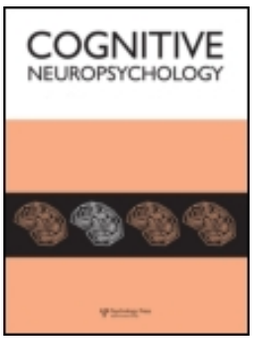

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FUNCTIONAL ONTOLOGIES FOR COGNITION: THE SYSTEMATIC DEFINITION OF STRUCTURE AND FUNCTION

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Cognitive scientists have traditionally specified the functional components of cognitive skills on the basis of behavioural studies of normal and neurologically impaired subjects. The results of functional imaging studies are challenging these classical models because there is a high degree of overlap among the neural systems activated by tasks that share no cognitive components. This suggests that a given neuronal structure can perform multiple functions that depend on the areas with which it interacts. However, there will be a limited range of functions that an area can perform given that its anatomical (intrinsic and extrinsic) connectivity is fixed. Assigning labels that encompass the operations that each area performs should enable a task to be re-described in terms of the functions of the areas activated. In other words, function should predict the structure and conversely structure should predict function. These systematic descriptions are referred to as ontologies. We argue that a systematic ontology for cognition would facilitate the integration of cognitive and anatomical models and organise the cognitive components of diverse tasks into a single framework. These points are illustrated with cognitive and anatomical models of reading and object recognition.

INTRODUCTION

Functional neuroimaging is now widely used to identify the neural correlates of cognitive processes. In initial applications of this technique, the experimental design and interpretation of the results were based on cognitive models that have been established on the basis of a long history of behavioural experiments with normal and neurologically impaired subjects. The simplest interpretation of functional neuroimaging data would be a one-to-one mapping between a cognitive process and an anatomical region. However, the brain clearly does not and cannot operate in this fashion, not least because the number of hypothesised cognitive processes exceeds the number of brain regions supporting them. Functional neuroimaging data preclude a one-to-one mapping in two ways. First, attempts to manipulate a "single" cognitive process (e.g., semantics) often elicit a distributed pattern of activation over many areas (i.e., a one-to-many mapping from function to structure). Second, the same brain region, or set of regions, may be activated by tasks with different cognitive processes (i.e., a many-to-one mapping). In short, there is a many-to-many mapping between cognitive functions and anatomical regions, with a range of cognitive processes emerging from different patterns of activation among a limited number of brain regions (McIntosh, 2000; Mesulam, 1990).

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As results from functional neuroimaging studies accumulate, the overlap among the neural systems engaged by different tasks is becoming more apparent. In some cases, it might be possible to ascribe a region with a functional label that describes a process common to all the tasks that activate it. The overlap in activations, however, does not generally correspond to the overlap in the cognitive processes hypothesised from behavioural studies. Consequently, we are left with a situation where the functional components of a given task could have two sets of labels: a "cognitive set" that is specified on the basis of behavioural dissociations, and an "anatomical set" that is specified on the basis of the regions that respond to the task. What we need is a systematic definition of structure–function relations whereby structures predict functions and functions predict structures. These systematic descriptions are called ontologies (Lan, Montelione, & Gerstein, 2003). In brief, we will suggest that the advent of functional neuroimaging speaks to a neurobiologicaly informed ontology that is constrained and "boot-strapped" by our increasing knowledge of functional anatomy. Ontologies for cognition will not only unify structure–function relationships, but will also provide a single theoretical framework to describe the functional components of diverse tasks.

The aims of this paper are to demonstrate how the same area can be engaged in more than one function/task and to discuss different levels of description for functional anatomy. Claims that an anatomical area can have multiple functions depend on the precision with which functional imaging techniques can locate and distinguish neuronal responses. Therefore, the first section addresses some of the methodological issues that attend assigning responses to specific neuronal populations. The following section considers different levels of structure–function relationships and the last section discusses some guiding principles for developing ontologies for cognition. We conclude that the hierarchical mapping between any functional ontology and anatomy should be recapitulated by hierarchical patterns of activation evoked by higher level functions. Critically, this recapitulation can, in principle, be used to constrain and guide the construction of cognitive ontologies.

