

Semantic memory and the brain: structure and processes

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Recent functional brain imaging studies suggest that object concepts may be represented, in part, by distributed networks of discrete cortical regions that parallel the organization of sensory and motor systems. In addition, different regions of the left lateral prefrontal cortex, and perhaps anterior temporal cortex, may have distinct roles in retrieving, maintaining and selecting semantic information.

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Abbreviations

fMRI functional MRI
 LIPC left inferior prefrontal cortex
 MRI magnetic resonance imaging
 MT middle temporal

Introduction

The domain of semantic memory consists of stored information about the features and attributes that define concepts and the processes that allow us to efficiently retrieve, act upon and produce this information in the service of thought and language. Before the advent of functional brain imaging, our knowledge of the neural bases of semantic memory was dependent on studies of patients with brain injury or disease. These investigations identified at least two brain regions, particularly in the left hemisphere, that play a critical role in semantic memory. Patients with damage to the left prefrontal cortex (LPC) often have difficulty retrieving words in response to specific cues (e.g. words beginning with a specific letter, the names of objects belonging to a specific semantic category), even in the absence of a frank aphasia [1]. This suggests that the LPC plays a general, albeit crucial, role in retrieving lexical and semantic information.

Patients with damage to the temporal lobes often have difficulty naming objects and retrieving information about object-specific characteristics [2–4]). This suggests that object-specific information may be stored, at least in part, in the temporal lobes.

Consistent with the clinical literature, early functional brain imaging studies of semantic processing revealed activity in broad expanses of the left prefrontal, parietal and posterior temporal lobes, commonly including ventral and lateral regions of temporal cortex [5]. Results from recent studies have begun to reveal specific functions and processes subserved by smaller regions within each of

these broadly defined areas. In this review, we will highlight studies that have shed new light both on the neural structures involved in representing object-specific features and attributes, and on the processes involved in retrieving and manipulating this information.

The structure of semantic representations

An old idea in behavioral neurology [6,7] is that object concepts are defined by sensory and motor attributes and features acquired during experience. Within this framework, many have suggested that object concepts may be represented in the brain as distributed networks of sensory, motor and/or more abstract functional information [8–14].

Investigations of word-generation have provided one body of evidence suggesting that information about different object features may be stored in different regions of the cortex. These studies have shown that the ventral and lateral regions of posterior temporal cortex can be differentially engaged depending on the type of information retrieved [15]. For example, we reported that asking subjects to generate the name of an action typically associated with an object activated the posterior region of the left middle temporal gyrus, just anterior to sites active during motion perception, whereas generating a color word activated the ventral temporal lobes (bilateral fusiform gyrus) just anterior to sites active during color perception [15].

Activation of the fusiform gyrus when subjects retrieve color word associates has recently been replicated in two additional studies [16,17]. Moreover, activation in a similar region has been reported during the spontaneous generation of color imagery in auditory color-word synaesthetes [18] and in normal individuals during color imagery [19].

