The neural and computational bases of semantic cognition.

Matthew A. Lambon Ralph1, Elizabeth Jefferies2, Karalyn Patterson3 & Timothy T. Rogers4

1. Neuroscience & Aphasia Research Unit, School of Psychological Sciences, University of Manchester, UK

2. Department of Psychology and York Neuroimaging Centre, University of York, UK

3. MRC Cognition & Brain Sciences Unit, Cambridge, UK & Department of Clinical Neurosciences, University of Cambridge, UK

4. Department of Psychology, University of Wisconsin-Madison, USA

Address for correspondence:

Prof. M.A. Lambon Ralph (matt.lambon-ralph@manchester.ac.uk)

Neuroscience and Aphasia Research Unit (NARU)

School of Psychological Sciences

University of Manchester

Zochonis Building

Brunswick Street

Manchester

M13 9PL

UK

Tel: +44 (0)161 275 2551

Abstract: 92 words

Main test: 5988 words

Display items: 3 Figures and 4 Boxes

Acknowledgements

We are indebted to all of the patients and their carers for their continued support of our research programme. This research was supported by an MRC Programme grant to MALR (MR/J004146/1). Jefferies was supported by a grant from the European Research Council (283530-SEMBIND).

**Abstract**

Semantic cognition refers to our ability to use, manipulate and generalise knowledge acquired over the lifespan in support of innumerable verbal and nonverbal behaviours. This review summarizes key findings and issues arising from a decade of research into the neuro-cognitive and neuro-computational underpinnings of this ability, leading to a new approach that we call *controlled semantic cognition* (CSC). CSC offers solutions to long-standing queries in philosophical and cognitive science, and yields a convergent framework for understanding the neural and computational bases of both healthy semantic cognition and its disorders in brain disease.

**Introduction**

*Semantic cognition* refers to the collection of neurocognitive mechanisms that support semantically-imbued behaviours. We deploy our semantic knowledge not only to produce and understand language but also in support of many nonverbal behaviours. Receptively, semantic knowledge transforms the sensory cacophony into a symphony of meaning, allowing us to recognize and make inferences about objects and events in the environment. Expressively, it provides the foundation for everyday behaviour. To spread jam on bread, for example, one must recognize the jam jar, bread and knife, infer their unobserved qualities (bread is soft, knives are rigid, jam is sticky, etc.) and deploy the appropriate praxis (seizing the knife handle in a particular grip so as to scoop out the jam) in service of the current goal (getting the jam out of the jar and spreading it across the bread so it can be eaten)—all tasks that require knowledge about both the objects and the actions. Accordingly, patients with semantic impairment consequent on brain disease have significant language and nonverbal disabilities that profoundly disrupt their everyday lives. Given its fundamental nature, semantic cognition has unsurprisingly received the attention of many disciplines, from the time of the ancient Greek philosophers through the rise of 19th century neurology and 20th century cognitive science, to contemporary neuroscience.

The current article reviews a decade of research suggesting that semantic cognition relies on two principal interacting neural systems. The first is a system of *representation* that encodes knowledge of conceptual structure through learning the higher-order relations among various sensory, motor, linguistic and affective components widely distributed in cortex. Conceptual representations are distilled within this system from life-long verbal and nonverbal experience1-4, and serve to promote knowledge generalisation across items and contexts5-7. The second is a system of *control* that shapes or manipulates activation within the representational system in order to generate inferences and behaviours suited to a specific temporal or task context8-12. We refer to this view as the *controlled semantic cognition (CSC)* framework. In what follows we review the converging evidence for each part of the CSC framework and consider how it reconciles long-standing puzzles from studies of both healthy and disordered semantic cognition.

**Semantic representation**

*The hub-and-spoke theory*

Around a decade ago, we and others proposed the ‘hub-and-spoke’ theory for semantic representation6,7 [Fig.1], which explained how knowledge of conceptual structure might arise through learning about the statistical structure of our multimodal experiences10, and also proposed some neuroanatomical underpinnings for these abilities, accounting for patterns of impairment observed in some semantic disorders7,13. The hub-and-spoke theory assimilated two important, existing ideas. First, in keeping with Meynert and Wernicke’s classical view14 and contemporary ‘embodied’ approaches1,15 [Box 1], the model assumed (a) that multimodal verbal and nonverbal experiences provide the core ‘ingredients’ for constructing concepts and (b) that these information sources are encoded in modality-specific cortices, distributed across the brain (the ‘spokes’)1,16. Second, the model proposed that cross-modal interactions for all conceptual domains are mediated, at least in part, by a single transmodal hub situated bilaterally in the anterior temporal lobes (ATL). This second idea runs counter to some classical hypotheses and to contemporary “distributed-only” semantic theories, which have assumed that concepts arise through direct connections among modality-specific regions without a common transmodal region.

The ATL-hub view was motivated by both empirical and computational observations. The empirical motivation stemmed from cognitive neuropsychology. It was already known that damage to higher-order association cortex could produce striking transmodal semantic impairments, leading some to propose the existence of multiple cross-modal “convergence zones”, possibly specialized to represent different conceptual domains17. Detailed study of the striking disorder called *semantic dementia*18 (SD; Fig.1E & Fig.S1.B), however, suggested that one transmodal region might be important for *all* conceptual domains19,20, since SD patients show semantic impairments across all modalities21 and virtually all types of concept13,22 (with the exception of simple numerical knowledge23). Several additional characteristics of the impairment in SD seem compatible only with an explanation in terms of disruption to a central, transmodal hub: there is a markedly consistent pattern of deficit across tasks despite wide variation in the modality of stimulus, response or type of knowledge required. SD patients’ likelihood of success can always be predicted by the item’s familiarity (lower is worse: Fig.1E), its typicality within its domain (atypical is worse: Fig.S2), and the specificity of the knowledge required24,25 [Fig.S2]. Unlike some forms of dementia (like Alzheimer’s disease) that produce widespread pathology26, atrophy and hypometabolism in SD are centred on the anterior ventral and polar temporal regions bilaterally27,28 [Fig.1E], generating the proposal that these regions serve as a transmodal domain-general conceptual hub.

Computationally, the hub-and-spoke hypothesis provided a solution to the challenges of building coherent, generalizable concepts which have been highlighted in philosophy29 and cognitive science30-32 (for a more detailed discussion, see5,10,33). One challenge is that information relevant to a given concept is experienced across different verbal and sensory modalities, contexts and time-points. Another is that conceptual structure is not transparently reflected in the sensory, motor or linguistic structure of the environment—instead, the relationship between conceptual structure and modality-specific features is complex, variable and non-linear5,20. It is difficult to see how these challenges could be met by a system that simply encodes direct associations amongst the modality-specific information sources, but they can be solved by neural network models that adopt an intermediating hub for all concepts and modalities10.

*New discoveries about the ATL hub*

While other brain regions have long been a target of research in semantics [Box 2], the ATL’s role had received little prior attention. Although patients with semantic dementia were reported over a century ago, the link between semantic impairment and ATL damage only became apparent with modern neuroimaging techniques19. Classical language models were based on patients with MCA stroke, which is unlikely to damage the middle to ventral ATL (and bilaterally)34. Likewise, there is a bias within fMRI studies which, due to various methodological issues, have consistently under-sampled activation in the middle and inferior ATL35. Since the initial ATL-hub proposal, the region’s role in semantic processing has been studied extensively using converging methodologies. Together, the work corroborates and extends several predictions of the hypothesis, and clarifies the anatomical organization and functioning of this region.

*The cross-modal hub is centred on the ventrolateral ATL.* Figure 1.D-F shows results from a range of methods validating key postulates of the original hub-and-spoke model. (a) The ATLs are engaged in semantic processing irrespective of input modality (e.g., words, pictures, sounds, etc.) and conceptual categories36-39. (b) Though the hub is more strongly engaged for more specific concepts40,41 (e.g., *Pekinese*), it also supports basic (e.g., *dog*) and domain-level (e.g., *animal*) distinctions39,42. (c) Both left and right ATLs are implicated in verbal and nonverbal semantic processing43,44 [Box 3; Fig.S3]. (d) ATL function is semantically-selective insofar as these regions are not engaged in equally-demanding non-semantic tasks36,40,45.

These methods also provide important information that cannot be extracted from SD studies alone. (a) Distortion-corrected fMRI, cortical grid-electrode stimulation and electrocorticography (ECoG), and functional-FDG PET in SD [Fig.2C], all indicate that the ventral/ventrolateral ATL is the cross-modal centre-point of the hub for multimodal naming46-48 and comprehension36,39,44,46. (b) As predicted by the hub-and-spoke model, multi-voxel pattern analyses of fMRI49 and ECoG50 data have shown semantic coding and the representational merging of modality-specific information sources51 in the same area [Fig.2D]. (c) Detailed semantic information is activated in the vATL from 250ms post onset [Fig.2D-E], while coarse, domain-level distinctions may be available earlier (~120ms)46,52-54. (d) Inhibitory transcranial magnetic stimulation (TMS) of the lateral ATL produces domain-general semantic slowing, while TMS of “spoke” regions produces a category-sensitive effect42 [Fig.1C]—confirming the importance of both hub and spokes in semantic representation. (e) In healthy participants, ATL regions exhibit intrinsic (resting-state fMRI) connectivity with modality-specific areas, and in SD patients, comprehension accuracy reflects both the degree of ATL atrophy and the reduction in hub-spoke functional connectivity28. Together this body of work suggests that the cross-modal hub is centred on the ventrolateral ATL and also corroborates core predictions of the hub-and-spoke view: namely, that this region plays the important predicted role of coordinating communication amongst modality-specific “spokes”; and that, in so doing, it encodes semantic similarity structure amongst items.