METHODOLOGICAL ISSUES

In this section we review two methodological issues that need to be considered before concluding that an area has an underlying function that accounts for all observed activations. The first is the precision with which functional neuroimaging techniques can locate an area or disambiguate responses of neuronal populations. The second relates to the application of cognitive models to functional imaging studies.

Resolving neuronal populations with functional imaging

Resolving the responses of neuronal populations depends on how accurately the neuroimaging technique can localise activation (i.e., the spatial precision). For example, activation within a prespecified area may be (1) in spatially proximate but functionally independent neuronal populations; or (2) expressed by the same, or highly interconnected, neuronal populations. Spatial precision is not the same as spatial resolution. Spatial resolution reflects the spread of activation underlying the peak and it is well recognised that the intrinsic resolution of fMRI is much higher (<1 mm) than that of PET (>6 mm)—although the final resolution will depend on the spatial smoothing applied to the data. In contrast, the spatial precision (the accuracy of locating the peak) of PET and fMRI are very similar. For a single subject analysis, spatial precision is usually in the order of 2 mm for PET (Mintun, Fox, & Raichle, 1989) and 1–6 mm for fMRI depending on the voxel size (activations within the same voxel cannot be spatially resolved). Individual differences in neuroanatomy, however, mean that spatial precision is greatly reduced when data from several subjects are pooled (as in most functional imaging studies). Thus, two different areas might be resolved, in terms of peak response, when data analysis proceeds at the individual subject level, but not when data are pooled

over subjects. For example, Kim, Relkin, Lee, and Hirsh (1997) found that, in subjects who learnt a second language late in life, different regions within Broca's area were activated for the first and second language relative to a baseline condition. The relative position of the first and second language areas, however, varied over subjects in both the caudal-rostral and ventral-dorsal dimensions. In other words, in some subjects the region for the first language lay anterior to that for the second language whereas in others the region for the first language lay posterior to that for the second language. The first and second language areas could therefore only be distinguished when activation was considered at the individual subject level. If data had been pooled over subjects, then the same area might have been identified for both languages.

The ability to distinguish two sources of activation can be further improved by using "neuronal adaptation techniques." This approach is based on the well-characterised effects of stimulus repetition on neuronal and behavioural responses (Henson & Rugg, 2003). In functional imaging experiments, neuronal adaptation is expressed as a response decrease to a target stimulus when the target is preceded (primed) with an identical stimulus (Grill-Spector, Kushnir, Edelman, Avidan, Itzchak, & Malach, 1999). The degree of adaptation depends on the nature of the response and the similarity of the prime to the target. For instance, if neuronal responses to objects are viewpoint dependent, then neuronal adaptation will be greater when the prime is in the same view as the target than when the prime is in a different view. In contrast, if the responses in a region are viewpoint independent, then neuronal adaptation will be the same irrespective of whether the prime and target are in the same or different views. The point here is that neuronal adaptation can be used to distinguish different neuronal populations, even if they are spatially overlapping (i.e., in the same area). Thus, if the same neuronal population responded to pictures of objects and their written names, then neuronal adaptation within modality (word followed by word) would be similar to adaptation between modality (word followed by picture). In contrast, if words and pictures were processed in the same area but in different neuronal populations, then neuronal adaptation within modality would be greater than adaptation between modality. In other words, differential effects of adaptation could distinguish word and picture responses even if the direct comparison of word and object activation did not reveal a difference.

In summary, asserting that different functions activate the same area depends critically on the precision with which activation is located. For PET and fMRI, spatial precision can be improved by examining data at the individual subject level and using designs that harness neuronal adaptation to isolate functional populations.

Cognitive models for behavioural and functional imaging studies

Mapping function to anatomy depends on a clear understanding of the cognitive processes that are being tapped by the experimental paradigm. Cognitive models for behavioural experiments usually only specify the cognitive components that are necessary for a particular task. Functional imaging, in contrast, detects activation that may be incidental to task requirements—i.e., evoked by a stimulus even when it is not necessary for the task. For example, a traditional cognitive model for naming pictures of tools might include: visual processes, object perception, semantic processing, phonological retrieval, and articulation. Semantic processing might also be segregated into perceptual and functional knowledge, where functional knowledge includes the type of actions that are used for tools. Traditional cognitive models do not, however, usually include "motor processing for hand movements" as this is not necessary for naming the tools, but if "motor processing for hand movements" was implicitly activated in response to seeing a tool, then brain areas involved in preparation of hand movements might be activated automatically. Interpretation of the activations solely on the basis of the cognitive model would be forced to attribute the "hand areas" with a cognitive process that was in the model