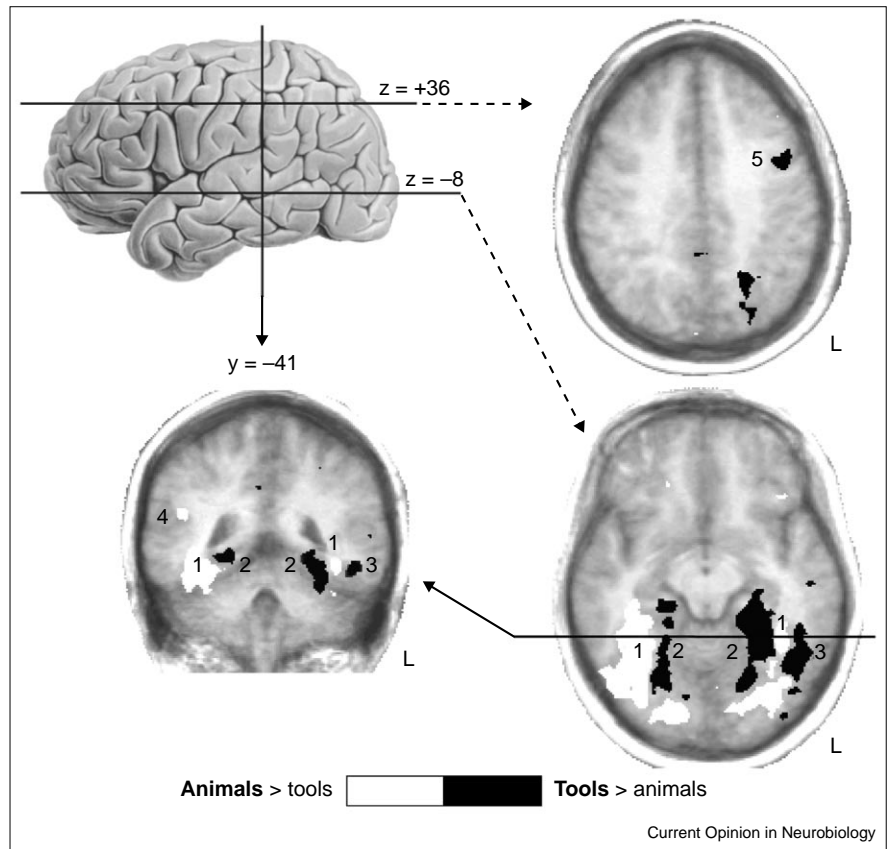
These data should be viewed in the context of over 20 reports in the literature that have found greater activity in the left posterior middle temporal gyrus during action word generation to visually and auditorily presented words and pictures (including re-analyses [20,21] of the original Petersen *et al.* study [22]; see [23] for a review). More recently, this corpus of findings has been extended to subjects tested across a wide variety of native languages [24,25], as well as to bilingual individuals responding in their native and second languages [26*]. Taken together, these word generation data are consistent with the idea that information about object-specific features may be stored within the same neural systems that are active during perception.

Distributed representations of object categories

Another body of evidence that object concepts may be represented by distributed feature networks comes from studies contrasting patterns of neural activity associated with performing the same type of task (e.g. naming) with

Figure 1

Group fMRI data (N = 7), superimposed on a group-averaged structural MRI, showing category-related activations associated with silently naming pictures of animals and tools. Regions showing greater activity for naming animals than for naming tools (1: lateral fusiform gyrus; 4: right superior temporal sulcus) are shown in white. Regions showing greater activity for naming tools than for animals (2: medial fusiform gyrus; 3: left middle temporal gyrus/inferior temporal sulcus; 5: left ventral premotor cortex) are shown in black.



different categories of objects. A common feature of all concrete objects is their physical form. Evidence is accumulating that suggests that all object categories elicit distinct patterns of neural activity in regions that mediate perception of object form (the ventral occipitotemporal cortex). Moreover, the locations of these category-related activations, especially for objects defined primarily by their visual form-related features such as animals, faces and landmarks, appear to be consistent across individual subjects and processing tasks.

Information about how objects move through space and patterns of motor movements associated with their use are other features that could aid object recognition and identification. This would be especially true for categories of man-made objects such as tools that have a more variable mapping between their name and their visual form than a category such as four-legged animals. Thus, access to these additional features may be required to identify them as unique entities. Here again, evidence is accumulating that naming and identifying objects with motion-related attributes activate areas close to regions that mediate perception of object motion (the posterior region of the lateral temporal lobe), with different patterns of activity associated with biological and man-made objects. Similarly, naming manipulable man-made objects selectively activates areas close to regions active during object manipulation.

Finally, these regions are active not only when objects are viewed and named: answering written questions and imagining them also elicits activity in these regions. Such findings are consistent with the idea that these activations reflect retrieval of stored information about object-specific attributes and features.