*The broader ATL is graded in its function.* The original hub-and-spoke model said little about different ATL subregions, partly because the atrophy distribution in SD is extremely consistent (being maximal in polar and ventral ATL regions)55 [Fig.2C]. Likewise there is little variation in the patients’ multimodal semantic impairments, apart from some impact of whether the ATL atrophy is more severe on the left or right early in the course of the disease [Box 3]. New evidence indicates not only that the ventrolateral ATL is the centre-point of the hub (as reviewed above) but also that function varies in a graded fashion across ATL subregions [Fig.2A-B].

The first clue for graded functional variation comes from cytoarchitecture. Brodmann56 divided the anterior temporal region into several different areas and modern neuroanatomical techniques have generated finer differentiations57. Brodmann also noted, however, that the cytoarchitectonic changes in temporal cortex were graded (*“to avoid erroneous interpretations it should again be stated that not all these regions are demarcated from each other by sharp borders but may undergo gradual transitions as, for example, in the temporal and parietal regions.”* [p.106]). This observation is replicated in the contemporary cytoarchitectonic investigations57, indicating potentially graded patterns of functional differentiation.

The second insight arises from structural and functional connectivity. Consistent with the hub-and-spoke model, major white-matter fasciculi in both humans and non-human primates converge in ATL regions58,59; however their points of termination are only partially overlapping, leading to graded partial differentiations in gross connectivity across ATL subregions58-60. For instance, the uncinate fasciculus connects orbitofrontal and pars orbitalis more heavily to temporopolar cortex; other prefrontal connections through the extreme capsule complex terminate more in superior ATL regions, as does the middle longitudinal fasciculus from the inferior parietal lobule; and the inferior longitudinal fasciculus connects most strongly to ventral and ventromedial ATL. The effects of these partially overlapping fasciculus terminations are made more graded through the strong local u-fibre connections in the ATL58. A similar pattern of partially-overlapping connectivity has also been observed in resting-state and active fMRI data61,62: in addition to strong intra-ATL connectivity, temporopolar cortex demonstrates greater functional connectivity to orbitofrontal areas; inferolateral ATL exhibits more connectivity to frontal and posterior regions associated with semantic processing; and superior ATL connects more strongly to primary auditory and premotor regions.

Third, recent neuroimaging results (which have addressed ATL-semantic methodological issues35,63) are highly consistent with a graded connectivity-driven model of ATL function [Fig.2A]. As noted above, the ventrolateral area activates strongly in semantic tasks irrespective of input modality or stimulus category36,39,44,64. Moving away from this centrepoint, semantic function becomes weaker yet tied more to a specific input modality [Fig.2B]. Thus more medial ATL regions show greater responsiveness to picture-based materials and concrete concepts than other types of material44,65,66. Anterior STS/STG exhibits the opposite pattern, with greater activation for auditory stimuli, spoken words and abstract concepts39,65,67 and an overlapping region of STG has been implicated in combinatorial semantic processes68,69. Finally, polar and dorsal ATL areas have shown preferential activity for social over other kinds of concept70,71.

One explanation of these variations would posit multiple mutually-exclusive areas dedicated to different categories or representational modalities17,72,73. Yet there are two problems with this view. First, it is not consistent with the cytoarchitectonic, connectivity and functional data, all of which suggest graded functional specialization rather than discrete functional regions. Second, such an account does not explain the role of the hub, which appears to support knowledge across virtually all domains and modalities. An alternative view is that the ATL hub exhibits *graded functional specialization*33,58,74,75[Fig.2], with the responsivity of different subregions reflecting graded differences in their connectivity to the rest of the network. On this view, the neuroimaging findings noted above reflect the fact that neighbouring ATL regions contribute somewhat more or less to representation of different kinds of information, depending on the strength of their interactions with various modality-specific representational systems.

Such graded functional specialization arises directly from the influence of connectivity on function58,76. In a close variant of the hub-and-spoke model, Plaut76 introduced distance-dependent connection strengths to the modality-specific spokes. The importance of each unit to a given function depended on its connectivity strength to the spokes. Central hub units furthest from all inputs contributed equally to all semantic tasks; units anatomically closer to a given modality-specific spoke took part in all types of semantic processing but contributed somewhat more to tasks involving the proximal modality. For instance, hub units situated near to visual representations would contribute more to tasks like picture naming but less to non-visual tasks (e.g., naming to definition). The *graded hub hypothesis* extends this proposal by assuming that ATL functionality is shaped by the long-range cortical connectivity [Fig.2A]. Thus, medial ATL responds more to visual/concrete concepts by virtue of greater connectivity to visual than to auditory or linguistic systems; STS/STG contributes more to abstract concepts and verbal semantic processing by virtue of its greater connectivity to language than to visual systems; and temporal pole contributes somewhat more to social concepts by virtue of its connectivity to networks that support social cognition and affect. The ventrolateral ATL remains important for all domains because it connects equally to these different systems.

We note here that this type of graded function is not unique to the ATL hub region or semantic processing. Indeed, other cortical regions and types of processing (e.g., the visual and auditory processing streams) also demonstrate graded functional profiles77,78 which follow the underlying patterns of connectivity79. As such it suggests (a) that connectivity-induced graded functions may be a neural universal and (b) that information arriving at the ATL hub has already been partially processed in these graded non-ATL regions and through the interaction between the ATL and modality-specific regions52,80.

*Category-specificity and the graded-hub framework*

Theories of semantic representation and its neural basis have been strongly influenced by two sets of neuropsychological and functional neuroimaging data, leading to two different theoretical positions. One literature has focussed on the general semantic impairment observed in some types of brain disease, demonstrating largely equivalent disruption across types of knowledge. Such data support proposals―including the hub-and-spoke model―that the cortical semantic system is widely distributed and interactive but needs a transmodal component to capture coherent, generalizable concepts5,7. The second literature focusses on ‘category-specific’ processing/deficits in which different categories of knowledge can be differentially disrupted in neurological disorders or yield differential activation in specific healthy brain regions. Perhaps the most commonly studied, though by no means the sole, contrast is between natural kinds vs. manmade items81,82. Such evidence has been used to argue that anatomically distinct and functionally independent neural systems have evolved to support knowledge about different conceptual domains (e.g. animals, tools, faces, scenes, etc.)83,84.

Recent empirical and computational investigations have enhanced the hub-and-spoke framework into a unified theory which may account for both sets of data. In the neuropsychological literature, several large case-series investigations provide contrastive patterns of semantic impairment and clear information about the critical neural regions. A few examples are: (a) SD patients with bilateral ATL atrophy who have generalised semantic impairment and largely similar performance levels across different categories of knowledge (once other important performance factors, especially stimulus familiarity and typicality, are controlled)25,85; (b) patients with posterior ventral occipito-temporal (vOT) lesions who can present with relatively poor performance on natural kinds86; (c) patients with anteromedially-centred temporal-lobe damage following an acute period of herpes simplex virus encephalitis (HSVE) who also tend to have strikingly worse performance on natural kinds13,87; and (d) patients with temporoparietal damage who show relatively greater deficits for praxis-related manmade items88,89. These contrastive behavioural-anatomical associations for general vs. category-specific semantic impairments find counterparts in convergent evidence from other techniques, including functional neuroimaging and inhibitory TMS in healthy participants, and cortical electrode studies of neurosurgical patients36,42,46,82,90.

All these findings can be captured by the connectivity-constrained version of the hub-and-spoke model91. The first key notion, already expressed but worth reiterating, is that semantic representations are not just hub-based but reflect collaboration between hub *and* spokes42[Fig.1A-C]. The second is that, consistent with embodied semantic models1, modality-specific information (e.g., praxis) will be differentially important for some categories (e.g., tools). It follows that the progressive degradation of the ATL transmodal hub in SD patients will generate a category-general pattern, whilst selective damage to spokes can lead to category-specific deficits. Thus impaired praxis/functional knowledge is deleterious for manipulable manmade items89,92 whereas reduced high acuity visual input is particularly challenging for the differentiating between animals given their shared visual contours86,93. The differential contributions of hub vs. spokes in semantic representation have been demonstrated using TMS in neurologically-intact participants. Participants exhibit a category-general effect following lateral ATL stimulation but a category-specific pattern with poorer performance for manmade objects when the praxis-coding parietal region is directly stimulated42. The connectivity-constrained hub-and-spoke model also offers insights into other empirical observations noted above. For example, the medial vOT region exhibits greater activation for manmade items, in part because it is directly connected to the parietal praxis-coding regions94; and an explanation in these terms91 accounts for the evidence that congenitally-blind participants show greater activation for manmade items in this ‘visual’ region84.

A remaining challenge is to explain the difference between semantically-impaired HSVE and SD patients: despite highly-overlapping areas of ATL damage (albeit more medially-focussed in HSVE)95, a significant advantage for manmade artefacts over natural-kind concepts is relatively common in HSVE4,95 and very rare in SD13. A critical factor in this particular category effect, acknowledged in one form or another by virtually all researchers who have studied it, is the following. Recall that concepts can be categorised at superordinate [*animal, tool*], basic [*dog, knife*] or specific [*poodle, bread knife*] levels. Most semantic research has focussed on the basic level and, at this conceptually salient level, animate or natural kind concepts tend to be visually and conceptually more similar to one another and hence more confusable, than manmade things13,66,96. It is therefore an extremely important clue that the artefact > animate pattern in HSVE holds for superordinate and basic levels but is eliminated at the subordinate level, where the HSVE cases are equally and severely impaired at both categories13. The obvious interpretation, though as yet requiring more evidence, is that the medial temporal lobe region typically damaged by the herpes virus is critical not for distinguishing between living things but between visually- or semantically-confusable things86,95,97, which include different types of knife as well as different breeds of dog. This possibility is compatible with the graded hub-and-spoke hypothesis and the existing evidence of graded, connectivity-driven differential contributions to abstract and concrete concepts across ATL subregions65 [Fig.2B], with a preference for concrete items in the medial ATL58,59.