(e.g., phonological processing). The fallacy of this interpretation could only be disclosed in the context of a fuller understanding of the functional anatomy underlying different types of motor processing. The point here is that it might be easy to ascribe a brain area a given function, but the validity of the functional label depends on the validity and scope of the cognitive model applied. This, in turn, depends on whether the model includes cognitive processes that are both necessary for the task and invoked incidentally. Furthermore, even if the cognitive model is fully specified, inferring that an area is involved in a function of interest is not the same as inferring that the area is specific to that function. To infer functional specificity requires a demonstration that an area is activated only by tasks that engage its function and no others.

LEVELS OF STRUCTURE–FUNCTION DESCRIPTIONS

The main aim of this paper is to consider whether a brain region can have more than one function. The answer can be either *yes* or *no* because it depends on the definition of a function and the level at which the structure–function relationship is described. In the following, we consider two questions that are posed to investigate structure–function relationships: (1) What are the neural correlates of a cognitive function? and (2) What is the function that best explains the responses of a brain region? To illustrate these approaches, we consider the paradigms that activate an area in the left posterior lateral fusiform (PLF).

Most functional imaging studies of cognitive function aim to find the neural correlates of a cognitive operation rather than trying to find a function that best predicts regional responses. Consequently, since most experimenters focus on one type of cognitive task, different investigators assign different labels to the same area. For example, studies of reading refer to a left posterior lateral fusiform region as the "visual word form area—VWFA" (Cohen et al., 2000). Studies of category-specific object processing refer to the same area as being sensitive to the visual attributes of animals (Martin & Chao, 2001); and Amedi and colleagues (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002) call this area "the lateral occipital tactile-visual region" (LOtv). Thus, this area appears to have more than one function. Is this because there are two or more different areas in close proximity? Or is there one function that can account for all activations and, if so, how should this area be labelled? To address these questions, we need to compare the exact location of the activations. How close are the activations in the left lateral fusiform for words and objects, are they really the same, or is there a consistent relationship? In order to address these questions, we need to change the focus of the question from "What are the neural correlates of a cognitive operation?" to "What is the function associated with activation of a brain region?" To answer the latter question, we need to examine the range of conditions under which an area responds.

Table 1 reports the coordinates from a collection of studies that have all reported activation in the left posterior lateral fusiform. Part (a) shows the inter-study and inter-subject variability in the activations reported for reading. Part (b) includes studies when subjects are asked to name or make actions to pictures of real and nonsense objects. Part (c) illustrates similar effects of neuronal adaptation for repetition priming of written words and pictures of objects. Part (d) illustrates that activation is not limited to the presence of visual form but is also observed when subjects name colours relative to saying "OK" to the same stimuli; and for simple shapes that move interactively relative to random movements of the same shapes. Part (e) illustrates that responses are not dependent on visual input because activation has also been reported in studies of tactile processing when subjects were not able to see the stimulus. Likewise, part (f) includes studies that have shown left posterior lateral fusiform activation in response to semantic or phonological decisions on auditory words. Examination of the activation foci for this range of paradigms reveals that the variability between these studies is no greater than the variability between reading activations for individual subjects (see part a). Thus, there is no

evidence that the activations for any of these paradigms come from distinct neuronal populations. This would require analysis of individual subjects performing a range of different tasks (see previous section).