Ventral occipitotemporal cortex and the representation of object form

A number of investigators have found that distinct regions of ventral temporal cortex show differential responses to different object categories. In a series of studies [27•], we found greater activity in the lateral region of the fusiform gyrus for animal than for tool stimuli. This finding was consistent among different tasks, including viewing, naming, and matching pictures, and answering written questions about object features. In contrast, the medial fusiform gyrus was more active for tools than for animals (see Figure 1). A similar, but not identical pattern of activation was found for viewing faces (in the lateral fusiform) relative to viewing houses (the medial fusiform) [27•]. Other investigators have also reported face-related activity in the lateral region of the fusiform gyrus [28–30] and house-related activity in more medial regions, including the fusiform and lingual gyri [31] and parahippocampal cortex (especially for landmarks [32]).

Fine-grained distinctions were documented between each of these categories (i.e. animals, tools, houses, and faces ([27[•],33[•]], although see [34]). Nevertheless, the data suggest that activations associated with animate objects or living things (i.e. animals, faces) cluster in the more lateral aspect of the fusiform gyrus, whereas activations associated with inanimate or man-made objects (i.e. tools, houses) cluster in the more medial aspect of the fusiform gyrus. Thus, category-related activations may conform to an animate/inanimate organizational scheme as most recently suggested by Caramazza and Shelton [35]. However, findings by Ishai *et al.* [36], using an arbitrary category that has no evolutionary significance, casts doubt on this possibility. In this study, subjects viewed and performed matching tasks with pictures of chairs, faces and houses. Rather than falling medial to the activation associated with faces (i.e. in the medial fusiform region, more active for houses than faces, and more active for tools than animals), the main peak of activity for chairs was lateral to the face-responsive area, falling in the inferior temporal gyrus.

These findings suggest that different object categories elicit activity in different regions of the ventral temporal cortex, as defined by the location of their peak activation. In addition, the typological arrangement of these peaks was consistent across subjects and tasks. However, it is important to note that the activity associated with each object category was not limited to one region, but rather involved a relatively large expanse of ventral cortex. Moreover, rather than a single peak, this activity was best characterized by a complex pattern of peaks and valleys distributed over much of ventral temporal and, as discussed below, occipital cortex as well. This suggests that the representations of different object categories are distributed and overlapping.

Activation of medial and ventrolateral occipital cortex for animals compared with tools has been reported using object-naming [27[•],37], picture-matching [38,39[•]], and word-reading [39[•]] tasks. Converging evidence has come from a report [40] that patients with unilateral lesions of the medial and ventral occipital cortex are more impaired at recognizing animals than tools and famous faces. Because the activations occurred so early in the visual-processing stream, we suggested that they might reflect top-down activation from more anterior sites. This may occur whenever detailed information about visual features is needed to identify a specific object [27[•],37,41]. However, evidence about the onset times of occipital and temporal activity will be needed to determine whether these occipital activations represent bottom-up or top-down effects (see [42,43] for additional evidence for category-related activations in occipital cortex).

More direct evidence for the distributed nature of object representations in the ventral temporal cortex comes from single-cell recordings from intracranial depth electrodes implanted in patients with epilepsy [44^{••}]. Here, Kreiman

et al. recorded from the medial temporal cortex (i.e. the entorhinal cortex, hippocampus and amygdala), which receives major inputs from the ventral temporal regions identified in the neuroimaging studies described above. Neurons were identified that showed highly selective responses to different object categories including animals, faces, and houses. Moreover, the responses of the neurons were category-specific rather than stimulus-specific. That is, animal-responsive cells responded to all pictures of animals, rather than to one picture or a select few.

Studies reporting similar patterns of activation when subjects view and imagine objects from different object categories provide further support that the responses in these regions are driven by stored object information. For example, O'Craven and Kanwisher [45] reported that the same regions were active when subjects both viewed and imagined famous faces and known landmarks. Similarly, Ishai *et al.* [46] found a correspondence between the brain regions active during viewing and imagining faces, houses and chairs. Finally, Kreiman *et al.* [44^{••}] reported that the majority of category-selective neurons (88%) in their study also responded selectively when the patients were asked to imagine these objects.

