*(23), 7986-7991.

Bonnici, H. M., Richter, F. R., Yazar, Y., & Simons, J. S. (2016). Multimodal feature integration in the angular gyrus during episodic and semantic retrieval. *Journal of Neuroscience, 36*(20), 5462-5471.

Borghesani, V., Pedregosa, F., Buiatti, M., Amadon, A., Eger, E., & Piazza, M. (2016). Word meaning in the ventral visual path: a perceptual to conceptual gradient of semantic coding. *NeuroImage, 143*, 128-140.

Borghi, A. M., & Caramelli, N. (2003). Situation bounded conceptual organization in children: From action to spatial relations. *Cognitive Development, 18*(1), 49-60. doi:10.1016/S0885-2014(02)00161-2

Boylan, C., Trueswell, J. C., & Thompson-Schill, S. L. (2015). Compositionality and the angular gyrus: A multi-voxel similarity analysis of the semantic composition of nouns and verbs. *Neuropsychologia, 78*, 130-141.

Boylan, C., Trueswell, J. C., & Thompson-Schill, S. L. (2017). Relational vs. attributive interpretation of nominal compounds differentially engages angular gyrus and anterior temporal lobe. *Brain and language, 169*, 8-21.

Braga, R. M., & Buckner, R. L. (2017). Parallel interdigitated distributed networks within the individual estimated by intrinsic functional connectivity. *Neuron, 95*(2), 457-471. e455.

Braga, R. M., Sharp, D. J., Leeson, C., Wise, R. J. S., & Leech, R. (2013). Echoes of the Brain within Default Mode, Association, and Heteromodal Cortices. *Journal of Neuroscience, 33*(35), 14031-14039. doi:10.1523/Jneurosci.0570-13.2013

Braga, R. M., Van Dijk, K. R., Polimeni, J. R., Eldaief, M. C., & Buckner, R. L. (2019). Parallel distributed networks resolved at high resolution reveal close juxtaposition of distinct regions. *Journal of neurophysiology, 121*(4), 1513-1534.

Brysbaert, M., Warriner, A. B., & Kuperman, V. (2014). Concreteness ratings for 40 thousand generally known English word lemmas. *Behavior Research Methods, 46*(3), 904-911.

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network. *Annals of the New York Academy of Sciences, 1124*(1), 1-38. doi:10.1196/annals.1440.011

Buckner, R. L., & Carroll, D. C. (2007). Self-projection and the brain. *Trends in cognitive sciences, 11*(2), 49-57.

Buckner, R. L., & DiNicola, L. M. (2019). The brain’s default network: updated anatomy, physiology and evolving insights. *Nature Reviews Neuroscience, 20*(10), 593-608.

Bullmore, E., & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. *Nature reviews neuroscience, 10*(3), 186-198.

Burgess, N., Maguire, E. A., & O'Keefe, J. (2002). The human hippocampus and spatial and episodic memory. *Neuron, 35*(4), 625-641.

Buxbaum, L. J., & Saffran, E. M. (2002). Knowledge of object manipulation and object function: dissociations in apraxic and nonapraxic subjects. *Brain and language, 82*(2), 179-199.

Bzdok, D., Langner, R., Schilbach, L., Jakobs, O., Roski, C., Caspers, S., . . . Eickhoff, S. B. (2013). Characterization of the temporo-parietal junction by combining data-driven parcellation, complementary connectivity analyses, and functional decoding. *Neuroimage, 81*, 381-392.

Caplan, R., & Dapretto, M. (2001). Making sense during conversation: an fMRI study. *Neuroreport, 12*(16), 3625-3632.

Caramazza, A., & Mahon, B. Z. (2003). The organization of conceptual knowledge: the evidence from category-specific semantic deficits. *Trends in cognitive sciences, 7*(8), 354-361.

Carreiras, M., Armstrong, B. C., Perea, M., & Frost, R. (2014). The what, when, where, and how of visual word recognition. *Trends in cognitive sciences, 18*(2), 90-98.

Caspers, S., Eickhoff, S. B., Rick, T., von Kapri, A., Kuhlen, T., Huang, R., . . . Zilles, K. (2011). Probabilistic fibre tract analysis of cytoarchitectonically defined human inferior parietal lobule areas reveals similarities to macaques. *NeuroImage, 58*(2), 362-380. doi:10.1016/j.neuroimage.2011.06.027

Chadwick, M. J., Hassabis, D., Weiskopf, N., & Maguire, E. A. (2010). Decoding individual episodic memory traces in the human hippocampus. *Current Biology, 20*(6), 544-547.

Chai, X. J., Castañón, A. N., Öngür, D., & Whitfield-Gabrieli, S. (2012). Anticorrelations in resting state networks without global signal regression. *NeuroImage, 59*(2), 1420-1428.

Chang, C.-C., & Lin, C.-J. (2011). LIBSVM: A library for support vector machines. *ACM transactions on intelligent systems and technology, 2*(3), 27.

Chao, L. L., Haxby, J. V., & Martin, A. (1999). Attribute-based neural substrates in temporal cortex for perceiving and knowing about objects. *Nature neuroscience, 2*(10), 913. Retrieved from <Go to ISI>://WOS:000083883200018

Chen, J., Leong, Y. C., Honey, C. J., Yong, C. H., Norman, K. A., & Hasson, U. (2017). Shared memories reveal shared structure in neural activity across individuals. *Nature neuroscience, 20*(1), 115-125.

Chiou, R., Humphreys, G. F., Jung, J., & Lambon Ralph, M. A. (2018). Controlled semantic cognition relies upon dynamic and flexible interactions between the executive 'semantic control'and hub-and-spoke 'semantic representation'systems. *Cortex, 103*, 100-116.

Chiou, R., Humphreys, G. F., & Lambon Ralph, M. A. (2019). Bipartite functional fractionation within the default network supports disparate forms of internally oriented cognition. *BioRxiv*, 864603.

Chiou, R., & Lambon Ralph, M. A. (2016a). The anterior temporal cortex is a primary semantic source of top-down influences on object recognition. *Cortex, 79*, 75-86.

Chiou, R., & Lambon Ralph, M. A. (2016b). Task-related dynamic division of labor between anterior temporal and lateral occipital cortices in representing object size. *Journal of Neuroscience, 36*(17), 4662-4668.

Chiou, R., & Lambon Ralph, M. A. (2019). Unveiling the dynamic interplay between the hub-and spoke-components of the brain's semantic system and its impact on human behaviour. *NeuroImage, 199*, 114-126.

Choi, W., Desai, R. H., & Henderson, J. M. (2014). The neural substrates of natural reading: a comparison of normal and nonword text using eyetracking and fMRI. *Frontiers in Human Neuroscience, 8*, 1024. doi:doi: org/10.3389/fnhum.2014.01024

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences, 106*(21), 8719-8724. doi:10.1073/pnas.0900234106

Christoff, K., Irving, Z. C., Fox, K. C., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: a dynamic framework. *Nature Reviews Neuroscience, 17*(11), 718-731. doi:10.1038/nrn.2016.113

Christoff, K., Ream, J. M., & Gabrieli, J. D. (2004). Neural basis of spontaneous thought processes. *Cortex, 40*(4), 623-630. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15505972

Clarke, A., Taylor, K. I., Devereux, B., Randall, B., & Tyler, L. K. (2013). From perception to conception: how meaningful objects are processed over time. *Cerebral Cortex, 23*(1), 187-197.

Clarke, A., & Tyler, L. K. (2014). Object-specific semantic coding in human perirhinal cortex. *Journal of Neuroscience, 34*(14), 4766-4775.

Coccia, M., Bartolini, M., Luzzi, S., Provinciali, L., & Lambon Ralph, M. A. (2004). Semantic memory is an amodal, dynamic system: Evidence from the interaction of naming and object use in semantic dementia. *Cognitive Neuropsychology, 21*(5), 513-527.

Cole, M. W., Reynolds, J. R., Power, J. D., Repovs, G., Anticevic, A., & Braver, T. S. (2013). Multi-task connectivity reveals flexible hubs for adaptive task control. *Nature neuroscience, 16*(9), 1348-1355. doi:10.1038/nn.3470

Collins, J. A., & Olson, I. R. (2014). Knowledge is power: How conceptual knowledge transforms visual cognition. *Psychonomic bulletin & review, 21*(4), 843-860.

Conway, M. A. (2001). Sensory–perceptual episodic memory and its context: Autobiographical memory. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 356*(1413), 1375-1384.

Corbett, F., Jefferies, E., Ehsan, S., & Lambon Ralph, M. A. (2009). Different impairments of semantic cognition in semantic dementia and semantic aphasia: evidence from the non-verbal domain. *Brain, 132*(9), 2593-2608. doi:10.1093/brain/awp146

Corbett, F., Jefferies, E., & Lambon Ralph, M. A. (2011). Deregulated semantic cognition follows prefrontal and temporo-parietal damage: evidence from the impact of task constraint on nonverbal object use. *Journal of Cognitive Neuroscience, 23*(5), 1125-1135.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature reviews neuroscience, 3*(3), 201-215. doi:10.1038/nrn755

Coutanche, M. N., & Thompson-Schill, S. L. (2015). Creating concepts from converging features in human cortex. *Cerebral cortex, 25*(9), 2584-2593.

Craik, F. I., & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of experimental Psychology: general, 104*(3), 268-294.

Crittenden, B. M., & Duncan, J. (2014). Task difficulty manipulation reveals multiple demand activity but no frontal lobe hierarchy. *Cerebral Cortex, 24*(2), 532-540.

Crittenden, B. M., Mitchell, D. J., & Duncan, J. (2015). Recruitment of the default mode network during a demanding act of executive control. *Elife, 4*, e06481. doi:10.7554/eLife.06481

Crittenden, B. M., Mitchell, D. J., & Duncan, J. (2016). Task encoding across the multiple demand cortex is consistent with a frontoparietal and cingulo-opercular dual networks distinction. *Journal of Neuroscience, 36*(23), 6147-6155. doi:10.1523/Jneurosci.4590-15.2016

Cusack, R., Mitchell, D. J., & Duncan, J. (2010). Discrete object representation, attention switching, and task difficulty in the parietal lobe. *Journal of Cognitive Neuroscience, 22*(1), 32-47.