One further factor meriting mention is the fact that SD is a neurodegenerative disease, yielding steady degradation of the ATL and consequently of conceptual knowledge. Although the patients continue to be surrounded by the multi-modal experiences that continuously reinforce and extend conceptual knowledge in a healthy brain, the slow-but-constant deterioration in SD is largely incompatible with re-learning. By contrast, successfully-treated HSVE is an acute illness followed by some degree of recovery and re-learning. These differences can be mimicked in the hub-and-spoke computational model by comparing progressive degradation against *en masse* hub damage followed by a period of retraining: the former generates a category-general effect whereas the latter results in manmade > animate performance. This outcome arises because, with reduced representational resources, the model struggles to recapture sufficient ‘semantic acuity’ to differentiate between the conceptually-tightly packed animate items and subordinate exemplars.

**Semantic control**

*What is semantic control?*

In everyday life, activity within the network for semantic representation must often be *controlled* to ensure that the system generates representations and inferences that are suited to the immediate task or context. Some tasks may require one to accentuate subordinate meanings, focus attention on non-dominant features, or suppress strong associates of a given concept. Furthermore, the critical aspects of meaning can change for the same concept over time, both in language and nonverbal behaviours. Imagine, for example, the very different uses of the same knife when making a cheese and chutney sandwich: packet *opening*, bread *cutting*, butter *spreading*, cheese *slicing*, chutney *scooping*, etc. Each requires different, specific aspects of the knife’s properties to be brought to the fore, one by one, whilst the most commonly listed property of *cutting* has to be regularly inhibited. In the case of *scooping*, the canonical function of the knife has to be disregarded altogether and replaced by a function typically served by another object (spoon). In addition, the semantic representations evoked by objects and words must be shaped to align with the immediate context—for instance, to overcome moments of ambiguity or confusion9,11,12 that follow when new inputs are hard to integrate with the meaning of the established or evolving context98.

The CSC framework proposes that control of semantic cognition is implemented within a distributed neural network that interacts with, but is largely separate from, the network for semantic representation. Consistent with extensive work on cognitive control generally9,99-101 and its role in semantic retrieval specifically11,12, the control network is thought to support working memory and executive representations that encode information about the temporal, situational and task context relevant to the current behaviour. These executive mechanisms constrain how activation propagates through the network for semantic representation. In well-practiced contexts where the relevant information is robustly encoded, the representation network needs little input from semantic control to produce the correct response. Contexts requiring retrieval of weakly encoded information, suppression of over-learned responses, emphasis of uncharacteristic features, and so on, depend more strongly on input from the control network. As with the hub-and-spoke model, this perspective has both converging empirical evidence (see below) and computational motivations (Box 4).

*Disorders of semantic control.* Head102 and later Luria103 investigated patients with disordered semantic retrieval arising from penetrative missile wounds to the temporoparietal region. They noted both that the patients had difficulties in manipulating and using knowledge rather than total loss of semantic knowledge, and that this deficit co-occurred with other types of ‘symbolic’ processing deficits. Head coined the term *semantic aphasia* (SA) to describe this pattern. A similar profile was also reported by Goldstein104 for a subset of patients with post-stroke aphasia. Later, Warrington and colleagues105,106 contrasted the consistent semantic ‘store’ deficits in SD with the inconsistent semantic ‘access’ deficits found in some patients with global aphasia following large MCA stroke. Detailed case-series comparisons of SD and SA8,25 have recently delineated several qualitative differences between the two patient groups [Fig.3D] in both verbal and nonverbal domains107,108 [Fig.S2]. In contrast to SD, patients with SA exhibit [Fig.3C & S3]: (a) poorest performance on the most executively-demanding tasks and stimuli, (b) inconsistent performance across tests, (c) relative insensitivity to the frequency/familiarity of the stimuli, (d) a strong influence of the ambiguity/semantic diversity of word meanings, (e) cueing and miscuing effects, (f) poor inhibition of strong competitors and associated items, (g) associative as well as coordinate and superordinate semantic errors in naming (associative errors, such as “milk” in response to a picture of a *cow*, are essentially never seen in SD), and (h) a tendency in category and letter fluency to produce strong associates of prior responses that fall outside of the target category8,25,107-110. The cueing and miscueing effects are a striking exemplar of the group differences108,110. Given a picture of a *tiger*, for example, both patients groups will likely fail to name it; with the phonological cue /t/, SD patients still fail but SA patients will often succeed; given the same picture plus /l/, SD patients again can say nothing but SA patients will often produce “lion”. All these differences are consistent with the view that the impairment in SD arises from degradation within the network for semantic representation, while the impairment in SA reflects disordered control of activation within that network.

*Converging evidence for a distributed semantic control network.* Beginning in the late 1990’s, a series of seminal fMRI studies suggested that prefrontal regions, while not encoding semantic representations *per se*, nevertheless are critical for access, retrieval or executive manipulation of semantic knowledge9,11,12. For instance, semantic tasks requiring participants to select a response from among many potentially correct options or to retrieve infrequent semantic associations, elicit greater activation in parts of PFC. Juxtaposed with the earlier patient work, this discovery generates a potential conundrum, since many patients with retrieval/access deficits had pathology in temporoparietal but not prefrontal cortex. This discrepancy has begun to resolve as evidence has amassed across methodologies [Fig.3A]. SA is now known to arise from either prefrontal or temporoparietal lesions (or both), with only small differences in the behavioural profile8,111. Likewise recent meta-analyses of fMRI studies [Fig.3B] identified regions beyond PFC where cortical responses also correlate with control demands, including posterior middle temporal gyrus (pMTG) and the intraparietal sulcus (IPS), as well as pre-supplementary motor area (pre-SMA) and anterior cingulate/ventromedial prefrontal cortex112,113. Inhibitory TMS [Fig.3C] applied to left inferior frontal, pMTG or IPS regions all transiently disrupt semantic functioning, more so in conditions that tax cognitive control114-117, suggesting that these regions jointly play a causal role in executively-demanding semantic tasks. Of course, the proposal that PFC and parietal regions function together to support cognitive control is familiar from theories about executive function and working memory more broadly (see below).

*Graded functional specialization within the control network.* A central question is whether the distributed semantic control network is functionally homogeneous or whether there are important functional subdivisions. With regard to the prefrontal versus temporoparietal distinction noted above, only relatively subtle differences are observed—for instance, anterior lesions are more likely to produce refractory effects (accumulated proactive interference from one trial to the next) in both verbal and nonverbal tasks as well as a higher rate of perseverative errors. Both phenomena may arise from an inability to properly inhibit previously-generated responses, which may be more seriously compromised by prefrontal damage8,111,118,119.

Other recent convergent evidence suggests a superior-inferior functional specialization of the control network. For instance, BOLD responses in the more dorsal and posterior aspects of the inferior frontal sulcus (IFS) correlate with executive demands across multiple domains120,121, whereas responses ventral and anterior to IFS correlate more specifically with executive demands of controlled memory retrieval – potentially supporting the promotion of relatively weak representations in both semantic and episodic memory systems9,108,122. A similar superior/inferior gradation has been observed for semantic retrieval when the nature and demands of the tasks are carefully varied9,123,124: ventral prefrontal and pMTG show increased activation during the retrieval of weak semantic associations, whilst dorsolateral prefrontal and IPS areas show increased responses when selection demands are high. Activation in the intermediate middle/lateral PFC correlated with both demands, suggesting graded specialization within PFC. Studies of functional and anatomical connectivity tell a similar story: both vPFC and pMTG robustly connect to the ATL, whereas superior aspects of the control network do not.58,62,125 Likewise, inhibitory TMS applied to ventral prefrontal cortex and pMTG (inferior network components) selectively slows semantic judgements114,115, whereas application to IPS (superior component) slows both difficult semantic *and* non-semantic decisions116. Together these results suggest a graded organization of the semantic control network in which more inferior regions, by virtue of their connectivity to the network for semantic representation, boost retrieval of weakly encoded information, while more superior regions, alongside pre-SMA and anterior cingulate cortex, contribute to a more domain-general control120.

**Relationship of the CSC to other theories**

The *controlled semantic cognition* (CSC) framework is, to our knowledge, unique in providing a joint account of representation and control within the human semantic system—an essential step towards a fuller understanding of semantic cognition and its disorders. Of course, there are already rich separate literatures on, and alternative theories of, these aspects of semantic memory. Here we briefly note the relationship between these approaches and the CSC framework.

a. *Executive-semantic processing*: The semantic control processes we described are intimately related to cognitive control frameworks that seek to explain the interaction between goals (coded in dorsal PFC) and posterior perceptual/knowledge systems (e.g., Fuster’s perception-action cycle126 and Braver’s 2014 dual control framework127). The top-down application of a task set or goal is proposed to engage the multiple-demand network, including IFS and IPS, irrespective of the type of representation (e.g., visual, motor, semantic) that has to be controlled. In the CSC, additional regions such as pMTG and vPFC that are specifically implicated in semantic control may allow the interaction of domain-general control processes with semantic representations123, for example, by allowing current goals to influence the propagation of activation within the hub-and-spoke representation network. These views also anticipate strong recruitment of pMTG and vPFC when activation within the semantic system itself triggers the engagement of control, for example, when inputs or retrieved meanings are ambiguous or unexpected98,112.

We also note that studies of semantic representation and semantic control have often advanced independently of one another. The joint consideration of both aspects is important for at least three reasons. First, there are multiple, distinct ways in which semantic knowledge can be difficult to deploy (e.g., weak, impoverished representations; ambiguous meanings; inconsistency between concepts and contexts; etc.). These depend upon the nature of the representation and may require different types of executive support.9,98 Second, semantic representation and control are very likely to be highly interactive—very little is known as yet about, for instance, the circumstances and neural systems that recruit semantic control. Third, the nature of this interaction will change if one or more of the CSC components is comprised by damage or neural stimulation, so a full understanding of these effects requires a framework addressing both control and representation.