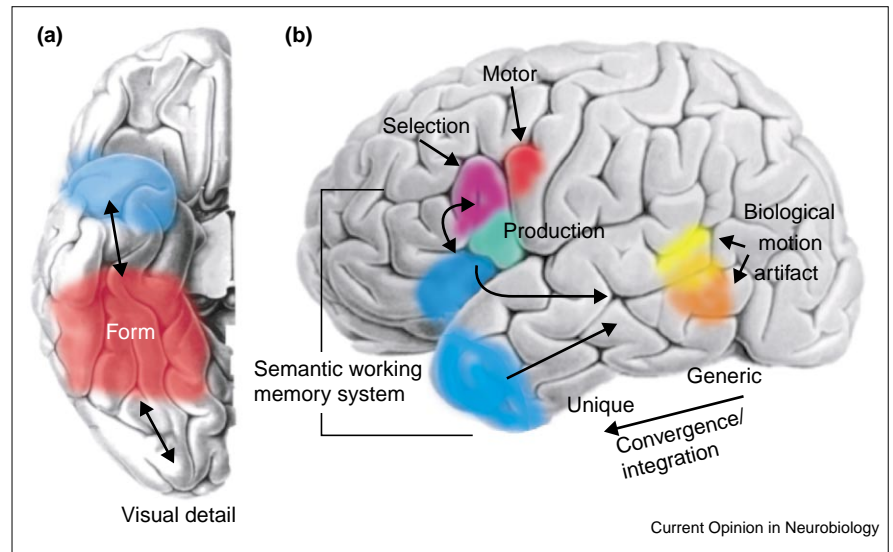
Taken together, these data suggest that ventral occipito-temporal cortex may be best viewed not as a mosaic of discrete category-specific areas, but rather as a lumpy feature-space, representing stored information about features of object form shared by members of a category [41,47,48]. A feature-based model can accommodate the observation that an arbitrary category such as chairs elicited a pattern of neural activity distinct from other object categories (i.e. faces and houses). Clearly, it would be difficult, as well as unwise, to argue that there is a 'chair area' in the brain. There are simply too many categories, and too little neural space to accommodate discrete, category-specific modules for every category. In fact, there is no limit on the number of object categories. Feature-based models can provide the flexibility needed to represent an infinite variety of objects. How this feature space is organized, and why its topological arrangement is so consistent from one subject to another, are critical questions for future investigations.

Lateral temporal cortex and the representation of object motion

A number of laboratories, using a variety of paradigms with pictures and words, have reported that tools elicit greater activity in the left posterior middle temporal gyrus than animals and other object categories [27[•],37,39[•],49^{••}]. Moreover, the active region is just anterior to area MT (middle temporal) and slightly posterior to, or overlapping with, the region active in the verb-generation studies discussed above (see [23] for a review). Damage to this region has been reported to selectively impair tool recognition and naming [40]. In contrast, naming animals [27[•]] and viewing faces [27[•],28,30] elicits greater activity in the superior temporal sulcus in approximately half the subjects

Figure 2

Schematic representation of (a) ventral and (b) lateral surfaces of the brain. Shown are the approximate locations of regions where information about object form, motion and object-use-associated motor patterns may be stored. Information from an increasing number of sources may be integrated in the temporal lobes, with specificity increasing along the posterior to anterior axis. Specific regions of the LIPC and the polar region of the temporal lobes may be involved differentially in retrieving, monitoring, selecting and maintaining semantic information.



tested (see Figure 1). This region is of particular interest because of its association with the perception of biological motion in monkeys [50] as well as humans [51,52].

As suggested for the ventral temporal cortex, neurons in the lateral temporal cortex may also be tuned to features that objects within a category share. The nature of these features is unknown; however, on the basis of its anatomical proximity to visual motion processing areas, this region may be tuned to features of motion associated with different objects. In support of this conjecture, increased activity in posterior lateral temporal cortex has been found when subjects view static pictures of objects that imply motion [53,54] and when subjects focused attention on the direction of eye gaze [55]. Investigation of the differences in the properties of motion associated with biological and man-made objects may provide clues to the organization of this region.