Damasio, H., Grabowski, T. J., Tranel, D., Hichwa, R. D., & Damasio, A. R. (1996). A neural basis for lexical retrieval. *Nature, 380*(6574), 499-505.

Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., & Damasio, A. (2004). Neural systems behind word and concept retrieval. *Cognition, 92*(1-2), 179-229.

Damian, M. F., Vigliocco, G., & Levelt, W. J. (2001). Effects of semantic context in the naming of pictures and words. *Cognition, 81*(3), B77-B86.

Davey, J., Cornelissen, P. L., Thompson, H. E., Sonkusare, S., Hallam, G., Smallwood, J., & Jefferies, E. (2015). Automatic and controlled semantic retrieval: TMS reveals distinct contributions of posterior middle temporal gyrus and angular gyrus. *Journal of Neuroscience, 35*(46), 15230-15239. doi:10.1523/JNEUROSCI.4705-14.2015

Davey, J., Rueschemeyer, S.-A., Costigan, A., Murphy, N., Krieger-Redwood, K., Hallam, G., & Jefferies, E. (2015). Shared neural processes support semantic control and action understanding. *Brain and Language, 142*, 24-35. doi:https://doi.org/10.1016/j.bandl.2015.01.002

Davey, J., Thompson, H. E., Hallam, G., Karapanagiotidis, T., Murphy, C., De Caso, I., . . . Jefferies, E. (2016). Exploring the role of the posterior middle temporal gyrus in semantic cognition: Integration of anterior temporal lobe with executive processes. *NeuroImage, 137*, 165-177. doi:10.1016/j.neuroimage.2016.05.051

Davis, C. J. (2005). N-Watch: A program for deriving neighborhood size and other psycholinguistic statistics. *Behavior Research Methods, 37*(1), 65-70.

Davis, C. P., & Yee, E. (2019). Features, labels, space, and time: Factors supporting taxonomic relationships in the anterior temporal lobe and thematic relationships in the angular gyrus. *Language, Cognition and Neuroscience, 34*(10), 1347-1357.

de Zubicaray, G. I., Hansen, S., & McMahon, K. L. (2013). Differential processing of thematic and categorical conceptual relations in spoken word production. *Journal of experimental Psychology: general, 142*(1), 131-142. doi:10.1037/a0028717

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences, 15*(6), 254-262. doi:10.1016/j.tics.2011.04.003

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience, 16*(4), 234-244. doi:10.1038/nrn3924

Demb, J. B., Desmond, J. E., Wagner, A. D., Vaidya, C. J., Glover, G. H., & Gabrieli, J. (1995). Semantic encoding and retrieval in the left inferior prefrontal cortex: a functional MRI study of task difficulty and process specificity. *Journal of Neuroscience, 15*(9), 5870-5878. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/7666172

Dijkstra, N., Zeidman, P., Ondobaka, S., van Gerven, M. A., & Friston, K. (2017). Distinct top-down and bottom-up brain connectivity during visual perception and imagery. *Scientific reports, 7*(1), 5677.

Dobbins, I. G., & Wagner, A. D. (2005). Domain-general and domain-sensitive prefrontal mechanisms for recollecting events and detecting novelty. *Cerebral Cortex, 15*(11), 1768-1778.

Dolan, R. J., Lane, R., Chua, P., & Fletcher, P. (2000). Dissociable temporal lobe activations during emotional episodic memory retrieval. *Neuroimage, 11*(3), 203-209.

Doniger, G. M., Foxe, J. J., Murray, M. M., Higgins, B. A., Snodgrass, J. G., Schroeder, C. E., & Javitt, D. C. (2000). Activation timecourse of ventral visual stream object-recognition areas: high density electrical mapping of perceptual closure processes. *Journal of cognitive neuroscience, 12*(4), 615-621.

Dosenbach, N. U., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in cognitive sciences, 12*(3), 99-105.

Dreyer, F. R., Frey, D., Arana, S., Saldern, S. v., Picht, T., Vajkoczy, P., & Pulvermüller, F. (2015). Is the motor system necessary for processing action and abstract emotion words? Evidence from focal brain lesions. *Frontiers in Psychology, 6*, 1661.

Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. *Trends in Cognitive Sciences, 14*(4), 172-179. doi:10.1016/j.tics.2010.01.004

Duval, C., Desgranges, B., de La Sayette, V., Belliard, S., Eustache, F., & Piolino, P. (2012). What happens to personal identity when semantic knowledge degrades? A study of the self and autobiographical memory in semantic dementia. *Neuropsychologia, 50*(2), 254-265.

Eichenbaum, H., Sauvage, M., Fortin, N., Komorowski, R., & Lipton, P. (2012). Towards a functional organization of episodic memory in the medial temporal lobe. *Neuroscience & Biobehavioral Reviews, 36*(7), 1597-1608.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *Journal of experimental Psychology: general, 128*(3), 309-331.

Estefan, D. P., Sánchez-Fibla, M., Duff, A., Principe, A., Rocamora, R., Zhang, H., . . . Verschure, P. F. (2019). Coordinated representational reinstatement in the human hippocampus and lateral temporal cortex during episodic memory retrieval. *Nature communications, 10*(1), 1-13.

Estes, Z., Golonka, S., & Jones, L. L. (2011). Thematic thinking: The apprehension and consequences of thematic relations. In *Psychology of learning and motivation* (Vol. 54, pp. 249-294): Elsevier.

Fedorenko, E., Duncan, J., & Kanwisher, N. (2013). Broad domain generality in focal regions of frontal and parietal cortex. *Proceedings of the National Academy of Sciences, 110*(41), 16616-16621.

Fernandino, L., Humphries, C. J., Conant, L. L., Seidenberg, M. S., & Binder, J. R. (2016). Heteromodal cortical areas encode sensory-motor features of word meaning. *Journal of Neuroscience, 36*(38), 9763-9769.

Ferstl, E. C., Neumann, J., Bogler, C., & Von Cramon, D. Y. (2008). The extended language network: a meta-analysis of neuroimaging studies on text comprehension. *Human Brain Mapping, 29*(5), 581-593. doi:10.1002/hbm.20422

Ferstl, E. C., Rinck, M., & Cramon, D. Y. v. (2005). Emotional and temporal aspects of situation model processing during text comprehension: An event-related fMRI study. *Journal of Cognitive Neuroscience, 17*(5), 724-739.

Ferstl, E. C., & von Cramon, D. Y. (2001). The role of coherence and cohesion in text comprehension: an event-related fMRI study. *Cognitive Brain Research, 11*(3), 325-340. doi:org/10.1016/S0926-6410(01)00007-6

Ferstl, E. C., & von Cramon, D. Y. (2002). What does the frontomedian cortex contribute to language processing: coherence or theory of mind? *NeuroImage, 17*(3), 1599-1612. doi:org/10.1006/nimg.2002.1247

Fox, K. C., Spreng, R. N., Ellamil, M., Andrews-Hanna, J. R., & Christoff, K. (2015). The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *Neuroimage, 111*, 611-621. doi:10.1016/j.neuroimage.2015.02.039

Fox, M. D., Snyder, A. Z., Vincent, J. L., Corbetta, M., Van Essen, D. C., & Raichle, M. E. (2005). The human brain is intrinsically organized into dynamic, anticorrelated functional networks. *Proceedings of the National Academy of Sciences of the United States of America, 102*(27), 9673-9678. doi:10.1073/pnas.0504136102

Franklin, M. S., Smallwood, J., & Schooler, J. W. (2011). Catching the mind in flight: Using behavioral indices to detect mindless reading in real time. *Psychonomic Bulletin & Review, 18*(5), 992-997. doi:10.3758/s13423-011-0109-6

Friederici, A. D., Meyer, M., & Von Cramon, D. Y. (2000). Auditory language comprehension: an event-related fMRI study on the processing of syntactic and lexical information. *Brain and language, 74*(2), 289-300.

Friederici, A. D., Rueschemeyer, S.-A., Hahne, A., & Fiebach, C. J. (2003). The role of left inferior frontal and superior temporal cortex in sentence comprehension: localizing syntactic and semantic processes. *Cerebral Cortex, 13*(2), 170-177. doi:doi: org/10.1093/cercor/13.2.170

Garrard, P., & Carroll, E. (2006). Lost in semantic space: a multi-modal, non-verbal assessment of feature knowledge in semantic dementia. *Brain, 129*(5), 1152-1163.

Gauthier, B., Eger, E., Hesselmann, G., Giraud, A.-L., & Kleinschmidt, A. (2012). Temporal tuning properties along the human ventral visual stream. *Journal of Neuroscience, 32*(41), 14433-14441.

Geng, J., & Schnur, T. T. (2016). Role of features and categories in the organization of object knowledge: Evidence from adaptation fMRI. *Cortex, 78*, 174-194. doi:10.1016/j.cortex.2016.01.006

Gilbert, S., Bird, G., Frith, C., & Burgess, P. (2012). Does "task difficulty" explain "task-induced deactivation?". *Frontiers in psychology, 3*, 125.

Glucksberg, S., Kreuz, R. J., & Rho, S. H. (1986). Context can constrain lexical access: Implications for models of language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 12*(3), 323-335.

Goel, V., Gold, B., Kapur, S., & Houle, S. (1997). The seats of reason? An imaging study of deductive and inductive reasoning. *Neuroreport, 8*(5), 1305-1310.

Gold, B. T., & Buckner, R. L. (2002). Common prefrontal regions coactivate with dissociable posterior regions during controlled semantic and phonological tasks. *Neuron, 35*(4), 803-812.