*b*. *Semantic convergence zones*: Others have proposed that the transmission of information across distributed modality-specific systems of representation flows through multiple discrete, neural regions known as “convergence zones”. 17,73 By virtue of their connectivity to input and output systems, different zones are proposed for receptive versus expressive semantic tasks, and for different semantic categories. These ideas resonate with key proposals of the CSC: first, that the semantic network is organized around a cross-modal hub, and second, that network connectivity shapes functional specialization in this network. The two views differ, however, in other key aspects.

First, convergence zones are characterized as “pointers” that bind together semantic features distributed through cortex, but with no important representation of semantic structure. In contrast, the hub plays a critical role in discovering cross-modal similarity structures that allow for generalization across conceptually similar items5,7. The proposal that multiple discrete zones exist for different tasks and categories makes it difficult to understand the now-widely-documented task- and domain-general contributions of the ATL to semantic cognition. The graded hub proposal of the CSC accounts for both domain and modality-general patterns of impairment and cases where some modalities/domains are more impaired than others72,73,128. Finally, where convergence zones propose different functions across hemispheres,72,73,128 the CSC proposes a functionally-integrated *bilateral* hub. Computational explorations129, combined TMS-fMRI130,131 and patient fMRI132 studies all suggest that bilateral interaction is crucial to preserving semantic performance after brain damage or dysfunction (see Box 3).

*c*. *Distributed domain-specific*: Like the CSC, Mahon and Caramazza92 have proposed that different parts of the semantic neural network become tuned towards a domain as a result of their differential patterns of functional connectivity. Thus both accounts emphasise that local function is strongly influenced by connectivity and this can explain patterns of category-specific deficits or differential fMRI activation. The distributed domain-specific hypothesis is silent, however, on (i) the need for an additional transmodal hub in order to form coherent, generalizable concepts; (ii) an explanation of the multimodal, pan-category semantic impairment in semantic dementia, and relatedly (iii) the important, general role of ATL regions in semantic representation.

*d*. *Fully-distributed feature-based views*: The CSC, in common with both classical neurological models14 and other contemporary theories,1 proposes that semantic representations involve the parallel re-activation of multiple modality-specific sources of information distributed across cortex. Contemporary methods including crowd-sourcing16 and state of the art multivariate decoding of neural signals133 have reinforced this view by probing the relative weighting of different sources of information in semantic representation as well as mapping their neural location. While there is little consensus regarding exactly which cortical regions encode which kinds of properties, most investigators appear to endorse a distributed feature-based view of semantic representation. The CSC theory substantially elaborates this general view in proposing (1) a specific architecture through which modality-specific representations interact, (2) how network connectivity shapes graded functional specificity and (3) a framework for understanding how semantic control shapes the flow of activation in the network to generate context-, task- and time-appropriate behaviour.

**Future directions and questions**

1. *What is the division of labour between the hub and spokes*? As described above, the hub-and-spoke model assumes that concepts reflect both the hub and spoke representations, and their interaction. As yet incompletely understood are (i) the relative contributions of hub vs. spoke to the overall semantic representation, and (ii) the importance and duration of the interaction between hub and spokes (e.g., is the kernel of the concept available when the hub is first activated or does it require ongoing interaction between the hub-and-spokes?)
2. *How do semantic control and representation interact to generate semantic cognition*? As summarised in this review, considerable advances have been made in understanding normal and impaired semantic representation and control. Although the core computations can be cognitively- and neurally-separated, all semantic behaviours require a synchronised interaction between the two [Box 4]. We know little as yet about the nature of this interaction or, in patients, how this changes following damage to one of the systems. Progress will require elucidation of the computational mechanisms that underpin semantic control as well as their integration into the graded hub-and-spoke model.
3. *Abstract, emotional and social concepts*: Future investigations are needed to improve our understanding of how these concepts are represented across the graded hub-and-spoke neurocomputational framework, as well as the challenges they present to the control network. These next steps will build upon recent investigations which include the demonstration that the abstract-concrete distinction is multi-dimensional134 and the importance of context and semantic control for processing abstract meanings65.
4. *Different types of semantic relationship*: Feature-based approaches to semantic representation struggle to account for knowledge about the relationship between features and concepts. For instance, the relationship between *car* and *vehicle* (class inclusion) is qualitatively different from the relationship between *car* and *wheels*. Different relations support very different patterns of inductive generalization: the proposition *all vehicles can move* should generalize to *car* by virtue of the class-inclusion relation, but the proposition *all wheels are round* does not generalize to the car (cars are not round) because this kind of induction is not supported by possessive relations. Other relations, such as causal or predictive relations amongst attributes, have been a focus of study in cognitive science for decades.135,136An early articulation of the CSC theory addressed such influences at length10 but cognitive neuroscience has only started to explore the neural bases of different types of semantic relationship (e.g., taxonomic vs. thematic/associative)61,137,138. A comprehensive understanding of the neural systems that support relational knowledge awaits future work.
5. *Item-independent generalizable ‘concepts’:* What is the relationship between item-based concepts (e.g., animals, objects, abstract words, etc.) and item-independent ‘concepts’ such as numbers, space/location, schema, syntax, etc.? There is clear evidence from neuropsychology and fMRI that these two types of ‘concept’ dissociate36,139,140. One set of computationally-informed hypotheses112,141,142 suggests that there are two orthogonal statistical extraction processes in the ventral (temporal) and dorsal (parietal) pathways. The ventral pathway may take our ongoing verbal and nonverbal experiences and integrate over time and contexts in order to extract coherent, generalisable item-based concepts. The dorsal pathway may, conversely, integrate over items in order to extract generalizable information about syntax, time, space and number which are all types of structure that are largely invariant to the items. As well as exploring this issue, future research also needs to investigate how these fundamentally different types of ‘concept’ interact and collaborate in order to generate time-extended, sophisticated verbal (e.g., speech) and nonverbal (e.g., sequential object use) behaviours.

**Boxes**

1. *Relationship of the hub-and-spoke model to embodied and symbolic accounts of semantics.*Over many years, multiple disciplines (e.g., philosophy, behavioural neurology, cognitive science and neuroscience, etc.) have grappled with the issue of concept formation. Two recurring contrasting approaches can be found in each of these literatures. One position assumes that concepts are a direct reflection of our accumulated knowledge from language, nonverbal experiences, or both. Such experiential knowledge is often referred to as ‘features’ and was called ‘engrams’ by the 19th century neurologists. Whether these experiential features are critical only at the point of acquiring or updating a concept, or whether they have to be re-activated each time the concept is retrieved, is unresolved in contemporary ‘embodied’ theories of semantic memory15. A second alternative approach is based on the observation that features alone are insufficient for the formation of coherent, generalizable concepts which might require manipulable, experientially-independent symbols143. Whilst these symbolic theories provide an account for sophisticated concept processing and generalisation, the solution fails to explain how concepts and their associated experiential features are linked, or the genesis of the concepts themselves. Partial unifying solutions have been proposed in philosophy29 and cognitive science31,32,144 which embrace the importance and centrality of verbal and nonverbal experience but also posit additional representations which can map between features and concepts, generalise knowledge, etc. The proposition of cortical convergence zones17 also contains a related idea, namely that modality-independent regions provide ‘pointers’ to the correct modality-specific features for each concept. The hub-and-spoke theory extends these ideas by providing a neurocomputational account for how coherent, generalisable concepts are built from experience, how the complex, nonlinear mappings between features and concepts are learnt, and also the neural instantiation of the processes (see Main Text).
2. *What contribution does the angular gyrus make to semantic cognition*?   
   Classical neurological models of language suggested that the multi-modally connected angular gyrus (AG) is the key neural location for semantic concepts145. More recent proposals have suggested that there might be a division of labour between the ATL and AG hubs, with the latter processing thematic or combinatorial semantics137,146. Accumulating evidence seems to render the AG’s role in semantic processing less rather than more clear. Most fMRI studies of semantic tasks find little or no AG activation147, although comparisons such as words>nonwords or concrete>abstract concepts reliably do generate differences in the AG148,149. In a recent large-scale meta-analysis112, several cognitive domains (episodic tasks, sentence syntax, number fact recall) positively activated the AG but, consistent with its contribution to the default mode network150, the AG demonstrated task-related *deactivation* for multiple domains including semantics. In addition and potentially importantly, the level of AG deactivation is correlated with task difficulty. Direct comparison of the default mode and semantic networks45 revealed that, although as expected the ATL semantic region exhibits deactivation for non-semantic tasks and positive activation for semantic tasks, the AG shows task-difficulty-correlated deactivation for both semantic and non-semantic tasks. These findings raise the possibility that previous demonstrations of greater AG activation for word>nonword, concrete>abstract, meaningful>novel word combinations or any other easy>hard comparison might reflect generic task-difficulty differential deactivation. This alternative hypothesis is consistent with the observation that when task instructions were changed to make decisions about concrete items harder than abstract, the typical AG activation difference was reversed151. Future targeted studies need to explore the circumstances in which the AG contributes to semantic tasks and whether its contribution can be more properly characterised in terms of non-semantic aspects of processing.
3. *The bilateral ATL hub: role of left vs. right in semantic representation*   
    SD patients always have bilateral (though, at least early in progression, often strikingly asymmetric) ATL atrophy [Fig.1E], suggesting that both left and right regions contribute to conceptualisation. Patients with unilateral ATL damage generally have much better semantic abilities than bilateral ATL patients although, with more sensitive assessments, semantic deficits following unilateral lesions can be observed152-154, consistent with left vs. right ATL TMS studies43. Likewise, classical comparative neurological investigations revealed chronic multimodal semantic impairment in primates after bilateral but not unilateral ATL resection155,156, which was replicated in a rare human single-case neurosurgery study157. A bilateral version of the hub-and-spoke model (see Figure) can mimic these clinical findings and provides some important clues as to why bilateral damage is more disabling than unilateral lesions, even when volume of damage is equated129.   
    There are currently different hypotheses regarding the contribution of each ATL to semantic representation74,128,158,159. One possibility is that a single functional transmodal hub might be supported by a bilateral, interconnected ATL neural network, making the resultant system robust to damage129,160 and able to upregulate the contribution of and interaction with the contralateral ATL after unilateral damage, as demonstrated by combined TMS-fMRI130,131. Neuropsychological studies also indicate that there may be important variations across the hemispheres in terms of the input/output modality and category of information159,161,162 with the most robust, reliable findings being greater anomia following left ATL damage and greater prosopagnosia with damage to the right ATL153,161,162. Furthermore, a recent large-scale fMRI meta-analysis indicated that the ATL hub system appears to be primarily bilateral but with left hemisphere predilection for speech production and written word stimuli75. Following the connectivity-constrained-hub hypothesis (see Main Text), this combination of a primarily bilateral system with graded asymmetries is captured by computational models which include a bilateral transmodal hub with graded differences in the white-matter connectivity to input/output systems129,160.