Ventral premotor cortex and the representation of use-associated motor movements

If activations associated with different object categories reflect stored information about object properties, one would expect tools to elicit activity in motor-related regions. Several laboratories have reported this association. Specifically, greater activation of left ventral premotor cortex has been found for naming tools relative to naming animals [37,56,57] (see Figure 1), viewing pictures of tools compared with viewing pictures of animals, faces and houses [57], and generating action words to tools [58]. As with studies of object form and object color, mental imagery (e.g. imaging manipulating objects with the right hand) also results in ventral premotor activation [59,60].

Electrophysiological studies have identified cells in monkey ventral premotor cortex that respond not only

when objects are grasped, but also when the animals view objects that they have previously manipulated [61]. The ventral premotor activation noted in the human neuroimaging studies may reflect a similar process. Alternatively, this activation may reflect action-planning [62]. Studies of patients with left premotor lesions will be needed to determine whether this region is necessary for naming and retrieving information about tools.

Representation of the subordinate level and unique objects

A common characteristic of the studies described above was that object categories were represented by items named at the basic level (i.e. house, face, chair, dog, hammer) rather than at the subordinate or unique-object level (e.g. the White House, Marilyn Monroe, rocking chair, collie, sledgehammer). The most commonly studied category of unique entities has been famous faces. These investigations typically have observed activity in the anterior middle temporal gyrus [63,64,65] and temporal pole [63,66].

Evidence that activity in anterior temporal regions may extend to other classes of objects was reported by Gauthier *et al.* [67], who used picture–word matching tasks on the basic and subordinate levels (although see [68]). These findings are consistent with Damasio's assertion that the anterior regions of the temporal lobes are critical for retrieving information about unique entities [66,69]. Why this should be so is not clear. It can be assumed, however, that naming unique entities and making subordinate-level distinctions require access to more information than basic-level identification. Thus, one possibility is that the temporal lobe object representation system is organized hierarchically, with increasing convergence and integration of information occurring along its posterior to anterior axis (see Figure 2).

Working with semantic representations

As noted previously, performing semantic tasks commonly activates a wide expanse of left lateral prefrontal cortex. More recently, evidence has accumulated suggesting that an anterior and inferior prefrontal region (roughly equivalent to Brodmann's Area BA 47 and the inferior aspect of BA 45) may be involved selectively in semantic processing. Specifically, as suggested by Gabrieli and co-workers, and Wagner [70,71,72*], this region may serve as a 'semantic working memory system' responsible for retrieving, maintaining, monitoring and manipulating semantic representations stored elsewhere. Evidence supporting this view comes from studies showing that the left inferior prefrontal cortex (LIPC) is more active when subjects make semantic judgements to words than when they make nonsemantic judgements to the same words [73], even when the tasks are equated for difficulty [72*,74]. Additional evidence comes from studies that find repetition-related decreases (and more efficient processing) in LIPC activity with repeated performance on semantic, but not nonsemantic, tasks [74,75*].

Whereas the studies mentioned above define semantic processing by abstract/concrete classification of single words, a recent study [76] has extended the selective activation of the LIPC to sentence-level semantic processing as well. Specifically, judging whether pairs of sentences have the same meaning activates LIPC when meaning is determined by synonyms (e.g. the car is in the garage; the auto is in the garage) relative to when meaning is determined by syntax (e.g. the pool is behind the gate; behind the gate is the pool).

Although these findings are broadly consistent with the idea that this region may subserve a number of working-memory-like processes, the precise role of LIPC is difficult to determine from these reports. In contrast, Thompson-Schill and colleagues have focused on the role of LIPC in mediating a single processing component: selection among competing alternatives. Support for this idea has been obtained by demonstrating that LIPC activity is modulated by selection demands. For example, generating verbs to nouns that typically have multiple competing responses (high selection demand; e.g. 'turn' or 'spin' or 'roll' to wheel) produces more LIPC activity than performing the same task with nouns that have more stereotypic verb responses (low selection demand; e.g. 'cut' to scissors) [77]. Moreover, patients with LIPC lesions are impaired when required to generate verbs to nouns with high, but not low, selection demand [78].