Goldberg, R. F., Perfetti, C. A., & Schneider, W. (2006). Perceptual knowledge retrieval activates sensory brain regions. *Journal of Neuroscience, 26*(18), 4917-4921. doi:10.1523/JNEUROSCI.5389-05.2006

Goldwater, M. B., Markman, A. B., & Stilwell, C. H. (2011). The empirical case for role-governed categories. *Cognition, 118*(3), 359-376. doi:10.1016/j.cognition.2010.10.009

Gonzale Alam, T. R. d. J., Karapanagiotidis, T., Smallwood, J., & Jefferies, E. (2019). Degrees of lateralisation in semantic cognition: Evidence from intrinsic connectivity. *NeuroImage, 202*, 116089.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*(1), 20-25. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/1374953

Gorgolewski, K. J., Lurie, D., Urchs, S., Kipping, J. A., Craddock, R. C., Milham, M. P., . . . Smallwood, J. (2014). A correspondence between individual differences in the brain's intrinsic functional architecture and the content and form of self-generated thoughts. *PloS One, 9*(5), e97176. doi:10.1371/journal.pone.0097176

Gorgolewski, K. J., Varoquaux, G., Rivera, G., Schwarz, Y., Ghosh, S. S., Maumet, C., . . . Poline, J.-B. (2015). NeuroVault. org: a web-based repository for collecting and sharing unthresholded statistical maps of the human brain. *Frontiers in Neuroinformatics, 9*, 8.

Gouws, A. D., Alvarez, I., Watson, D. M., Uesaki, M., Rogers, J., & Morland, A. B. (2014). On the role of suppression in spatial attention: evidence from negative BOLD in human subcortical and cortical structures. *Journal of Neuroscience, 34*(31), 10347-10360.

Graesser, A. C., Singer, M., & Trabasso, T. (1994). Constructing inferences during narrative text comprehension. *Psychological review, 101*(3), 371-395.

Graham, K. S., Lee, A. C., Brett, M., & Patterson, K. (2003). The neural basis of autobiographical and semantic memory: new evidence from three PET studies. *Cognitive, Affective, & Behavioral Neuroscience, 3*(3), 234-254.

Graham, K. S., Patterson, K., Powis, J., Drake, J., & Hodges, J. R. (2002). Multiple inputs to episodic memory: Words tell another story. *Neuropsychology, 16*(3), 380-389.

Greenberg, D. L., & Rubin, D. C. (2003). The neuropsychology of autobiographical memory. *Cortex, 39*(4-5), 687-728.

Greicius, M. D., Krasnow, B., Reiss, A. L., & Menon, V. (2003). Functional connectivity in the resting brain: a network analysis of the default mode hypothesis. *Proceedings of the National Academy of Sciences, 100*(1), 253-258. doi:10.1073/pnas.0135058100

Guo, C. C., Gorno-Tempini, M. L., Gesierich, B., Henry, M., Trujillo, A., Shany-Ur, T., . . . Rankin, K. P. (2013). Anterior temporal lobe degeneration produces widespread network-driven dysfunction. *Brain, 136*(10), 2979-2991.

Hallam, G. P., Whitney, C., Hymers, M., Gouws, A. D., & Jefferies, E. (2016). Charting the effects of TMS with fMRI: Modulation of cortical recruitment within the distributed network supporting semantic control. *Neuropsychologia, 93*, 40-52.

Hampton, J. A. (2006). Concepts as prototypes. *Psychology of learning and motivation, 46*, 79-113.

Hanke, M., Halchenko, Y. O., Sederberg, P. B., Hanson, S. J., Haxby, J. V., & Pollmann, S. (2009). PyMVPA: a python toolbox for multivariate pattern analysis of fMRI data. *Neuroinformatics, 7*(1), 37-53.

Harvey, D. Y., Wei, T., Ellmore, T. M., Hamilton, A. C., & Schnur, T. T. (2013). Neuropsychological evidence for the functional role of the uncinate fasciculus in semantic control. *Neuropsychologia, 51*(5), 789-801.

Hashimoto, N., McGregor, K. K., & Graham, A. (2007). Conceptual organization at 6 and 8 years of age: Evidence from the semantic priming of object decisions. *Journal of Speech, Language, and Hearing Research, 50*(1), 161-176. doi:10.1044/1092-4388(2007/014)

Hasson, U., Nusbaum, H. C., & Small, S. L. (2007). Brain networks subserving the extraction of sentence information and its encoding to memory. *Cerebral Cortex, 17*(12), 2899-2913. doi:org/10.1093/cercor/bhm016

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*(2), 301-307. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/14741110

Hodges, J. R., Bozeat, S., Lambon Ralph, M. A., Patterson, K., & Spatt, J. (2000). The role of conceptual knowledge in object use evidence from semantic dementia. *Brain, 123*(9), 1913-1925.

Hodges, J. R., Patterson, K., Oxbury, S., & Funnell, E. (1992). Semantic dementia: Progressive fluent aphasia with temporal lobe atrophy. *Brain, 115*(6), 1783-1806.

Hodges, J. R., Spatt, J., & Patterson, K. (1999). "What" and "how": evidence for the dissociation of object knowledge and mechanical problem-solving skills in the human brain. *Proceedings of the National Academy of Sciences, 96*(16), 9444-9448.

Hoenig, K., & Scheef, L. (2009). Neural correlates of semantic ambiguity processing during context verification. *Neuroimage, 45*(3), 1009-1019.

Hoffman, P. (2018). An individual differences approach to semantic cognition: Divergent effects of age on representation, retrieval and selection. *Scientific reports, 8*(1), 1-13.

Hoffman, P., Binney, R. J., & Lambon Ralph, M. A. (2015). Differing contributions of inferior prefrontal and anterior temporal cortex to concrete and abstract conceptual knowledge. *Cortex, 63*, 250-266. doi:10.1016/j.cortex.2014.09.001

Hoffman, P., Evans, G. A., & Lambon Ralph, M. A. (2014). The anterior temporal lobes are critically involved in acquiring new conceptual knowledge: evidence for impaired feature integration in semantic dementia. *Cortex, 50*, 19-31.

Hoffman, P., Jefferies, E., & Lambon Ralph, M. A. (2010). Ventrolateral prefrontal cortex plays an executive regulation role in comprehension of abstract words: convergent neuropsychological and repetitive TMS evidence. *Journal of Neuroscience, 30*(46), 15450-15456.

Hoffman, P., Jones, R. W., & Lambon Ralph, M. A. (2012). The degraded concept representation system in semantic dementia: damage to pan-modal hub, then visual spoke. *Brain, 135*(12), 3770-3780. doi:10.1093/brain/aws282

Horner, A. J., Bisby, J. A., Bush, D., Lin, W.-J., & Burgess, N. (2015). Evidence for holistic episodic recollection via hippocampal pattern completion. *Nature communications, 6*(1), 1-11.

Horowitz-Kraus, T., Vannest, J. J., Gozdas, E., & Holland, S. K. (2014). Greater utilization of neural-circuits related to executive functions is associated with better reading: a longitudinal fMRI study using the verb generation task. *Frontiers in Human Neuroscience, 8*, 447.

Hoscheidt, S. M., Nadel, L., Payne, J., & Ryan, L. (2010). Hippocampal activation during retrieval of spatial context from episodic and semantic memory. *Behavioural Brain Research, 212*(2), 121-132.

Hsu, N. S., Kraemer, D. J., Oliver, R. T., Schlichting, M. L., & Thompson-Schill, S. L. (2011). Color, context, and cognitive style: Variations in color knowledge retrieval as a function of task and subject variables. *Journal of Cognitive Neuroscience, 23*(9), 2544-2557.

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

Humphreys, G. F., & Lambon Ralph, M. A. (2014). Fusion and fission of cognitive functions in the human parietal cortex. *Cerebral Cortex, 25*(10), 3547-3560. doi:10.1093/cercor/bhu198

Hurley, R. S., Bonakdarpour, B., Wang, X., & Mesulam, M.-M. (2015). Asymmetric connectivity between the anterior temporal lobe and the language network. *Journal of cognitive neuroscience, 27*(3), 464-473.

Inman, C. S., James, G. A., Vytal, K., & Hamann, S. (2018). Dynamic changes in large-scale functional network organization during autobiographical memory retrieval. *Neuropsychologia, 110*, 208-224.

Irish, M., Addis, D. R., Hodges, J. R., & Piguet, O. (2012). Considering the role of semantic memory in episodic future thinking: evidence from semantic dementia. *Brain, 135*(7), 2178-2191.

Jackson, R. L. (2020). The Neural Correlates of Semantic Control Revisited. *BioRxiv*.

Jackson, R. L., Bajada, C. J., Rice, G. E., Cloutman, L. L., & Lambon Ralph, M. A. (2018). An emergent functional parcellation of the temporal cortex. *Neuroimage, 170*, 385-399.

Jackson, R. L., Hoffman, P., Pobric, G., & Lambon Ralph, M. A. (2015). The nature and neural correlates of semantic association versus conceptual similarity. *Cerebral Cortex, 25*(11), 4319-4333. doi:10.1093/cercor/bhv003

Jackson, R. L., Hoffman, P., Pobric, G., & Lambon Ralph, M. A. (2016). The semantic network at work and rest: Differential connectivity of anterior temporal lobe subregions. *Journal of Neuroscience, 36*(5), 1490-1501. doi:10.1523/Jneurosci.2999-15.2016

Jackson, R. L., Rogers, T. T., & Lambon Ralph, M. A. (2019). Reverse-Engineering the Cortical Architecture for Controlled Semantic Cognition. *bioRxiv*, 860528.

James, T. W., Culham, J., Humphrey, G. K., Milner, A. D., & Goodale, M. A. (2003). Ventral occipital lesions impair object recognition but not object-directed grasping: an fMRI study. *Brain, 126*(11), 2463-2475.

Jang, G., Yoon, S.-a., Lee, S.-E., Park, H., Kim, J., Ko, J. H., & Park, H.-J. (2013). Everyday conversation requires cognitive inference: neural bases of comprehending implicated meanings in conversations. *NeuroImage, 81*, 61-72.

Jangraw, D. C., Gonzalez-Castillo, J., Handwerker, D. A., Ghane, M., Rosenberg, M. D., Panwar, P., & Bandettini, P. A. (2018). A functional connectivity-based neuromarker of sustained attention generalizes to predict recall in a reading task. *NeuroImage, 166*, 99-109. doi:10.1016/j.neuroimage.2017.10.019

Jefferies, E. (2013). The neural basis of semantic cognition: Converging evidence from neuropsychology, neuroimaging and TMS. *Cortex, 49*(3), 611-625. doi:https://doi.org/10.1016/j.cortex.2012.10.008

Jefferies, E., Baker, S. S., Doran, M., & Lambon Ralph, M. A. (2007). Refractory effects in stroke aphasia: a consequence of poor semantic control. *Neuropsychologia, 45*(5), 1065-1079.