Figure for Box 3 here

1. *Controlled semantic cognition (CSC)*

Computationally, separate but interacting networks for semantic control and representation resolve a long-standing puzzle. On one hand, concepts must generalize across contexts (e.g., canaries, like other birds, lay eggs). On the other hand, different situations often require us to retrieve diverse conceptual properties to complete tasks (e.g., <yellow> vs. <hops> when either spotting or catching a canary). As shown in the Figure (Panel A), both challenges are solved by implemented computational models which have separate but interacting networks for control and representation10. As per the hub-and-spoke framework, modality-specific information interacts with a transmodal hub (purple square). A separate region represents the current task context (yellow square). These two components interact with an integrative system (black circle), which dynamically and transiently reshapes the multidimensional similarity structure arising at the context-independent hub in order to generate task-, time- and context-relevant behavioural responses. Thus, as shown in Panel B, if two contrastive tasks (e.g., spotting vs. catching the canary) require focus on colour vs. movement properties, then the conceptual∩task) integrative layer generates context-relevant internal representations congruent with the target behaviour. Because the hub is not directly connected to task/context information, it learns representations which capture structure that is independent of the various and idiosyncratic contexts encountered, providing the core computational basis for cross-context conceptual generalization (see ‘The hub-and-spoke’ Section in the main text). The same computational characteristic does not arise in models that blend task/context and perceptual inputs, immediately, within a single intermediating hub10. Thus, while this model was initially advanced solely to account for cognitive phenomena, it leads to the conclusion that semantic cognition requires separate and interacting neural networks for representation and control (as implicated in the clinical and cognitive neuroscience literatures; see Main Text).

Figure for Box 4 here

**References**

1 Martin, A. GRAPES—Grounding representations in action, perception, and emotion systems: How object properties and categories are represented in the human brain. *Psychonomic Bulletin & Review*, 1-12, doi:10.3758/s13423-015-0842-3 (2015).

2 Allport, D. A. in *Current perspectives in dysphasia* (eds S Newman & R Epstein) (Churchill Livingstone, 1985).

3 Farah, M. J. & McClelland, J. L. A computational model of semantic memory impairment: Modality specificity and emergent category specificity. *Journal of Experimental Psychology General* **120**, 339-357 (1991).

4 Warrington, E. K. & Shallice, T. Category specific semantic impairments. *Brain* **107**, 829-854 (1984).

5 Lambon Ralph, M. A., Sage, K., Jones, R. W. & Mayberry, E. J. Coherent concepts are computed in the anterior temporal lobes. *Proceedings of the National Academy of Sciences* **107**, 2717-2722, doi:10.1073/pnas.0907307107 (2010).

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

7 Rogers, T. T. *et al.* The structure and deterioration of semantic memory: A neuropsychological and computational investigation. *Psychological Review* **111**, 205-235 (2004).

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

9 Badre, D., Poldrack, R. A., Paré-Blagoev, E. J., Insler, R. Z. & Wagner, A. D. Dissociable Controlled Retrieval and Generalized Selection Mechanisms in Ventrolateral Prefrontal Cortex. *Neuron* **47**, 907-918, doi:10.1016/j.neuron.2005.07.023 (2005).

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

11 Thompson-Schill, S. L., Desposito, M., Aguirre, G. K. & Farah, M. J. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences of the United States of America* **94**, 14792-14797 (1997).

12 Wagner, A. D., Pare-Blagoev, E. J., Clark, J. & Poldrack, R. A. Recovering meaning: Left prefrontal cortex guides controlled semantic retrieval. *Neuron* **31**, 329-338 (2001).

13 Lambon Ralph, M. A., Lowe, C. & Rogers, T. T. Neural basis of category-specific semantic deficits for living things: evidence from semantic dementia, HSVE and a neural network model. *Brain* **130**, 1127-1137 (2007).

14 Eggert, G. H. *Wernicke's works on aphasia: A source-book and review*. (Mouton, 1977).

15 Meteyard, L., Cuadrado, S. R., Bahrami, B. & Vigliocco, G. Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex* **48**, 788-804 (2012).

16 Binder, J. R. *et al.* Toward a brain-based componential semantic representation. *Cognitive Neuropsychology* **in press** (2016).

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

18 Snowden, J. S., Goulding, P. J. & Neary, D. Semantic dementia: A form of circumscribed cerebral atrophy. *Behavioural Neurology* **2**, 167-182 (1989).

19 Hodges, J. R. & Patterson, K. Semantic dementia: a unique clinicopathological syndrome. *Lancet Neurology* **6**, 1004-1014 (2007).

20 Lambon Ralph, M. A. & Patterson, K. Generalisation and differentiation in semantic memory: Insights from semantic dementia. *Annals of the NY Academy of Science* **1124**, 61-76 (2008).

21 Bozeat, S., Lambon Ralph, M. A., Patterson, K., Garrard, P. & Hodges, J. R. Non-verbal semantic impairment in semantic dementia. *Neuropsychologia* **38**, 1207-1215 (2000).

22 Jefferies, E., Patterson, K., Jones, R. W. & Lambon Ralph, M. A. Comprehension of Concrete and Abstract Words in Semantic Dementia. *Neuropsychology* **23**, 492-499 (2009).

23 Cappelletti, M., Butterworth, B. & Kopelman, M. Spared numerical abilities in a case of semantic dementia. *Neuropsychologia* **39**, 1224-1239 (2001).

24 Patterson, K. *et al.* "Presemantic" cognition in semantic dementia: Six deficits in search of an explanation. *Journal of Cognitive Neuroscience* **18**, 169-183 (2006).

25 Rogers, T. T., Patterson, K., Jefferies, E. & Lambon Ralph, M. A. Disorders of representation and control in semantic cognition: Effects of familiarity, typicality, and specificity. *Neuropsychologia* **76**, 220-239, doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2015.04.015> (2015).

26 Nestor, P. J., Fryer, T. D. & Hodges, J. R. Declarative memory impairments in Alzheimer's disease and semantic dementia. *Neuroimage* **30**, 1010-1020 (2006).

27 Acosta-Cabronero, J. *et al.* Atrophy, hypometabolism and white matter abnormalities in semantic dementia tell a coherent story. *Brain* **134**, 2025-2035, doi:10.1093/brain/awr119 (2011).

28 Guo, C. C. *et al.* Anterior temporal lobe degeneration produces widespread network-driven dysfunction. *Brain* **136**, 2979-2991, doi:10.1093/brain/awt222 (2013).

29 Wittgenstein, L. *Philosophical Investigations: The German Text, with a Revised English Translation 50th Anniversary Commemorative Edition*. (Wiley-Blackwell, 1953/2001).

30 Murphy, G. L. & Medin, D. L. The role of theories in conceptual coherence. *Psychological Review* **92**, 289-316 (1985).

31 Smith, E. E. & Medin, D. L. *Categories and concepts*. (Harvard University Press, 1981).

32 Rosch, E. Cognitive representations of semantic categories. *Journal of Experimental Psychology: General* **104**, 192-233 (1975).

33 Lambon Ralph, M. A. Neurocognitive insights on conceptual knowledge and its breakdown. *Philosophical Transactions of the Royal Society B: Biological Sciences* **369**, 20120392, doi:10.1098/rstb.2012.0392 (2014).

34 Phan, T. G., Donnan, G. A., Wright, P. M. & Reutens, D. C. A Digital Map of Middle Cerebral Artery Infarcts Associated With Middle Cerebral Artery Trunk and Branch Occlusion. *Stroke* **36**, 986-991, doi:10.1161/01.STR.0000163087.66828.e9 (2005).

35 Visser, M., Jefferies, E. & Lambon Ralph, M. A. Semantic processing in the anterior temporal lobes: A meta-analysis of the functional neuroimaging literature. *Journal of Cognitive Neuroscience* **22**, 1083-1094 (2010).

36 Binney, R. J., Embleton, K. V., Jefferies, E., Parker, G. J. M. & Lambon Ralph, M. A. 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**, 2728-2738, doi:10.1093/cercor/bhq019 (2010).

37 Marinkovic, K. *et al.* Spatiotemporal dynamics of modality-specific and supramodal word processing. *Neuron* **38**, 487–497 (2003).

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

39 Visser, M. & Lambon Ralph, M. A. Differential Contributions of Bilateral Ventral Anterior Temporal Lobe and Left Anterior Superior Temporal Gyrus to Semantic Processes. *Journal of Cognitive Neuroscience* **23**, 3121-3131 (2011).

40 Pobric, G. G., Jefferies, E. & Lambon Ralph, M. A. Anterior temporal lobes mediate semantic representation: Mimicking semantic dementia by using rTMS in normal participants. *Proceedings of the National Academy of Sciences* **104**, 20137-20141 (2007).