If the same left lateral fusiform area is involved in many different functions, what is its appropriate label? Labels such as "visual word form area" are not particularly useful because they only indicate that the area is involved in the function but

Table 1. *Activations reported in left posterior lateral fusiform area*[a]

Reference		*Activation > Baseline*	*Coordinates*	*Voxel size*
		(a) Reading written words		
Cohen et al., 2000			−42, −57, −6	3 mm
Cohen et al., 2000			−43, −54, −12	3 mm
Cohen et al., 2002:	Sub. 1	View words > chequerboards	−42, −60, −15	5 mm
	Sub. 2	View words > chequerboards	−42, −63, −21	5 mm
	Sub. 3	View words > chequerboards	−51, −63, −12	5 mm
	Sub. 4	View words > chequerboards	−36, −48, −18	5 mm
	Sub. 5	View words > chequerboards	−36, −54, −18	5 mm
	Sub. 6	View words > chequerboards	−48, −57, −9	5 mm
	Sub. 7	View words > chequerboards	−42, −51, −15	5 mm
	Mean	**View words > chequerboards**	**−42, −57, −15**	5 mm
Brunswick et al., 1998		Reading aloud > Rest	−42, −56, −16	3 mm
		(b) Objects and nonobjects		
Bookheimer et al., 1995		Picture naming > View random lines	−42, −58, −20	3 mm
Murtha et al., 1999		Picture naming > View plus signs	−44, −59, −21	5 mm
Moore and Price, 1999		Picture naming > Say OK—same stimuli	−42, −54, −14	3 mm
Moore and Price, 1999		Picture naming > Reading object names	−42, −60, −14	3 mm
Chao et al., 1999		View pictures of animals > tools	−40, −59, −10	5 mm
VanTurennout et al., 2000		View nonobjects > Visual noise	−38, −56, −20	5 mm
Phillips et al., 2002		Action dec. to objects > Nonobjects	−40, −58, −12	3 mm
Phillips et al., 2002		Actions dec. > Size dec. to nonobjects	−46, −56, −14	3 mm
		(c) Visual priming		
Van Turennout et al., 2000		Picture name: Unprimed > primed	−44, −54, −12	5 mm
Dehaene et al., 2001		Words sem. dec.: Unprimed > primed	−44, −52, −20	5 mm
		(d) Other visual discrimination		
Price et al., 1996		Colour patches: Name > say "OK"	−42, −54, −14	3 mm
Castelli et al., 2002		Moving shapes: Interactive > random	−46, −60, −10	3 mm
		(e) Tactile words/objects (no visual input)		
Buchel et al., 1998		Feature dec. braille words > nonwords	−46, −56, −14	3 mm
Amedi et al., 2002		Sem. dec. Objects > textures	−47, −62, −10	5 mm
		(f) Auditory words (no visual input)		
Booth et al., 2002a, 2002b		Rhyming dec. words > pitch dec.—noise	−45, −60, −18	4 mm
Thompson-Schill et al., 1999		Sem. dec. object names > reversed words	−41, −53, −11	5 mm
Mellet et al., 1998		Imagine object > rest	−48, −60, −14	–

[a] Coordinates according to Talairach and Tournoux (1988).

this is not the same as identifying the role the area plays in that function. Therefore, task-specific labels of this sort can not predict the cause of activation in other tasks. For example, why is left posterior fusiform activation observed when subjects are required to make action decisions in response to pictures of unfamiliar objects relative to perceptual judgments on the same stimuli (Phillips, Humphreys, Noppeney, & Price, 2002; Price & Devlin, 2003)? After all, action decisions in response to nonobjects do not require visual word form, animal, or object representations. To explain why we see activation in this region during action decisions, we need an alternative functional label with predictive validity that generalises beyond the cognitive domain studied. In other words, given that the same area is also activated by reading and object recognition, it would be preferable to use a functional label that explains activation in other contexts (see Table 1). In short, the most useful functional labels are those that explain and predict how an area responds in different contexts.

What functional label would explain the causal basis of left posterior lateral fusiform activation? Figure 1 summarises the conditions under which this area responds. Responses are strongest when a motor response (name or action) is retrieved from sensory cues; and this effect is observed irrespective of stimulus modality. In other words, it appears to function as a sensorimotor integration area. This does not exclude the possibility that there are other sensorimotor areas that integrate different types of inputs and outputs. Nor does it exclude the possibility that within the left posterior lateral fusiform, there are different neuronal populations that integrate different types of information. For example, there may be different neuronal populations for integrating visual objects with the corresponding hand movements (Phillips et al., 2002), and for integrating tactile inputs with speech output (Buchel, Price, & Friston, 1998). On the other hand it is also possible that the same neuronal populations integrate both visual and tactile information with either hand or mouth responses. In this case, the type of sensorimotor integration would depend on which regions were sending signals to the posterior lateral fusiform. For example, when visual–hand responses are required, there might be bottom-up inputs for visual cortex and top-down inputs from the motor regions for the hand. In contrast, when tactile–speech responses are required, there might be bottom-up inputs from parietal cortex, and top-down inputs from articulation regions.