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

Jefferies, E., Patterson, K., & Lambon Ralph, M. A. (2008). Deficits of knowledge versus executive control in semantic cognition: Insights from cued naming. *Neuropsychologia, 46*(2), 649-658.

Jefferies, E., Thompson, H., Cornelissen, P., & Smallwood, J. (2020). The neurocognitive basis of knowledge about object identity and events: dissociations reflect opposing effects of semantic coherence and control. *Philosophical Transactions of the Royal Society B, 375*(1791), 20190300.

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage, 17*(2), 825-841. doi:10.1006/nimg.2002.1132

Jung, J., Cloutman, L. L., Binney, R. J., & Lambon Ralph, M. A. (2017). The structural connectivity of higher order association cortices reflects human functional brain networks. *Cortex, 97*, 221-239. doi:10.1016/j.cortex.2016.08.011

Kable, J. W., Kan, I. P., Wilson, A., Thompson-Schill, S. L., & Chatterjee, A. (2005). Conceptual representations of action in the lateral temporal cortex. *Journal of cognitive neuroscience, 17*(12), 1855-1870.

Kalénine, S., Buxbaum, L. J., & Coslett, H. B. (2010). Critical brain regions for action recognition: lesion symptom mapping in left hemisphere stroke. *Brain, 133*(11), 3269-3280.

Kalénine, S., Peyrin, C., Pichat, C., Segebarth, C., Bonthoux, F., & Baciu, M. (2009). The sensory-motor specificity of taxonomic and thematic conceptual relations: A behavioral and fMRI study. *NeuroImage, 44*(3), 1152-1162. doi:10.1016/j.neuroimage.2008.09.043

Kalénine, S., Shapiro, A. D., Flumini, A., Borghi, A. M., & Buxbaum, L. J. (2014). Visual context modulates potentiation of grasp types during semantic object categorization. *Psychonomic bulletin & review, 21*(3), 645-651.

Kam, J. W., Dao, E., Farley, J., Fitzpatrick, K., Smallwood, J., Schooler, J. W., & Handy, T. C. (2011). Slow fluctuations in attentional control of sensory cortex. *Journal of Cognitive Neuroscience, 23*(2), 460-470. doi:10.1162/jocn.2010.21443

Kan, I. P., Barsalou, L. W., Olseth Solomon, K., Minor, J. K., & Thompson-Schill, S. L. (2003). Role of mental imagery in a property verification task: fMRI evidence for perceptual representations of conceptual knowledge. *Cognitive Neuropsychology, 20*(3-6), 525-540.

Keidel, J. L., Oedekoven, C. S., Tut, A. C., & Bird, C. M. (2018). Multiscale integration of contextual information during a naturalistic task. *Cerebral Cortex, 28*(10), 3531-3539.

Kiefer, M., Trumpp, N., Herrnberger, B., Sim, E.-J., Hoenig, K., & Pulvermüller, F. (2012). Dissociating the representation of action-and sound-related concepts in middle temporal cortex. *Brain and Language, 122*(2), 120-125.

Kilgarriff, A., Rychly, P., Smrz, P., & Tugwell, D. (2004). Itri-04-08 the sketch engine. *Information Technology, 105*, 116.

Kilner, J. M. (2011). More than one pathway to action understanding. *Trends in cognitive sciences, 15*(8), 352-357.

Kim, H. (2016). Default network activation during episodic and semantic memory retrieval: a selective meta-analytic comparison. *Neuropsychologia, 80*, 35-46. doi:10.1016/j.neuropsychologia.2015.11.006

Kim, S.-i., Yoon, M., Kim, W., Lee, S., & Kang, E. (2012). Neural correlates of bridging inferences and coherence processing. *Journal of Psycholinguistic Research, 41*(4), 311-321.

Kintsch, W. (1988). The role of knowledge in discourse comprehension: A construction-integration model. *Psychological review, 95*(2), 163-182.

Kirwan, C. B., Bayley, P. J., Galván, V. V., & Squire, L. R. (2008). Detailed recollection of remote autobiographical memory after damage to the medial temporal lobe. *Proceedings of the National Academy of Sciences, 105*(7), 2676-2680.

Koenig, P., & Grossman, M. (2007). Process and content in semantic memory. In J. J. Hart & M. A. Kraut (Eds.), (pp. 247–264): Cambridge University Press.

Konu, D., Turnbull, A., Karapanagiotidis, T., Wang, H.-t., Brown, L., Jefferies, E., & Smallwood, J. (2020). A role for ventromedial prefrontal cortex in self-generated episodic social cognition. *Neuroimage*, 116977.

Krieger-Redwood, K., Jefferies, E., Karapanagiotidis, T., Seymour, R., Nunes, A., Ang, J. W. A., . . . Smallwood, J. (2016). Down but not out in posterior cingulate cortex: Deactivation yet functional coupling with prefrontal cortex during demanding semantic cognition. *NeuroImage, 141*, 366-377.

Krieger-Redwood, K., Teige, C., Davey, J., Hymers, M., & Jefferies, E. (2015). Conceptual control across modalities: graded specialisation for pictures and words in inferior frontal and posterior temporal cortex. *Neuropsychologia, 76*, 92-107.

Kriegeskorte, N., Goebel, R., & Bandettini, P. (2006). Information-based functional brain mapping. *Proceedings of the National Academy of Sciences, 103*(10), 3863-3868.

Kühn, S., Ritter, S. M., Müller, B. C., Baaren, R. B., Brass, M., & Dijksterhuis, A. (2014). The importance of the default mode network in creativity—a structural MRI study. *The Journal of Creative Behavior, 48*(2), 152-163.

Kumar, U. (2018). The neural realm of taxonomic and thematic relation: an fMRI study. *Language, Cognition and Neuroscience, 33*(5), 648-658.

Kuperberg, G. R., Lakshmanan, B. M., Caplan, D. N., & Holcomb, P. J. (2006). Making sense of discourse: An fMRI study of causal inferencing across sentences. *NeuroImage, 33*(1), 343-361. doi:10.1016/j.neuroimage.2006.06.001

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

Lambon Ralph, M. A., & Patterson, K. (2008). Generalization and differentiation in semantic memory: insights from semantic dementia. *Annals of the New York Academy of Sciences, 1124*(1), 61-76.

Lambon Ralph, M. A., Sage, K., Jones, R. W., & Mayberry, E. J. (2010). Coherent concepts are computed in the anterior temporal lobes. *Proceedings of the National Academy of Sciences, 107*(6), 2717-2722.

Landrigan, J.-F., & Mirman, D. (2018). The cost of switching between taxonomic and thematic semantics. *Memory & Cognition, 46*(2), 191-203.

Lanzoni, L., Ravasio, D., Thompson, H., Vatansever, D., Margulies, D., Smallwood, J., & Jefferies, E. (2020). The role of default mode network in semantic cue integration. *NeuroImage*, 117019.

Lanzoni, L., Thompson, H., Beintari, D., Berwick, K., Demnitz-King, H., Raspin, H., . . . Jefferies, E. (2019). Emotion and location cues bias conceptual retrieval in people with deficient semantic control. *Neuropsychologia, 131*, 294-305.

Lau, E. F., Gramfort, A., Hämäläinen, M. S., & Kuperberg, G. R. (2013). Automatic semantic facilitation in anterior temporal cortex revealed through multimodal neuroimaging. *Journal of Neuroscience, 33*(43), 17174-17181. doi:10.1523/Jneurosci.1018-13.2013

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

Leech, R., Kamourieh, S., Beckmann, C. F., & Sharp, D. J. (2011). Fractionating the default mode network: distinct contributions of the ventral and dorsal posterior cingulate cortex to cognitive control. *Journal of Neuroscience, 31*(9), 3217-3224. doi:10.1523/JNEUROSCI.5626-10.2011

Lewis, G. A., Poeppel, D., & Murphy, G. L. (2015). The neural bases of taxonomic and thematic conceptual relations: An MEG study. *Neuropsychologia, 68*, 176-189. doi:10.1016/j.neuropsychologia.2015.01.011

Lin, E. L., & Murphy, G. L. (2001). Thematic relations in adults' concepts. *Journal of experimental Psychology: general, 130*(1), 3-28. doi:10.1037/0096-3445.130.1.3

Maguire, E. A., Frith, C. D., & Morris, R. (1999). The functional neuroanatomy of comprehension and memory: the importance of prior knowledge. *Brain, 122*(10), 1839-1850.

Mahon, B. Z., & Caramazza, A. (2005). The orchestration of the sensory-motor systems: Clues from neuropsychology. *Cognitive neuropsychology, 22*(3-4), 480-494.

Mahon, B. Z., Milleville, S. C., Negri, G. A., Rumiati, R. I., Caramazza, A., & Martin, A. (2007). Action-related properties shape object representations in the ventral stream. *Neuron, 55*(3), 507-520.

Margulies, D. S., Ghosh, S. S., Goulas, A., Falkiewicz, M., Huntenburg, J. M., Langs, G., . . . Petrides, M. (2016). Situating the default-mode network along a principal gradient of macroscale cortical organization. *Proceedings of the National Academy of Sciences, 113*(44), 12574-12579. doi:10.1073/pnas.1608282113

Margulies, D. S., Kelly, A. C., Uddin, L. Q., Biswal, B. B., Castellanos, F. X., & Milham, M. P. (2007). Mapping the functional connectivity of anterior cingulate cortex. *NeuroImage, 37*(2), 579-588. doi:10.1016/j.neuroimage.2007.05.019

Margulies, D. S., & Smallwood, J. (2017). Converging evidence for the role of transmodal cortex in cognition. *Proceedings of the National Academy of Sciences, 114*(48), 201717374. doi:10.1073/pnas.1717374114

Marinkovic, K., Dhond, R. P., Dale, A. M., Glessner, M., Carr, V., & Halgren, E. (2003). Spatiotemporal dynamics of modality-specific and supramodal word processing. *Neuron, 38*(3), 487-497.