41 Rogers, T. T. *et al.* Anterior temporal cortex and semantic memory: Reconciling findings from neuropsychology and functional imaging. *Cognitive Affective & Behavioral Neuroscience* **6**, 201-213 (2006).

42 Pobric, G., Jefferies, E. & Lambon Ralph, M. A. Category-Specific versus Category-General Semantic Impairment Induced by Transcranial Magnetic Stimulation. *Current Biology* **20**, 964-968 (2010).

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

44 Visser, M., Jefferies, E., Embleton, K. V. & Lambon Ralph, M. A. 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**, 1766-1778 (2012).

45 Humphreys, G. F., Hoffman, P., Visser, M., Binney, R. J. & Lambon Ralph, M. A. Establishing task- and modality-dependent dissociations between the semantic and default mode networks. *Proceedings of the National Academy of Sciences* **112**, 7857-7862, doi:10.1073/pnas.1422760112 (2015).

46 Shimotake, A. *et al.* Direct Exploration of the Role of the Ventral Anterior Temporal Lobe in Semantic Memory: Cortical Stimulation and Local Field Potential Evidence From Subdural Grid Electrodes. *Cerebral Cortex* **25**, 3802-3817, doi:10.1093/cercor/bhu262 (2015).

47 Mion, M. *et al.* What the left and right anterior fusiform gyri tell us about semantic memory. *Brain* **133**, 3256-3268, doi:10.1093/brain/awq272 (2010).

48 Abel, T. J. *et al.* Direct Physiologic Evidence of a Heteromodal Convergence Region for Proper Naming in Human Left Anterior Temporal Lobe. *The Journal of Neuroscience* **35**, 1513-1520, doi:10.1523/jneurosci.3387-14.2015 (2015).

49 Peelen, M. V. & Caramazza, A. Conceptual Object Representations in Human Anterior Temporal Cortex. *The Journal of Neuroscience* **32**, 15728-15736, doi:10.1523/jneurosci.1953-12.2012 (2012).

50 Chen, Y. *et al.* The when and where of semantics in the anterior temporal lobe: temporal RSA of ECoG data. *Cortex* **in press** (2016).

51 Coutanche, M. N. & Thompson-Schill, S. L. Creating Concepts from Converging Features in Human Cortex. *Cerebral Cortex* **25**, 2584-2593, doi:10.1093/cercor/bhu057 (2015).

52 Chan, A. M. *et al.* First-Pass Selectivity for Semantic Categories in Human Anteroventral Temporal Lobe. *The Journal of Neuroscience* **31**, 18119-18129, doi:10.1523/jneurosci.3122-11.2011 (2011).

53 Clarke, A., Taylor, K. I., Devereux, B., Randall, B. & Tyler, L. K. From Perception to Conception: How Meaningful Objects Are Processed over Time. *Cerebral Cortex* **23**, 187-197, doi:10.1093/cercor/bhs002 (2013).

54 Jackson, R. L., Lambon Ralph, M. A. & Pobric, G. The Timing of Anterior Temporal Lobe Involvement in Semantic Processing. *Journal of Cognitive Neuroscience* **27**, 1388-1396, doi:10.1162/jocn\_a\_00788 (2015).

55 Galton, C. J. *et al.* Differing patterns of temporal atrophy in Alzheimer's disease and semantic dementia. *Neurology* **57** (2001).

56 Brodmann, K. *Vergleichende lokalisationslehre der Grosshirnrinde*. (Barth, 1909).

57 Ding, S., Van Hoesen, G. W., Cassell, M. D. & Poremba, A. Parcellation of human temporal polar cortex: A combined analysis of multiple cytoarchitectonic, chemoarchitectonic, and pathological markers. *Journal of Comparative Neurology* **514**, 595-623 (2009).

58 Binney, R. J., Parker, G. J. M. & Lambon Ralph, M. A. Convergent Connectivity and Graded Specialization in the Rostral Human Temporal Lobe as Revealed by Diffusion-Weighted Imaging Probabilistic Tractography. *Journal of Cognitive Neuroscience* **24**, 1998-2014 (2012).

59 Morán, M. A., Mufson, E. J. & Mesulam, M. M. Neural inputs into the temporopolar cortex of the rhesus monkey. *The Journal of Comparative Neurology* **256**, 88-103 (1987).

60 Makris, N. *et al.* Delineation of the Middle Longitudinal Fascicle in Humans: A Quantitative, In Vivo, DT-MRI Study. *Cereb. Cortex* **19**, 777-785, doi:10.1093/cercor/bhn124 (2009).

61 Jackson, R. L., Hoffman, P., Pobric, G. & Lambon Ralph, M. A. The Nature and Neural Correlates of Semantic Association versus Conceptual Similarity. *Cerebral Cortex* **25**, 4319-4333, doi:10.1093/cercor/bhv003 (2015).

62 Pascual, B. *et al.* Large-Scale Brain Networks of the Human Left Temporal Pole: A Functional Connectivity MRI Study. *Cerebral Cortex*, doi:10.1093/cercor/bht260 (2013).

63 Devlin, J. T. *et al.* Susceptibility-induced loss of signal: Comparing PET and fMRI on a semantic task. *Neuroimage* **11**, 589-600 (2000).

64 Spitsyna, G., Warren, J. E., Scott, S. K., Turkheimer, F. E. & Wise, R. J. S. Converging Language Streams in the Human Temporal Lobe. *J. Neurosci.* **26**, 7328-7336, doi:10.1523/jneurosci.0559-06.2006 (2006).

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

66 Clarke, A. & Tyler, L. K. Understanding What We See: How We Derive Meaning From Vision. *Trends in Cognitive Sciences* **19**, 677-687, doi:<http://dx.doi.org/10.1016/j.tics.2015.08.008> (2015).

67 Scott, S. K., Blank, C., Rosen, S. & Wise, R. J. S. Identification of a pathway for intelligible speech in the left temporal lobe. *Brain* **123**, 2400-2406 (2000).

68 Hickok, G. & Poeppel, D. The cortical organization of speech processing. *Nature Reviews Neuroscience* **8**, 393-402 (2007).

69 Vandenberghe, R., Nobre, A. C. & Price, C. J. The Response of Left Temporal Cortex to Sentences. *Journal of Cognitive Neuroscience* **14**, 550-560 (2002).

70 Ross, L. A. & Olson, I. R. Social cognition and the anterior temporal lobes. *NeuroImage* **49**, 3452-3462 (2010).

71 Zahn, R. *et al.* Social concepts are represented in the superior anterior temporal cortex. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 6430-6435 (2007).

72 Gainotti, G. Why Are the Right and Left Hemisphere Conceptual Representations Different? *Behavioural Neurology* **2014**, 10, doi:10.1155/2014/603134 (2014).

73 Tranel, D., Damasio, H. & Damasio, A. R. A neural basis for the retrieval of conceptual knowledge. *Neuropsychologia* **35**, 1319-1327 (1997).

74 Rice, G. E., Hoffman, P. & Lambon Ralph, M. A. Graded specialization within and between the anterior temporal lobes. *Annals of the New York Academy of Sciences* **1359**, 84-97, doi:10.1111/nyas.12951 (2015).

75 Rice, G. E., Lambon Ralph, M. A. & Hoffman, P. The Roles of Left Versus Right Anterior Temporal Lobes in Conceptual Knowledge: An ALE Meta-analysis of 97 Functional Neuroimaging Studies. *Cerebral Cortex* **25**, 4374-4391, doi:10.1093/cercor/bhv024 (2015).

76 Plaut, D. C. Graded modality-specific specialization in semantics: A computational account of optic aphasia. *Cognitive Neuropsychology* **19**, 603-639 (2002).

77 Albright, T. D. On the Perception of Probable Things: Neural Substrates of Associative Memory, Imagery, and Perception. *Neuron* **74**, 227-245 (2012).

78 Griffiths, T. D. & Warren, J. D. What is an auditory object? *Nat Rev Neurosci* **5**, 887-892 (2004).

79 Ungerleider, L. G. & Mishkin, M. in *Analysis of visual behaviour* (eds D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield) (MIT Press, 1982).

80 Chiou, R. & Lambon Ralph, M. A. Task-Related Dynamic Division of Labor Between Anterior Temporal and Lateral Occipital Cortices in Representing Object Size. *The Journal of Neuroscience* **36**, 4662-4668, doi:10.1523/jneurosci.2829-15.2016 (2016).

81 Capitani, E., Laiacona, M., Mahon, B. & Caramazza, A. What are the facts of semantic category-specific deficits? A critical review of the clinical evidence. *Cognitive Neuropsychology* **20**, 213-261 (2003).

82 Chouinard, P. A. & Goodale, M. A. Category-specific neural processing for naming pictures of animals and naming pictures of tools: An ALE meta-analysis. *Neuropsychologia* **48**, 409-418 (2009).

83 Kanwisher, N. Functional specificity in the human brain: A window into the functional architecture of the mind. *Proceedings of the National Academy of Sciences* **107**, 11163-11170, doi:10.1073/pnas.1005062107 (2010).

84 Mahon, B. Z., Anzellotti, S., Schwarzbach, J., Zampini, M. & Caramazza, A. Category-Specific Organization in the Human Brain Does Not Require Visual Experience. *Neuron* **63**, 397-405 (2009).

85 Woollams, A. M., Cooper-Pye, E., Hodges, J. R. & Patterson, K. Anomia: A doubly typical signature of semantic dementia. *Neuropsychologia* **46**, 2503-2514 (2008).

86 Humphreys, G. W. & Riddoch, M. J. A case series analysis of "category-specific" deficits of living things: the HIT account. *Cognitive Neuropsychology* **20**, 263-306 (2003).