If the left posterior lateral fusiform area is a sensorimotor area, some may wonder where the visual word form area is. The answer is that there is no evidence for a brain area that is specifically dedicated to visual word form processing. Instead, visual word form processing is likely to result from

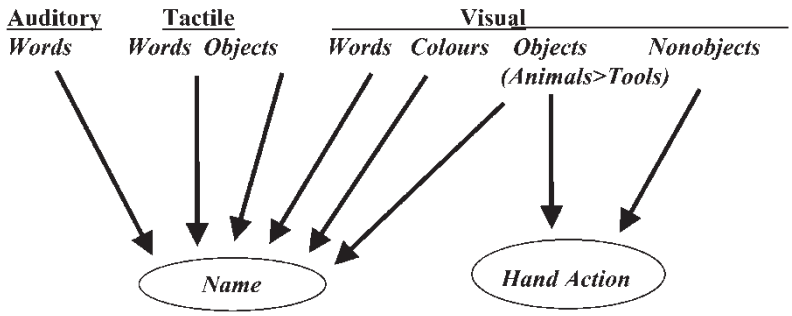


Figure 1. *Examples of some of the conditions that activate the left posterior lateral fusiform. The top row corresponds to stimulus type. The bottom row corresponds to task. The arrows represent some of the stimulus–response computations that activate the left posterior lateral fusiform.*

the pattern of activation in multiple regions that each serve many different functions. For example, the left posterior lateral fusiform area plays a role in visual word form processing when the stimuli are words, the task is reading, and there is coactivation in occipital, temporal, and frontal areas. In contrast, the same area plays a role in action retrieval when the stimuli are novel objects, the task is manipulation, and there is coactivation in occipital parietal and motor regions. Thus, at one level of the description, the area has multiple functions that are determined by the regions that it coactivates with, whereas at another level, the area can be assigned a single function—to integrate sensory cues with motor output.

To help clarify the importance of interactions with other areas, consider the structure–function relationships that might be used to describe the role of the forefinger. At one level, the forefinger can be attributed multiple and diverse functions including "piano playing," "typing," "scratching," "pinching," "feeding." At a second level, these functions could be classified so as to distinguish them from those that the forefinger cannot perform—such as "digestion," "thinking," or "walking." The functions of the forefinger could, for example, be categorised as "interactions between body and environment" or "hand actions." At a third level of description, however, the forefinger can only do one thing—"bend" and "straighten." Its role in other tasks is therefore entirely dependent on what the other fingers and thumbs are doing and what environmental context they are in—scratching requires only one finger whereas pinching requires the opposition of the finger and thumb. Likewise, the function of a neuron or neuronal population depends on its interactions with other neurons. At one level of description, a neuron can only do one thing—fire. The firing will stimulate activation in a fixed set of output regions. Therefore, there will be a limited range of functions that an area can perform. However, at another level of description, the consequence of the firing will depend on which neuronal populations (input regions) caused the firing, and which neuronal populations send concurrent signals to the output regions. In this sense, a neuron participates in multiple functions. Likewise, the type of sensorimotor integration provided by the left posterior lateral fusiform area will depend on the inputs to this region (visual, auditory, tactile) and the task (naming, hand action) being performed.

In summary, structure–function relationships can be described at multiple levels. Each level may be appropriate in a different context. Nevertheless, we argue that it is more useful to label a region with a function that explains all patterns of activation. As an example, we have described the range of tasks that the posterior lateral fusiform is engaged by, and proposed that the common denominator is a role in sensorimotor integration. Understandably, a sensorimotor integration label may not be particularly attractive to cognitive psychologists as it does not correspond to any of the components hypothesised to be involved in reading or object processing. Nevertheless, it does provide a prediction about the conditions under which the left posterior lateral fusiform area responds. In this sense the sensorimotor label is more useful than task-specific labels.