Markowitsch, H. J. (1995). Which brain regions are critically involved in the retrieval of old episodic memory? *Brain Research Reviews, 21*(2), 117-127.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology, 58*, 25-45. doi:10.1146/annurev.psych.57.102904.190143

Martin, A. (2016). GRAPES—Grounding representations in action, perception, and emotion systems: How object properties and categories are represented in the human brain. *Psychonomic Bulletin & Review, 23*(4), 979-990.

Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L., & Ungerleider, L. G. (1995). Discrete cortical regions associated with knowledge of color and knowledge of action. *Science, 270*(5233), 102-105. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/7569934

Mason, M. F., Norton, M. I., Van Horn, J. D., Wegner, D. M., Grafton, S. T., & Macrae, C. N. (2007). Wandering minds: the default network and stimulus-independent thought. *Science, 315*(5810), 393-395. doi:10.1126/science.1131295

Mattheiss, S. R., Levinson, H., & Graves, W. W. (2018). Duality of Function: Activation for Meaningless Nonwords and Semantic Codes in the Same Brain Areas. *Cerebral Cortex, 28*(7), 2516-2524. doi:10.1093/cercor/bhy053

Mazoyer, B., Zago, L., Mellet, E., Bricogne, S., Etard, O., Houdé, O., . . . Tzourio-Mazoyer, N. (2001). Cortical networks for working memory and executive functions sustain the conscious resting state in man. *Brain Research Bulletin, 54*(3), 287-298. doi:10.1016/S0361-9230(00)00437-8

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences, 7*(7), 293-299. doi:org/10.1016/S1364-6613(03)00134-7

Mckiernan, K. A., Kaufman, J. N., Kucera-Thompson, J., & Binder, J. R. (2003). A parametric manipulation of factors affecting task-induced deactivation in functional neuroimaging. *Journal of cognitive neuroscience, 15*(3), 394-408.

McLaren, D. G., Ries, M. L., Xu, G., & Johnson, S. C. (2012). A generalized form of context-dependent psychophysiological interactions (gPPI): a comparison to standard approaches. *NeuroImage, 61*(4), 1277-1286.

McVay, J. C., & Kane, M. J. (2010). Adrift in the stream of thought: The effects of mind wandering on executive control and working memory capacity. In *Handbook of individual differences in cognition* (pp. 321-334): Springer.

McVay, J. C., & Kane, M. J. (2012). Why does working memory capacity predict variation in reading comprehension? On the influence of mind wandering and executive attention. *Journal of experimental Psychology: general, 141*(2), 302-320.

Mellet, E., Tzourio, N., Denis, M., & Mazoyer, B. (1998). Cortical anatomy of mental imagery of concrete nouns based on their dictionary definition. *Neuroreport, 9*(5), 803-808.

Mikolov, T., Chen, K., Corrado, G., & Dean, J. (2013). Efficient estimation of word representations in vector space. *arXiv preprint arXiv:1301.3781*.

Mirman, D., & Graziano, K. M. (2012a). Damage to temporo-parietal cortex decreases incidental activation of thematic relations during spoken word comprehension. *Neuropsychologia, 50*(8), 1990-1997. doi:10.1016/j.neuropsychologia.2012.04.02

Mirman, D., & Graziano, K. M. (2012b). Individual differences in the strength of taxonomic versus thematic relations. *Journal of experimental Psychology: general, 141*(4), 601-609. doi:10.1037/a0026451

Mirman, D., Landrigan, J.-F., & Britt, A. E. (2017). Taxonomic and thematic semantic systems. *Psychological bulletin, 143*(5), 499-520. doi:10.1037/bul0000092

Mollo, G., Cornelissen, P. L., Millman, R. E., Ellis, A. W., & Jefferies, E. (2017). Oscillatory dynamics supporting semantic cognition: MEG evidence for the contribution of the anterior temporal lobe hub and modality-specific spokes. *PloS one, 12*(1), e0169269.

Mollo, G., Jefferies, E., Cornelissen, P., & Gennari, S. P. (2018). Context-dependent lexical ambiguity resolution: MEG evidence for the time-course of activity in left inferior frontal gyrus and posterior middle temporal gyrus. *Brain and language, 177*, 23-36.

Morris, R. K. (2006). Lexical processing and sentence context effects. In *Handbook of psycholinguistics* (pp. 377-401): Elsevier.

Moss, H., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., & Tyler, L. (2005). Selecting among competing alternatives: selection and retrieval in the left inferior frontal gyrus. *Cerebral Cortex, 15*(11), 1723-1735.

Moss, H. E., & Marslen-Wilson, W. D. (1993). Access to word meanings during spoken language comprehension: effects of sentential semantic context. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*(6), 1254-1276.

Moss, H. E., Rodd, J. M., Stamatakis, E. A., Bright, P., & Tyler, L. K. (2004). Anteromedial temporal cortex supports fine-grained differentiation among objects. *Cerebral Cortex, 15*(5), 616-627.

Mummery, C. J., Patterson, K., Price, C. J., Ashburner, J., Frackowiak, R. S., & Hodges, J. R. (2000). A voxel-based morphometry study of semantic dementia: relationship between temporal lobe atrophy and semantic memory. *Annals of neurology, 47*(1), 36-45.

Murphy, C., Jefferies, E., Rueschemeyer, S.-A., Sormaz, M., Wang, H.-T., Margulies, D. S., & Smallwood, J. (2018). Distant from input: Evidence of regions within the default mode network supporting perceptually-decoupled and conceptually-guided cognition. *NeuroImage, 171*, 393-401. doi:10.1016/j.neuroimage.2018.01.017

Murphy, C., Rueschemeyer, S.-A., Smallwood, J., & Jefferies, E. (2019). Imagining sounds and images: Decoding the contribution of unimodal and transmodal brain regions to semantic retrieval in the absence of meaningful input. *Journal of Cognitive Neuroscience, 31*(11), 1599-1616.

Murphy, C., Rueschemeyer, S.-A., Watson, D., Karapanagiotidis, T., Smallwood, J., & Jefferies, E. (2017). Fractionating the anterior temporal lobe: MVPA reveals differential responses to input and conceptual modality. *NeuroImage, 147*, 19-31. doi:10.1016/j.neuroimage.2016.11.067

Murphy, C., Wang, H.-T., Konu, D., Lowndes, R., Margulies, D. S., Jefferies, E., & Smallwood, J. (2019). Modes of operation: A topographic neural gradient supporting stimulus dependent and independent cognition. *NeuroImage, 186*, 487-496.

Murphy, G. L. (2010). What are categories and concepts. *The making of human concepts*, 11-28. doi:10.1093/acprof:oso/9780199549221.003.02

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

Nielson, D. M., Smith, T. A., Sreekumar, V., Dennis, S., & Sederberg, P. B. (2015). Human hippocampus represents space and time during retrieval of real-world memories. *Proceedings of the National Academy of Sciences, 112*(35), 11078-11083.

Nobre, A. C., Allison, T., & McCarthy, G. (1994). Word recognition in the human inferior temporal lobe. *Nature, 372*(6503), 260-263.

Noonan, K. A., Jefferies, E., Corbett, F., & Lambon Ralph, M. A. (2010). Elucidating the nature of deregulated semantic cognition in semantic aphasia: evidence for the roles of prefrontal and temporo-parietal cortices. *Journal of Cognitive Neuroscience, 22*(7), 1597-1613. doi:10.1162/jocn.2009.21289

Noonan, K. A., Jefferies, E., Visser, M., & Lambon Ralph, M. A. (2013). Going beyond inferior prefrontal involvement in semantic control: evidence for the additional contribution of dorsal angular gyrus and posterior middle temporal cortex. *Journal of Cognitive Neuroscience, 25*(11), 1824-1850. doi:10.1162/jocn_a_00442

Noppeney, U., & Price, C. J. (2004). Retrieval of abstract semantics. *NeuroImage, 22*(1), 164-170. doi:10.1016/j.neuroimage.2003.12.010

Novick, J. M., Trueswell, J. C., & Thompson-Schill, S. L. (2005). Cognitive control and parsing: Reexamining the role of Broca's area in sentence comprehension. *Cognitive, Affective, & Behavioral Neuroscience, 5*(3), 263-281.

Nyberg, L., McIntosh, A. R., Cabeza, R., Habib, R., Houle, S., & Tulving, E. (1996). General and specific brain regions involved in encoding and retrieval of events: what, where, and when. *Proceedings of the National Academy of Sciences, 93*(20), 11280-11285.

Nyberg, L., Mclntosh, A., Houle, S., Nilsson, L.-G., & Tulving, E. (1996). Activation of medial temporal structures during episodic memory retrieval. *Nature, 380*(6576), 715-717.

O'Callaghan, C., Shine, J. M., Lewis, S. J., Andrews-Hanna, J. R., & Irish, M. (2015). Shaped by our thoughts–A new task to assess spontaneous cognition and its associated neural correlates in the default network. *Brain and cognition, 93*, 1-10.

Osaka, N., Osaka, M., Kondo, H., Morishita, M., Fukuyama, H., & Shibasaki, H. (2004). The neural basis of executive function in working memory: an fMRI study based on individual differences. *NeuroImage, 21*(2), 623-631.

Østby, Y., Walhovd, K. B., Tamnes, C. K., Grydeland, H., Westlye, L. T., & Fjell, A. M. (2012). Mental time travel and default-mode network functional connectivity in the developing brain. *Proceedings of the National Academy of Sciences, 109*(42), 16800-16804.

Pammer, K., Hansen, P. C., Kringelbach, M. L., Holliday, I., Barnes, G., Hillebrand, A., . . . Cornelissen, P. L. (2004). Visual word recognition: the first half second. *NeuroImage, 22*(4), 1819-1825.

Pascual, B., Masdeu, J. C., Hollenbeck, M., Makris, N., Insausti, R., Ding, S.-L., & Dickerson, B. C. (2015). Large-scale brain networks of the human left temporal pole: a functional connectivity MRI study. *Cerebral cortex, 25*(3), 680-702.