87 Noppeney, U. *et al.* Temporal lobe lesions and semantic impairment: a comparison of herpes simplex virus encephalitis and semantic dementia. *Brain* **130**, 1138-1147 (2007).

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

89 Campanella, F., D’Agostini, S., Skrap, M. & Shallice, T. Naming manipulable objects: Anatomy of a category specific effect in left temporal tumours. *Neuropsychologia* **48**, 1583-1597, doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2010.02.002> (2010).

90 Hasson, U., Levy, I., Behrmann, M., Hendler, T. & Malach, R. Eccentricity Bias as an Organizing Principle for Human High-Order Object Areas. *Neuron* **34**, 479-490, doi:<http://dx.doi.org/10.1016/S0896-6273(02)00662-1> (2002).

91 Chen, L. & Rogers, T. T. A Model of Emergent Category-specific Activation in the Posterior Fusiform Gyrus of Sighted and Congenitally Blind Populations. *Journal of Cognitive Neuroscience* **27**, 1981-1999, doi:10.1162/jocn\_a\_00834 (2015).

92 Mahon, B. Z. & Caramazza, A. What drives the organization of object knowledge in the brain? *Trends in Cognitive Sciences* **15**, 97-103 (2011).

93 Tranel, D., Logan, C. G., Frank, R. J. & Damasio, A. R. Explaining category related effects in the retrieval of conceptual and lexical knowledge for concrete entities: Operationalization and analysis of factors. *Neuropsychologia* **35**, 1329-1339 (1997).

94 Schmahmann, J. D. & Pandya, D. *Fiber Pathways of the Brain*. (Oxford University Press, 2009).

95 Gainotti, G., Silveri, M. C., Daniele, A. & Giustolisi, L. Neuroanatomical correlates of category-specific semantic disorders: a critical survey. *Memory* **3**, 247-264 (1995).

96 Garrard, P., Lambon Ralph, M. A., Hodges, J. R. & Patterson, K. Prototypicality, distinctiveness and intercorrelation: Analyses of the semantic attributes of living and nonliving concepts. *Cognitive Neuropsychology* **18**, 125-174 (2001).

97 Gainotti, G. & Silveri, M. C. Cognitive and anatomical locus of lesion in a patient with a category-specific semantic impairment for living beings. *Cognitive Neuropsychology* **13**, 357-390 (1996).

98 Jefferies, E. The neural basis of semantic cognition: Converging evidence from neuropsychology, neuroimaging and TMS. *Cortex* **49**, 611-625 (2013).

99 O'Reilly, R. C., Noelle, D. C., Braver, T. S. & Cohen, J. D. Prefrontal cortex and dynamic categorization tasks: representational organization and neuromodulatory control. *Cerebral Cortex* **12**, 246-257 (2002).

100 Cole, M. W. *et al.* Multi-task connectivity reveals flexible hubs for adaptive task control. *Nat Neurosci* **16**, 1348-1355 (2013).

101 Badre, D. & D'Esposito, M. Is the rostro-caudal axis of the frontal lobe hierarchical? *Nat Rev Neurosci* **10**, 659-669 (2009).

102 Head, H. *Aphasia and kindred disorders of speech*. (Cambridge University Press, 1926).

103 Luria, A. R. *The working brain: An introduction to neuropsychology*. (Penguin, 1976).

104 Goldstein, K. The problem of the meaning of words based upon observation of aphasic patients. *Journal of Psychology* **2**, 301-316 (1936).

105 Crutch, S. J. & Warrington, E. K. Abstract and concrete concepts have structurally different representational frameworks. *Brain* **128**, 615-627 (2005).

106 Warrington, E. K. & McCarthy, R. Category specific access dysphasia. *Brain* **106**, 859-878 (1983).

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

108 Noonan, K. A., Jefferies, E., Corbett, F. & Lambon Ralph, M. A. 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**, 1597-1613, doi:doi:10.1162/jocn.2009.21289 (2010).

109 Hoffman, P., Rogers, T. T. & Lambon Ralph, M. A. Semantic Diversity Accounts for the "Missing" Word Frequency Effect in Stroke Aphasia: Insights Using a Novel Method to Quantify Contextual Variability in Meaning. *Journal of Cognitive Neuroscience* **23**, 2432-2446, doi:doi:10.1162/jocn.2011.21614 (2011).

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

111 Gardner, H. E. *et al.* The Differential Contributions of pFC and Temporo-parietal Cortex to Multimodal Semantic Control: Exploring Refractory Effects in Semantic Aphasia. *Journal of Cognitive Neuroscience* **24**, 778-793 (2012).

112 Humphreys, G. F. & Lambon Ralph, M. A. Fusion and Fission of Cognitive Functions in the Human Parietal Cortex. *Cerebral Cortex* **25**, 3547-3560, doi:10.1093/cercor/bhu198 (2015).

113 Noonan, K. A., Jefferies, E., Visser, M. & Lambon Ralph, M. A. 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**, 1824-1850 (2013).

114 Hoffman, P., Jefferies, E. & Lambon Ralph, M. A. Ventrolateral Prefrontal Cortex Plays an Executive Regulation Role in Comprehension of Abstract Words: Convergent Neuropsychological and Repetitive TMS Evidence. *J. Neurosci.* **30**, 15450-15456, doi:10.1523/jneurosci.3783-10.2010 (2010).

115 Whitney, C., Kirk, M., O'Sullivan, J., Lambon Ralph, M. A. & Jefferies, E. The Neural Organization of Semantic Control: TMS Evidence for a Distributed Network in Left Inferior Frontal and Posterior Middle Temporal Gyrus. *Cerebral Cortex* **21**, 1066-1075, doi:10.1093/cercor/bhq180 (2011).

116 Whitney, C., Kirk, M., O'Sullivan, J., Lambon Ralph, M. A. & Jefferies, E. 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**, 133-147 (2012).

117 Davey, J. *et al.* Automatic and Controlled Semantic Retrieval: TMS Reveals Distinct Contributions of Posterior Middle Temporal Gyrus and Angular Gyrus. *The Journal of Neuroscience* **35**, 15230-15239, doi:10.1523/jneurosci.4705-14.2015 (2015).

118 Campanella, F., Mondani, M., Skrap, M. & Shallice, T. Semantic access dysphasia resulting from left temporal lobe tumours. *Brain* **132**, 87-102, doi:10.1093/brain/awn302 (2009).

119 Thompson, H. E., Robson, H., Lambon Ralph, M. A. & Jefferies, E. Varieties of semantic ‘access’ deficit in Wernicke’s aphasia and semantic aphasia. *Brain* **138**, 3776-3792, doi:10.1093/brain/awv281 (2015).

120 Duncan, J. The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. *Trends in Cognitive Sciences* **14**, 172-179 (2010).

121 Fedorenko, E., Duncan, J. & Kanwisher, N. Language-Selective and Domain-General Regions Lie Side by Side within Broca's Area. *Current Biology* **22**, 2059-2062 (2012).

122 Barredo, J., Öztekin, I. & Badre, D. Ventral Fronto-Temporal Pathway Supporting Cognitive Control of Episodic Memory Retrieval. *Cerebral Cortex* **25**, 1004-1019, doi:10.1093/cercor/bht291 (2015).

123 Davey, J. *et al.* Exploring the role of the posterior middle temporal gyrus in semantic cognition: integration of ATL with executive processes. *NeuroImage*, doi:10.1016/j.neuroimage.2016.05.051 (2016).

124 Nagel, I. E., Schumacher, E. H., Goebel, R. & D'Esposito, M. Functional MRI investigation of verbal selection mechanisms in lateral prefrontal cortex. *NeuroImage* **43**, 801-807 (2008).

125 Jackson, R. L., Hoffman, P., Pobric, G. & Lambon Ralph, M. A. The Semantic Network at Work and Rest: Differential Connectivity of Anterior Temporal Lobe Subregions. *The Journal of Neuroscience* **36**, 1490-1501, doi:10.1523/jneurosci.2999-15.2016 (2016).

126 Fuster, J. n. M. Upper processing stages of the perception–action cycle. *Trends in Cognitive Sciences* **8**, 143-145, doi:<http://dx.doi.org/10.1016/j.tics.2004.02.004> (2004).

127 Braver, T. S. The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences* **16**, 106-113, doi:<http://dx.doi.org/10.1016/j.tics.2011.12.010> (2012).

128 Drane, D. L. *et al.* Famous face identification in temporal lobe epilepsy: Support for a multimodal integration model of semantic memory. *Cortex* **49**, 1648-1667, doi:<http://dx.doi.org/10.1016/j.cortex.2012.08.009> (2013).

129 Schapiro, A. C., McClelland, J. L., Welbourne, S. R., Rogers, T. T. & Lambon Ralph, M. A. Why Bilateral Damage Is Worse than Unilateral Damage to the Brain. *Journal of Cognitive Neuroscience* **25**, 2107-2123 (2013).

130 Binney, R. J. & Lambon Ralph, M. A. Using a combination of fMRI and anterior temporal lobe rTMS to measure intrinsic and induced activation changes across the semantic cognition network. *Neuropsychologia* **76**, 170-181, doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.009> (2015).

131 Jung, J. & Lambon Ralph, M. A. Mapping the dynamic network interactions underpinning cognition: a cTBS-fMRI study of the flexible adaptive neural system for semantics. *Cerebral Cortex*, doi:10.1093/cercor/bhw149 (in press).

132 Warren, J. E., Crinion, J. T., Lambon Ralph, M. A. & Wise, R. J. S. Anterior temporal lobe connectivity correlates with functional outcome after aphasic stroke. *Brain* **132**, 3428-3442, doi:10.1093/brain/awp270 (2009).

133 Huth, A. G., de Heer, W. A., Griffiths, T. L., Theunissen, F. E. & Gallant, J. L. Natural speech reveals the semantic maps that tile human cerebral cortex. *Nature* **532**, 453-458, doi:10.1038/nature17637

<http://www.nature.com/nature/journal/v532/n7600/abs/nature17637.html#supplementary-information> (2016).