Because high-selection-demand tasks also place greater demands on retrieval, these findings may reflect retrieval demands, rather than selection demands *per se*. To distinguish between these alternatives, subjects were asked to generate different features (e.g. action word, color word) to the names of concrete objects [79**]. The authors reasoned that in both conditions, a common set of semantic features would be retrieved, but different attributes would be selected depending on the task demand. As in previous

reports using semantic classification [74,75*] and word generation [22] tasks, repeated performance of the same task (i.e. repeated generation of an action word to the same concrete noun) resulted in decreased activity in the LIPC. However, crossing the tasks (i.e. generating an action word to a concrete noun when the subjects had previously generated a color word to that noun) produced increased LIPC activity, even though the same concept and set of attributes were retrieved under both conditions.

Thus, when recently selected information was irrelevant, selection demands and LIPC activity increased, whereas when recently selected information was relevant, selection demands and LIPC activity decreased. In contrast, temporal lobe activity decreases when the same concept is retrieved, regardless of the type of feature that has to be selected. Taken together, these findings are consistent with the idea that LIPC is involved in the selection among competing semantic features (color and action object associates) stored in temporal cortex.

Interestingly, the location of the selection-related LIPC activity is actually in the dorsal aspect of BA 44, placing it posterior and superior to the semantic working memory region identified by Gabrieli, Wagner and colleagues [70,71,72*]. This suggests that the process of selecting among competing alternatives may occur in a different cortical region than other working memory processes.

Although helping to clarify the role of different subregions of the LIPC, this story is complicated by the fact that phonological processing tasks also activate dorsal BA 44 (as well as the more inferior portion of BA 44; see [72*] for a review). One possibility is that the phonological tasks also require selection. Alternatively, BA 44 may be fractionated functionally into two regions, with the inferior portion involved in phonological processing—especially transforming orthographic to phonologic representations for speech production [80]—and the superior portion engaged in selection processes (see Figure 2).

Finally, recent evidence suggests that the polar region of the left temporal lobe may also contribute to the overall functioning of a semantic working memory system. Mummery *et al.* [81**] tested normal subjects and patients with semantic dementia on a semantic association task. Although the patients had extensive anterior temporal lobe atrophy, they showed either normal or heightened activity in subregions of the left anterior temporal lobe (and the LIPC). In contrast, whereas normal individuals showed strong activation of the ventral and lateral regions of the posterior left temporal cortex, these patients failed to activate this region. Thus, within the context of the material reviewed here, normal functioning of the polar region of the left temporal lobe may provide top-down modulatory input necessary for successful retrieval of semantic representations stored in posterior regions (see Figure 2). In line with this idea, lesions of the anterior temporal cortex in

monkeys have recently been shown to interfere with maintaining items in visual working memory [82].

Clearly, the role of different regions of left prefrontal cortex in semantic memory processes and, more generally, in lexical retrieval and production, remain to be specified. In particular, the idea that the polar region of the left temporal lobe is part of a 'semantic working memory network' awaits further study.

Conclusions

Distributed networks of discrete cortical regions are active during object processing. The distribution of these regions varies as a function of semantic category. The same regions are active, at least in part, when objects from a category are recognized, named, imagined, and when reading and answering questions about them.

Critical questions for future research will be to clarify the precise role of these regions in object semantics and how are they influenced by experience. In addition, it has yet to be determined how the lexicon is organized and how lexical representations are linked to the semantic feature networks described here. Finally, little is known about the neural representations of nonfeatural semantic object information and abstract concepts. Nevertheless, the findings reviewed here suggest that we are beginning to make progress in identifying the distributed cortical networks associated with semantic object representations, and the networks underlying our ability to retrieve, select and operate upon them.

Acknowledgements

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