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience, 8*(12), 976-987. doi:10.1038/nrn2277

Peelen, M. V., & Caramazza, A. (2012). Conceptual object representations in human anterior temporal cortex. *Journal of Neuroscience, 32*(45), 15728-15736.

Pereira, F., Gershman, S., Ritter, S., & Botvinick, M. (2016). A comparative evaluation of off-the-shelf distributed semantic representations for modelling behavioural data. *Cognitive neuropsychology, 33*(3-4), 175-190.

Philippi, C. L., Tranel, D., Duff, M., & Rudrauf, D. (2014). Damage to the default mode network disrupts autobiographical memory retrieval. *Social cognitive affective neuroscience, 10*(3), 318-326.

Pobric, G., Jefferies, E., & Lambon Ralph, M. A. (2010a). Amodal semantic representations depend on both anterior temporal lobes: evidence from repetitive transcranial magnetic stimulation. *Neuropsychologia, 48*(5), 1336-1342.

Pobric, G., Jefferies, E., & Lambon Ralph, M. A. (2010b). Category-specific versus category-general semantic impairment induced by transcranial magnetic stimulation. *Current Biology, 20*(10), 964-968.

Poerio, G. L., Sormaz, M., Wang, H.-T., Margulies, D., Jefferies, E., & Smallwood, J. (2017). The role of the default mode network in component processes underlying the wandering mind. *Social cognitive and affective neuroscience, 12*(7), nsx041. doi:10.1093/scan/nsx041

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage, 10*(1), 15-35.

Popov, V., Zhang, Q., Koch, G. E., Calloway, R. C., & Coutanche, M. N. (2019). Semantic knowledge influences whether novel episodic associations are represented symmetrically or asymmetrically. *Memory & Cognition, 47*(8), 1567-1581.

Price, A. R., Bonner, M. F., Peelle, J. E., & Grossman, M. (2015). Converging evidence for the neuroanatomic basis of combinatorial semantics in the angular gyrus. *Journal of Neuroscience, 35*(7), 3276-3284. doi:10.1523/JNEUROSCI.3446-14.2015

Price, A. R., Peelle, J. E., Bonner, M. F., Grossman, M., & Hamilton, R. H. (2016). Causal evidence for a mechanism of semantic integration in the angular gyrus as revealed by high-definition transcranial direct current stimulation. *Journal of Neuroscience, 36*(13), 3829-3838.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience, 6*(7), 576-582. doi:10.1038/nrn1706

Raichle, M. E., MacLeod, A. M., Snyder, A. Z., Powers, W. J., Gusnard, D. A., & Shulman, G. L. (2001). A default mode of brain function. *Proceedings of the National Academy of Sciences, 98*(2), 676-682. doi:10.1073/pnas.98.2.676

Rapcsak, S. Z., Ochipa, C., Anderson, K. C., & Poizner, H. (1995). Progressive ideomotor apraxia: evidence for a selective impairment of the action production system. *Brain and cognition, 27*(2), 213-236.

Reich, L., Szwed, M., Cohen, L., & Amedi, A. (2011). A ventral visual stream reading center independent of visual experience. *Current Biology, 21*(5), 363-368.

Reilly, J., Garcia, A., & Binney, R. J. (2016). Does the sound of a barking dog activate its corresponding visual form? An fMRI investigation of modality-specific semantic access. *Brain and language, 159*, 45-59.

Rice, G. E., Hoffman, P., Binney, R. J., & Lambon Ralph, M. A. (2018). Concrete versus abstract forms of social concept: an fMRI comparison of knowledge about people versus social terms.

*Philosophical Transactions of the Royal Society B: Biological Sciences, 373*(1752), 20170136.

Rice, G. E., Lambon Ralph, M. A., & Hoffman, P. (2015). The roles of left versus right anterior temporal lobes in conceptual knowledge: an ALE meta-analysis of 97 functional neuroimaging studies. *Cerebral Cortex, 25*(11), 4374-4391.

Robinson, G., Blair, J., & Cipolotti, L. (1998). Dynamic aphasia: an inability to select between competing verbal responses? *Brain: a journal of neurology, 121*(1), 77-89.

Rodd, J. M., Davis, M. H., & Johnsrude, I. S. (2005). The neural mechanisms of speech comprehension: fMRI studies of semantic ambiguity. *Cerebral Cortex, 15*(8), 1261-1269. doi:10.1093/cercor/bhi009

Rodd, J. M., Johnsrude, I. S., & Davis, M. H. (2011). Dissociating frontotemporal contributions to semantic ambiguity resolution in spoken sentences. *Cerebral Cortex, 22*(8), 1761-1773.

Rogers, S. L., & Friedman, R. B. (2008). The underlying mechanisms of semantic memory loss in Alzheimer's disease and semantic dementia. *Neuropsychologia, 46*(1), 12-21.

Rogers, T. T., Hocking, J., Noppeney, U., Mechelli, A., Gorno-Tempini, M. L., Patterson, K., & Price, C. J. (2006). Anterior temporal cortex and semantic memory: reconciling findings from neuropsychology and functional imaging. *Cognitive, Affective, & Behavioral Neuroscience, 6*(3), 201-213.

Rogers, T. T., & McClelland, J. L. (2004). *Semantic cognition: A parallel distributed processing approach*: MIT press.

Rosci, C., Chiesa, V., Laiacona, M., & Capitani, E. (2003). Apraxia is not associated to a disproportionate naming impairment for manipulable objects. *Brain and Cognition, 53*(2), 412-415.

Roskies, A., Fiez, J., Balota, D. A., Raichle, M., & Petersen, S. (2001). Task-dependent modulation of regions in the left inferior frontal cortex during semantic processing. *Journal of cognitive neuroscience, 13*(6), 829-843.

Rossell, S. L., Bullmore, E. T., Williams, S. C., & David, A. S. (2001). Brain activation during automatic and controlled processing of semantic relations: a priming experiment using lexical-decision. *Neuropsychologia, 39*(11), 1167-1176.

Rugg, M. D., & Vilberg, K. L. (2013). Brain networks underlying episodic memory retrieval. *Current opinion in neurobiology, 23*(2), 255-260.

Ryan, L., Cox, C., Hayes, S. M., & Nadel, L. (2008). Hippocampal activation during episodic and semantic memory retrieval: Comparing category production and category cued recall. *Neuropsychologia, 46*(8), 2109-2121.

Sachs, O., Weis, S., Krings, T., Huber, W., & Kircher, T. (2008). Categorical and thematic knowledge representation in the brain: Neural correlates of taxonomic and thematic conceptual relations. *Neuropsychologia, 46*(2), 409-418.

Sanders, J. G., Wang, H.-T., Schooler, J., & Smallwood, J. (2017). Can I get me out of my head? Exploring strategies for controlling the self-referential aspects of the mind-wandering state during reading. *The Quarterly Journal of Experimental Psychology, 70*(6), 1053-1062. doi:10.1080/17470218.2016.1216573

Sanjuán, A., Forn, C., Ventura-Campos, N., Rodríguez-Pujadas, A., García-Porcar, M., Belloch, V., . . . Ávila, C. (2010). The sentence verification task: a reliable fMRI protocol for mapping receptive language in individual subjects. *European Radiology, 20*(10), 2432-2438.

Sass, K., Sachs, O., Krach, S., & Kircher, T. (2009). Taxonomic and thematic categories: Neural correlates of categorization in an auditory-to-visual priming task using fMRI. *Brain research, 1270*, 78-87.

Saur, D., Kreher, B. W., Schnell, S., Kümmerer, D., Kellmeyer, P., Vry, M.-S., . . . Abel, S. (2008). Ventral and dorsal pathways for language. *Proceedings of the national academy of Sciences, 105*(46), 18035-18040.

Schacter, D. L., & Addis, D. R. (2007). The cognitive neuroscience of constructive memory: remembering the past and imagining the future. *Philosophical Transactions of the Royal Society B: Biological Sciences, 362*(1481), 773-786.

Schwartz, M. F., Kimberg, D. Y., Walker, G. M., Brecher, A., Faseyitan, O. K., Dell, G. S., . . . Coslett, H. B. (2011). Neuroanatomical dissociation for taxonomic and thematic knowledge in the human brain. *Proceedings of the National Academy of Sciences, 108*(20), 8520-8524. doi:10.1073/pnas.1014935108

Semenza, C., Bisiacchi, P. S., & Romani, L. (1992). Naming disorders and semantic representations. *Journal of Psycholinguistic Research, 21*(5), 349-364.

Sesma, H. W., Mahone, E. M., Levine, T., Eason, S. H., & Cutting, L. E. (2009). The contribution of executive skills to reading comprehension. *Child Neuropsychology, 15*(3), 232-246.

Sestieri, C., Corbetta, M., Romani, G. L., & Shulman, G. L. (2011). Episodic memory retrieval, parietal cortex, and the default mode network: functional and topographic analyses. *Journal of Neuroscience, 31*(12), 4407-4420. doi:10.1523/JNEUROSCI.3335-10.2011

Sestieri, C., Shulman, G. L., & Corbetta, M. (2012). Orienting to the environment: Separate contributions of dorsal and ventral frontoparietal attention networks. In M. GR (Ed.), *The Neuroscience of Attention: Attentional Control and Selection.* (pp. 100–130). New York: Oxford University Press.

Shashidhara, S., Mitchell, D. J., Erez, Y., & Duncan, J. (2019). Progressive recruitment of the frontoparietal multiple-demand system with increased task complexity, time pressure, and reward. *Journal of cognitive neuroscience, 31*(11), 1617-1630.

Shaywitz, S. E., & Shaywitz, B. A. (2008). Paying attention to reading: the neurobiology of reading and dyslexia. *Development and Psychopathology, 20*(4), 1329-1349. doi:org/10.1017/S0954579408000631

Sheldon, S., Farb, N., Palombo, D. J., & Levine, B. (2016). Intrinsic medial temporal lobe connectivity relates to individual differences in episodic autobiographical remembering. *Cortex, 74*, 206-216.