134 Vigliocco, G. *et al.* The Neural Representation of Abstract Words: The Role of Emotion. *Cerebral Cortex* **24**, 1767-1777, doi:10.1093/cercor/bht025 (2014).

135 Holyoak, K. J. & Cheng, P. W. Causal Learning and Inference as a Rational Process: The New Synthesis. *Annual Review of Psychology* **62**, 135-163, doi:doi:10.1146/annurev.psych.121208.131634 (2011).

136 Fenker, D. B., Waldmann, M. R. & Holyoak, K. J. Accessing causal relations in semantic memory. *Mem Cogn* **33**, 1036-1046, doi:10.3758/bf03193211 (2005).

137 Binder, J. R. & Desai, R. H. The neurobiology of semantic memory. *Trends in Cognitive Sciences* **15**, 527-536 (2011).

138 Schwartz, M. F. *et al.* Neuroanatomical dissociation for taxonomic and thematic knowledge in the human brain. *Proceedings of the National Academy of Sciences* **108**, 8520-8524, doi:10.1073/pnas.1014935108 (2011).

139 Butterworth, B., Cappelletti, M. & Kopelman, M. Category specificity in reading and writing: the case of number words. *Nature Neuroscience* **4**, 784-786 (2001).

140 Schwartz, M. F., Marin, O. S. M. & Saffran, E. M. Dissociations of language function in dementia: A case study. *Brain and Language* **7**, 277-306 (1979).

141 Bornkessel-Schlesewsky, I. & Schlesewsky, M. Reconciling time, space and function: A new dorsalâ€“ventral stream model of sentence comprehension. *Brain and Language* **125**, 60-76 (2013).

142 Ueno, T., Saito, S., Rogers, Timothy T. & Lambon Ralph, Matthew A. Lichtheim 2: Synthesizing Aphasia and the Neural Basis of Language in a Neurocomputational Model of the Dual Dorsal-Ventral Language Pathways. *Neuron* **72**, 385-396 (2011).

143 Fodor, J. A. *Modularity of Mind: An Essay on Faculty Psychology.*, (MIT Press, 1983).

144 Barsalou, L. W. Grounded Cognition. *Annual Review of Psychology* **59**, 617-645, doi:doi:10.1146/annurev.psych.59.103006.093639 (2008).

145 Geschwind, N. Language and the brain. *Scientific America* **226**, 76 - 83 (1972).

146 Price, A. R., Bonner, M. F., Peelle, J. E. & Grossman, M. Converging Evidence for the Neuroanatomic Basis of Combinatorial Semantics in the Angular Gyrus. *The Journal of Neuroscience* **35**, 3276-3284, doi:10.1523/jneurosci.3446-14.2015 (2015).

147 Geranmayeh, F., Leech, R. & Wise, R. J. S. Semantic retrieval during overt picture description: Left anterior temporal or the parietal lobe? *Neuropsychologia* **76**, 125-135, doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2014.12.012> (2015).

148 Binder, J. R., Desai, R. H., Graves, W. W. & Conant, L. L. Where Is the Semantic System? A Critical Review and Meta-Analysis of 120 Functional Neuroimaging Studies. *Cereb. Cortex* **19**, 2767-2796, doi:10.1093/cercor/bhp055 (2009).

149 Wang, J., Conder, J. A., Blitzer, D. N. & Shinkareva, S. V. Neural representation of abstract and concrete concepts: A meta-analysis of neuroimaging studies. *Human Brain Mapping* **31**, 1459-1468 (2010).

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

151 Pexman, P. M., Hargreaves, I. S., Edwards, J. D., Henry, L. C. & Goodyear, B. G. Neural Correlates of Concreteness in Semantic Categorization. *Journal of Cognitive Neuroscience* **19**, 1407-1419, doi:10.1162/jocn.2007.19.8.1407 (2007).

152 Bi, Y. *et al.* The role of the left anterior temporal lobe in language processing revisited: Evidence from an individual with ATL resection. *Cortex* **47**, 575-587 (2011).

153 Lambon Ralph, M. A., Ehsan, S., Baker, G. A. & Rogers, T. T. Semantic memory is impaired in patients with unilateral anterior temporal lobe resection for temporal lobe epilepsy. *Brain* **135**, 242-258, doi:10.1093/brain/awr325 (2012).

154 Patterson, K. *et al.* Semantic memory: Which side are you on? *Neuropsychologia* **76**, 182-191, doi:<http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.024> (2015).

155 Brown, S. & Schafer, E. A. An Investigation into the Functions of the Occipital and Temporal Lobes of the Monkey's Brain. *Philosophical Transactions of the Royal Society of London. B* **179**, 303-327 (1888).

156 Klüver, H. & Bucy, P. Preliminary analysis of functions of the temporal lobes in monkeys. *Archives of Neurology & Psychiatry* **42**, 979-1000 (1939).

157 Terzian, H. & Dalle Ore, G. Syndrome of Kluver-Bucy reproduced in man by bilateral removal of the temporal lobes. *Neurology* **5**, 373-380 (1955).

158 Gainotti, G. Is the difference between right and left ATLs due to the distinction between general and social cognition or between verbal and non-verbal representations? *Neuroscience & Biobehavioral Reviews* **51**, 296-312, doi:<http://dx.doi.org/10.1016/j.neubiorev.2015.02.004> (2015).

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

160 Lambon Ralph, M. A., McClelland, J. L., Patterson, K., Galton, C. J. & Hodges, J. R. No right to speak? The relationship between object naming and semantic impairment: Neuropsychological evidence and a computational model. *Journal of Cognitive Neuroscience* **13**, 341-356 (2001).

161 Tranel, D. The left temporal pole is important for retrieving words for unique concrete entities. *Aphasiology* **23**, 867-884 (2009).

162 Gainotti, G. The format of conceptual representations disrupted in semantic dementia: A position paper. *Cortex* **48**, 521-529 (2012).

**Figure Captions**

Figure 1: Panel A shows the computational architecture for the original version of the hub-and-spoke model7 in which modality-specific sources of information (spokes) are distilled into coherent, generalizable concepts through their interaction with an anterior temporal lobe (ATL) transmodal ‘hub’ layer. Panel B denotes a neuroanatomical sketch of the location of the hub and spokes. Panel C summaries inhibitory TMS data42 for the division of representational labour across hub and spokes, with the spokes providing specific sources of information (e.g., inferior parietal lobule (IPL) for praxis) and thus generating a transient impairment only on concepts for which this source is relevant (e.g., manipulable, manmade items). In comparison, the transmodal ATL hub contributes to all categories and types of concept. Panels D-F summarise converging evidence for the contribution of the ATL to semantic representation (as assessed by synonym judgement) from distortion-corrected fMRI (Panel D)36, semantic dementia (Panel E)22 and TMS in healthy participants (Panel F)40. [See Fig.S1 for the same three-way comparison for verbal and nonverbal semantic association judgements.]

Figure 2: Panel A shows the computational framework and neuroanatomical sketch of the graded hub-and-spoke model39,44,58,74. The 8×8 grid represents the ATL hub. All units support semantic processing but the relative contribution of each unit depends on its connectivity to the input modalities (e.g., hub units with stronger visual input become flavoured more by this information source – denoted by their partial light blue colour). At the centrepoint, with input from all inputs, the function of units remains evenly transmodal (denoted by their white colour). The neuroanatomical figure sketches how this graded hub might map onto the human ATL with respect to three example input sources. Empirical evidence for this sketch is summarised in Panels B and C. The graded differences in a coronal ATL cross-section are shown in Panel B. STG shows relatively greater semantic activation for words>pictures and for abstract>concrete words, MTG and ITG exhibit strong (see Panel C) yet equal involvement, whereas FG’s contribution is somewhat greater for pictures>words and concrete>abstract words44,65. The importance of the ventrolateral ATL transmodal region to semantic function overall is summarised in C. Hypometabolism in this region correlates with semantic function in SD patients47. Likewise the greater contribution of ventrolateral regions (MTG, ITG, FG) to semantic processing is observed in parallel results from the relative distribution of gyral atrophy in SD patients55 and the graded variation of semantic activation observed in distortion-corrected fMRI in healthy participants36. Panel D shows representational similarity analysis of grid electrode data from ten neurosurgical patients identifying the vATL subregion as the semantic ‘hotspot’: detailed semantic information is activated in this area from 250ms post stimulus onset50. A similar time-course for ATL semantic processing has also been observed in healthy participants using chronometric TMS54 (Panel E).

Figure 3: Regions critical for executively-controlled semantic processing are revealed through the lesion overlap for semantic aphasia119 (prefrontal and temporoparietal areas – Panel A) and a meta-analysis of the fMRI literature113 (prefrontal, pMTG and intraparietal sulcus – Panel B). Panel C summarises convergent TMS and neuropsychological data for the necessity of these regions for semantic control. Inhibitory TMS to left prefrontal cortex (pars trangularis) or pMTG (i.e., the same TMS targets as the peaks identified in the meta-analysis) produces selective slowing of executively-demanding semantic decisions. The SA patients also show strong effects of word ambiguity (e.g., poorer comprehension of the subordinate vs. dominant meaning of words such as “bark”) which are modulated by the type of context/cue provided. Panel D summarise some of the key behavioural differences between semantic dementia (degraded semantic representations) and semantic aphasia (deregulated semantic processing)8. SD patients exhibit substantial effects of word frequency, moderate influence of imageability and minimal impact of semantic diversity (how much a word’s meaning varies across contexts). SA patients show the reverse profile109. In verbal production tasks, SD patients show little effect of executive demand whilst SA patients’ performance declines in line with the required level of executive control and working memory (naming>category fluency>letter fluency)108. [See also Fig.S2 for the differential effect of representational typicality.]