Shulman, G. L., Fiez, J. A., Corbetta, M., Buckner, R. L., Miezin, F. M., Raichle, M. E., & Petersen, S. E. (1997). Common blood flow changes across visual tasks: II. Decreases in cerebral cortex. *Journal of Cognitive Neuroscience, 9*(5), 648-663. doi:10.1162/jocn.1997.9.5.648

Simons, J. S., Graham, K. S., & Hodges, J. R. (2002). Perceptual and semantic contributions to episodic memory: evidence from semantic dementia and Alzheimer's disease. *Journal of Memory and Language, 47*(2), 197-213.

Singh, K. D., & Fawcett, I. (2008). Transient and linearly graded deactivation of the human default-mode network by a visual detection task. *Neuroimage, 41*(1), 100-112.

Skipper-Kallal, L. M., Mirman, D., & Olson, I. R. (2015). Converging evidence from fMRI and aphasia that the left temporoparietal cortex has an essential role in representing abstract semantic knowledge. *Cortex, 69*, 104-120.

Smallwood, J. (2011). Mind-wandering while reading: Attentional decoupling, mindless reading and the cascade model of inattention. *Language and Linguistics Compass, 5*(2), 63-77.

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

Smallwood, J., Beach, E., Schooler, J. W., & Handy, T. C. (2008). Going AWOL in the brain: Mind wandering reduces cortical analysis of external events. *Journal of Cognitive Neuroscience, 20*(3), 458-469. doi:10.1162/jocn.2008.20037

Smallwood, J., Gorgolewski, K. J., Golchert, J., Ruby, F. J., Engen, H. G., Baird, B., . . . Margulies, D. S. (2013). The default modes of reading: modulation of posterior cingulate and medial prefrontal cortex connectivity associated with comprehension and task focus while reading. *Frontiers in Human Neuroscience, 7*, 734. doi:10.3389/fnhum.2013.00734

Smallwood, J., Karapanagiotidis, T., Ruby, F., Medea, B., de Caso, I., Konishi, M., . . . Jefferies, E. (2016). Representing representation: Integration between the temporal lobe and the posterior cingulate influences the content and form of spontaneous thought. *PloS One, 11*(4), e0152272. doi:10.1371/journal.pone.0152272

Smallwood, J., McSpadden, M., & Schooler, J. W. (2008). When attention matters: The curious incident of the wandering mind. *Memory & Cognition, 36*(6), 1144-1150. doi:10.3758/Mc.36.6.1144

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: empirically navigating the stream of consciousness. *Annual Review of Psychology, 66*, 487-518. doi:10.1146/annurev-psych-010814-015331

Smilek, D., Carriere, J. S., & Cheyne, J. A. (2010). Out of mind, out of sight: eye blinking as indicator and embodiment of mind wandering. *Psychological Science, 21*(6), 786-789.

Smith, R., Keramatian, K., Smallwood, J., Schooler, J., Luus, B., & Christoff, K. (2006). *Mind-wandering with and without awareness: An fMRI study of spontaneous thought processes.* Paper presented at the Proceedings of the 28th annual conference of the Cognitive Science Society.

Smith, S. M., & Nichols, T. E. (2009). Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. *NeuroImage, 44*(1), 83-98.

Snowden, J. S., Thompson, J., & Neary, D. (2004). Knowledge of famous faces and names in semantic dementia. *Brain, 127*(4), 860-872.

Snyder, H. R., Feigenson, K., & Thompson-Schill, S. L. (2007). Prefrontal cortical response to conflict during semantic and phonological tasks. *Journal of cognitive neuroscience, 19*(5), 761-775.

Solan, H. A., Shelley-Tremblay, J., Ficarra, A., Silverman, M., & Larson, S. (2003). Effect of attention therapy on reading comprehension. *Journal of Learning Disabilities, 36*(6), 556-563. doi:org/10.1177/00222194030360060601

Sormaz, M., Murphy, C., Wang, H.-t., Hymers, M., Karapanagiotidis, T., Poerio, G., . . . Smallwood, J. (2018). Default mode network can support the level of detail in experience during active task states. *Proceedings of the National Academy of Sciences, 115*(37), 9318-9323.

Spitsyna, G., Warren, J. E., Scott, S. K., Turkheimer, F. E., & Wise, R. J. (2006). Converging language streams in the human temporal lobe. *Journal of Neuroscience, 26*(28), 7328-7336. Retrieved from http://www.jneurosci.org/content/jneuro/26/28/7328.full.pdf

Spreng, R. N., & Grady, C. L. (2010). Patterns of brain activity supporting autobiographical memory, prospection, and theory of mind, and their relationship to the default mode network. *Journal of cognitive neuroscience, 22*(6), 1112-1123.

Spreng, R. N., Mar, R. A., & Kim, A. S. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: a quantitative meta-analysis. *Journal of Cognitive Neuroscience, 21*(3), 489-510. doi:10.1162/jocn.2008.21029

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

Springer, K., & Keil, F. C. (1991). Early differentiation of causal mechanisms appropriate to biological and nonbiological kinds. *Child Development, 62*(4), 767-781. doi:10.1111/j.1467-8624.1991.tb01568.x

Stampacchia, S., Thompson, H. E., Ball, E., Nathaniel, U., Hallam, G., Smallwood, J., . . . Jefferies, E. (2018). Shared processes resolve competition within and between episodic and semantic memory: Evidence from patients with LIFG lesions. *Cortex, 108*, 127-143.

Staresina, B. P., Henson, R. N., Kriegeskorte, N., & Alink, A. (2012). Episodic reinstatement in the medial temporal lobe. *Journal of Neuroscience, 32*(50), 18150-18156.

Stawarczyk, D., Majerus, S., Maquet, P., & D'Argembeau, A. (2011). Neural correlates of ongoing conscious experience: both task-unrelatedness and stimulus-independence are related to default network activity. *PloS one, 6*(2), e16997.

Steinvorth, S., Levine, B., & Corkin, S. (2005). Medial temporal lobe structures are needed to re-experience remote autobiographical memories: evidence from HM and WR. *Neuropsychologia, 43*(4), 479-496.

Stiers, P., & Goulas, A. (2018). Functional connectivity of task context representations in prefrontal nodes of the multiple demand network. *Brain Structure and Function, 223*(5), 2455-2473.

Stiers, P., Mennes, M., & Sunaert, S. (2010). Distributed task coding throughout the multiple demand network of the human frontal–insular cortex. *Neuroimage, 52*(1), 252-262.

Summerfield, J. J., Hassabis, D., & Maguire, E. A. (2009). Cortical midline involvement in autobiographical memory. *Neuroimage, 44*(3), 1188-1200.

Svoboda, E., McKinnon, M. C., & Levine, B. (2006). The functional neuroanatomy of autobiographical memory: a meta-analysis. *Neuropsychologia, 44*(12), 2189-2208.

Swinney, D. A. (1979). Lexical access during sentence comprehension:(Re) consideration of context effects. *Journal of verbal learning and verbal behavior, 18*(6), 645-659.

Tabossi, P. (1982). Sentential context and the interpretation of unambiguous words. *The Quarterly Journal of Experimental Psychology, 34*(1), 79-90.

Tabossi, P. (1988). Accessing lexical ambiguity in different types of sentential contexts. *Journal of memory and language, 27*(3), 324-340.

Tarhan, L. Y., Watson, C. E., & Buxbaum, L. J. (2015). Shared and distinct neuroanatomic regions critical for tool-related action production and recognition: Evidence from 131 left-hemisphere stroke patients. *Journal of Cognitive Neuroscience, 27*(12), 2491-2511.

Teige, C., Cornelissen, P. L., Mollo, G., Alam, T. R. d. J. G., McCarty, K., Smallwood, J., & Jefferies, E. (2019). Dissociations in semantic cognition: Oscillatory evidence for opposing effects of semantic control and type of semantic relation in anterior and posterior temporal cortex. *Cortex, 120*, 308-325.

Teige, C., Mollo, G., Millman, R., Savill, N., Smallwood, J., Cornelissen, P. L., & Jefferies, E. (2018). Dynamic semantic cognition: Characterising coherent and controlled conceptual retrieval through time using magnetoencephalography and chronometric transcranial magnetic stimulation. *Cortex, 103*, 329-349.

Thompson-Schill, S., Aguirre, G., Desposito, M., & Farah, M. (1999). A neural basis for category and modality specificity of semantic knowledge. *Neuropsychologia, 37*(6), 671-676.

Thompson-Schill, S. L., Bedny, M., & Goldberg, R. F. (2005). The frontal lobes and the regulation of mental activity. *Current Opinion in Neurobiology, 15*(2), 219-224. doi:org/10.1016/j.conb.2005.03.006

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proceedings of the National Academy of Sciences, 94*(26), 14792-14797.

Thompson, H., Almaghyuli, A., Noonan, K. A., Ralph, L., Matthew, A., & Jefferies, E. (2018). The contribution of executive control to semantic cognition: Convergent evidence from semantic aphasia and executive dysfunction. *Journal of Neuropsychology, 12*(2), 312-340. doi:10.1111/jnp.12142

Thompson, H., Davey, J., Hoffman, P., Hallam, G., Kosinski, R., Howkins, S., . . . Jefferies, E. (2017). Semantic control deficits impair understanding of thematic relationships more than object identity. *Neuropsychologia, 104*, 113-125. doi:10.1016/j.neuropsychologia.2017.08.013

Thompson, H. E., Henshall, L., & Jefferies, E. (2016). The role of the right hemisphere in semantic control: A case-series comparison of right and left hemisphere stroke. *Neuropsychologia, 85*, 44-61. doi:10.1016/j.neuropsychologia.2016.02.030

Tranel, D., Kemmerer, D., Adolphs, R., Damasio, H., & Damasio, A. R. (2003). Neural correlates of conceptual knowledge for actions. *Cognitive Neuropsychology, 20*(3-6), 409-432.

Trumpp, N. M., Kliese, D., Hoenig, K., Haarmeier, T., & Kiefer, M. (2013). Losing the sound of concepts: Damage to auditory association cortex impairs the processing of sound-related concepts. *Cortex, 49*(2), 474-486.

Tsagkaridis, K., Watson, C. E., Jax, S. A., & Buxbaum, L. J. (2014). The role of action representations in thematic object relations. *Frontiers in human neuroscience, 8*, 140.

Turken, A. U., & Dronkers, N. F. (2011). The neural architecture of the language comprehension network: converging evidence from lesion and connectivity analyses. *Frontiers in systems neuroscience, 5*, 1.

Turnbull, A., Wang, H.-T., Schooler, J. W., Jefferies, E., Margulies, D. S., & Smallwood, J. (2019). The ebb and flow of attention: Between-subject variation in intrinsic connectivity and cognition associated with the dynamics of ongoing experience. *NeuroImage, 185*, 286-299. doi:10.1016/j.neuroimage.2018.09.069

Turnbull, A., Wang, H., Murphy, C., Ho, N., Wang, X., Sormaz, M., . . . Smallwood, J. (2019). Left dorsolateral prefrontal cortex involvement in context-dependent prioritisation of off-task thought. *Nature Communications, 10*(1), 1-10.

Tyler, L. K., Chiu, S., Zhuang, J., Randall, B., Devereux, B. J., Wright, P., . . . Taylor, K. I. (2013). Objects and categories: feature statistics and object processing in the ventral stream. *Journal of Cognitive Neuroscience, 25*(10), 1723-1735.

Tyler, S. C., Dasgupta, S., Agosta, S., Battelli, L., & Grossman, E. D. (2015). Functional connectivity of parietal cortex during temporal selective attention. *cortex, 65*, 195-207.

Uddin, L. Q., Supekar, K., Amin, H., Rykhlevskaia, E., Nguyen, D. A., Greicius, M. D., & Menon, V. (2010). Dissociable connectivity within human angular gyrus and intraparietal sulcus: evidence from functional and structural connectivity. *Cerebral Cortex, 20*(11), 2636-2646. doi:10.1093/cercor/bhq011

Van Dijk, T. A., Kintsch, W., & Van Dijk, T. A. (1983). *Strategies of discourse comprehension*. New York: Academic Press.

van Loon, A. M., Olmos-Solis, K., Fahrenfort, J. J., & Olivers, C. N. (2018). Current and future goals are represented in opposite patterns in object-selective cortex. *Elife, 7*, e38677.

Vandenberghe, R., Price, C., Wise, R., Josephs, O., & Frackowiak, R. S. (1996). Functional anatomy of a common semantic system for words and pictures. *Nature, 383*(6597), 254-256.

Vatansever, D., Bzdok, D., Wang, H.-T., Mollo, G., Sormaz, M., Murphy, C., . . . Jefferies, E. (2017). Varieties of semantic cognition revealed through simultaneous decomposition of intrinsic brain connectivity and behaviour. *NeuroImage, 158*, 1-11. doi:10.1016/j.neuroimage.2017.06.067

Vatansever, D., Karapanagiotidis, T., Margulies, D. S., Jefferies, E., & Smallwood, J. (2019). Distinct patterns of thought mediate the link between brain functional connectome and psychological well-being. *bioRxiv*, 762344.

Vatansever, D., Menon, D. K., Manktelow, A. E., Sahakian, B. J., & Stamatakis, E. A. (2015). Default mode dynamics for global functional integration. *Journal of Neuroscience, 35*(46), 15254-15262.

Vetter, P., Smith, F. W., & Muckli, L. (2014). Decoding sound and imagery content in early visual cortex. *Current Biology, 24*(11), 1256-1262.

Vidaurre, D., Smith, S. M., & Woolrich, M. W. (2017). Brain network dynamics are hierarchically organized in time. *Proceedings of the National Academy of Sciences, 114*(48), 12827-12832. doi:10.1073/pnas.1705120114

Visser, M., Jefferies, E., Embleton, K. V., & Lambon Ralph, M. A. (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. doi:10.1162/jocn_a_00244

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

Visser, M., & Lambon Ralph, M. (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. doi:10.1162/jocn_a_00007

Wagner, A. D., Paré-Blagoev, E. J., Clark, J., & Poldrack, R. A. (2001). Recovering meaning: left prefrontal cortex guides controlled semantic retrieval. *Neuron, 31*(2), 329-338. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/11502262

Wallentin, M., Nielsen, A. H., Vuust, P., Dohn, A., Roepstorff, A., & Lund, T. E. (2011). BOLD response to motion verbs in left posterior middle temporal gyrus during story comprehension. *Brain and language, 119*(3), 221-225.

Wang, H.-T., Bzdok, D., Margulies, D., Craddock, C., Milham, M., Jefferies, E., & Smallwood, J. (2018). Patterns of thought: population variation in the associations between large-scale network organisation and self-reported experiences at rest. *Neuroimage, 176*, 518-527. doi:10.1016/j.neuroimage.2018.04.064

Wang, X., Gao, Z., Smallwood, J., & Jefferies, E. (2020). Both default and multiple-demand regions represent semantic goal information. *bioRxiv*.

Wang, X., Margulies, D. S., Smallwood, J., & Jefferies, E. (2020). A gradient from long-term memory to novel cognition: graded transitions through default mode and executive cortex. *bioRxiv*.

Wang, X., Xu, Y., Wang, Y., Zeng, Y., Zhang, J., Ling, Z., & Bi, Y. (2018). Representational similarity analysis reveals task-dependent semantic influence of the visual word form area. *Scientific reports, 8*(1), 3047. doi:10.1038/s41598-018-21062-0

Wen, T., Duncan, J., & Mitchell, D. J. (2020). Hierarchical representation of multi-step tasks in multiple-demand and default mode networks. *bioRxiv*, 582858.

Whitfield-Gabrieli, S., & Nieto-Castanon, A. (2012). Conn: a functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain connectivity, 2*(3), 125-141.

Whitmore, J. M., Shore, W. J., & Smith, P. H. (2004). Partial knowledge of word meanings: Thematic and taxonomic representations. *Journal of Psycholinguistic Research, 33*(2), 137-164.

Whitney, C., Kirk, M., O'sullivan, J., Lambon Ralph, M. A., & Jefferies, E. (2010). The neural organization of semantic control: TMS evidence for a distributed network in left inferior frontal and posterior middle temporal gyrus. *Cerebral Cortex, 21*(5), 1066-1075. doi:10.1093/cercor/bhq180

Whitney, C., Kirk, M., O'Sullivan, J., Lambon Ralph, M. A., & Jefferies, E. (2012). Executive semantic processing is underpinned by a large-scale neural network: revealing the contribution of left prefrontal, posterior temporal, and parietal cortex to controlled retrieval and selection using TMS. *Journal of Cognitive Neuroscience, 24*(1), 133-147. doi:DOI 10.1162/jocn_a_00123

Wirth, M., Jann, K., Dierks, T., Federspiel, A., Wiest, R., & Horn, H. (2011). Semantic memory involvement in the default mode network: a functional neuroimaging study using independent component analysis. *NeuroImage, 54*(4), 3057-3066. doi:10.1016/j.neuroimage.2010.10.039

Witt, J. K., Kemmerer, D., Linkenauger, S. A., & Culham, J. (2010). A functional role for motor simulation in identifying tools. *Psychological science, 21*(9), 1215-1219.

Woolgar, A., Hampshire, A., Thompson, R., & Duncan, J. (2011). Adaptive coding of task-relevant information in human frontoparietal cortex. *Journal of Neuroscience, 31*(41), 14592-14599. doi:10.1523/JNEUROSCI.2616-11.2011

Woolgar, A., & Zopf, R. (2017). Multisensory coding in the multiple-demand regions: vibrotactile task information is coded in frontoparietal cortex. *Journal of Neurophysiology, 118*(2), 703-716.

Woolrich, M. (2008). Robust group analysis using outlier inference. *NeuroImage, 41*(2), 286-301. doi:10.1016/j.neuroimage.2008.02.042

Woolrich, M. W., Ripley, B. D., Brady, M., & Smith, S. M. (2001). Temporal autocorrelation in univariate linear modeling of FMRI data. *NeuroImage, 14*(6), 1370-1386.

Xu, J., Kemeny, S., Park, G., Frattali, C., & Braun, A. (2005). Language in context: emergent features of word, sentence, and narrative comprehension. *NeuroImage, 25*(3), 1002-1015. doi:org/10.1016/j.neuroimage.2004.12.013

Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. *Nature methods, 8*(8), 665-670. doi:10.1038/nmeth.1635

Yee, E., Chrysikou, E. G., Hoffman, E., & Thompson-Schill, S. L. (2013). Manual experience shapes object representations. *Psychological science, 24*(6), 909-919. doi:10.1177/0956797612464658

Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., . . . Polimeni, J. R. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology, 106*(3), 1125-1165. doi:10.1152/jn.00338.2011

Zempleni, M.-Z., Renken, R., Hoeks, J. C., Hoogduin, J. M., & Stowe, L. A. (2007). Semantic ambiguity processing in sentence context: Evidence from event-related fMRI. *Neuroimage, 34*(3), 1270-1279.

Zhang, J. X., Zhuang, J., Ma, L., Yu, W., Peng, D., Ding, G., . . . Weng, X. (2004). Semantic processing of Chinese in left inferior prefrontal cortex studied with reversible words. *NeuroImage, 23*(3), 975-982. doi:10.1016/j.neuroimage.2004.07.008

Zhang, M., Savill, N., Margulies, D. S., Smallwood, J., & Jefferies, E. (2019). Distinct individual differences in default mode network connectivity relate to off-task thought and text memory during reading. *Scientific reports, 9*(1), 1-13.

Zhao, Y., Song, L., Ding, J., Lin, N., Wang, Q., Du, X., . . . Han, Z. (2017). Left anterior temporal lobe and bilateral anterior cingulate cortex are semantic hub regions: Evidence from behavior-nodal degree mapping in brain-damaged patients. *Journal of Neuroscience, 37*(1), 141-151. doi:10.1523/JNEUROSCI.1946-16.2016

Zwaan, R. A., & Radvansky, G. A. (1998). Situation models in language comprehension and memory. *Psychological bulletin, 123*(2), 162-185.