Attempts to find functional labels that explain the cause of activation focuses our questions about functional attribution on what the area is important or necessary for. Furthermore, it calls into question our understanding of the cognitive components involved in a task. For example, we have argued that appreciating the range of tasks that elicit left lateral fusiform activation forces us to re-evaluate the cognitive model of reading. In some cases, this might require the inclusion of cognitive components that were not there previously (e.g., a region/component specialised for sensory-motor integration). In other cases, it might require that a cognitive component was replaced or removed. For example, there does not appear to be an area that is specialised for orthography or visual word forms—instead, visual word form processing may arise from the interactions among early visual and later reading stages. Finding the range of attributes or dimensions that determine responses in a given area will clearly require an enormous amount of empirical study and cannot be covered by a handful of language studies predicated on traditional cognitive models. In the long term, however, a new

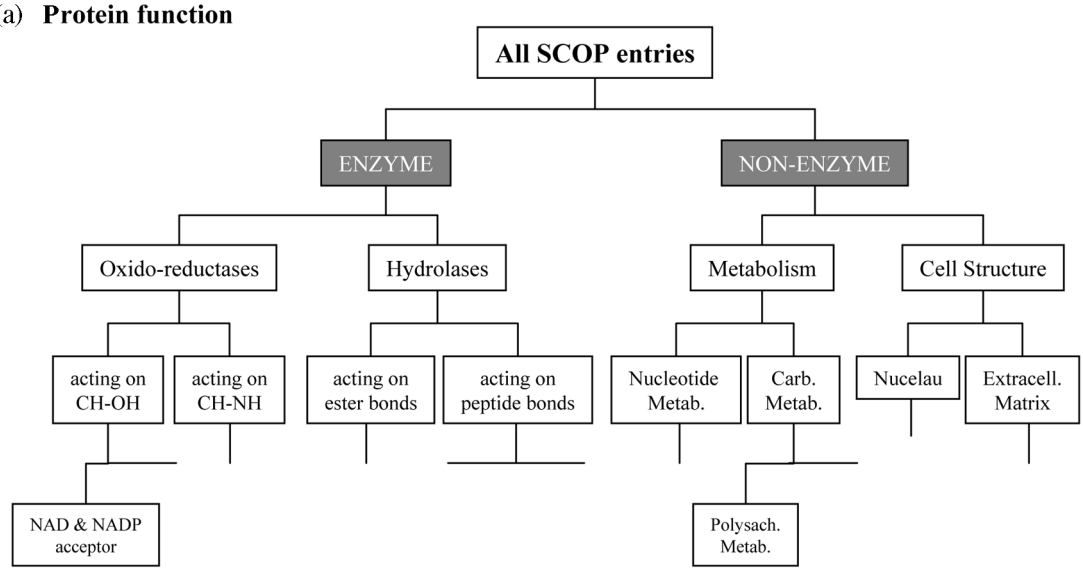
ontology of this sort will enable cognitive and anatomical models to converge and be built in a mutually consistent way.

WHAT ARE THE GUIDING PRINCIPLES FOR FUNCTIONAL ONTOLOGIES

In this section we consider the nature of structure–function and function–structure mappings and how they can be established empirically. Although it may seem an odd place to start, we will introduce ontologies though their use in proteomics. There are many homologies between functional genomics and functional anatomy and the problems faced in both these fields. After the successes of genome sequencing the focus of molecular and cell biology has "shifted from DNA to RNA and proteins and the main challenge for bio-informatics is to integrate the ever growing amount of data to fully ascribe the biological role of proteins, cells, and ultimately organisms" (Lan et al., 2003). This calls for the development of ontologies that conceptualise and represent key information on proteins that can scale to the genomic level and be sufficiently standardised to support data mining. By analogy, cognitive neuroscience aims to ascribe the cognitive role of cortical areas and neuronal structures. Indeed, current excitement about databasing, and related neuroinformatic challenges in imaging neuroscience, reflects the need to organise and relate information from cognitive science, functional neuroimaging, and neuropsychology, (http://www.fmridc.org). The development of ontologies in structural genomics and functional proteomics is somewhat more advanced than in cognitive neuroscience (e.g., the hierarchical representations adopted by Structural Classification of Proteins Database [SCOP]; http://scop.mrclmb.cam.ac.uk/scop, Hubbard, Alley, Brenner, Murzin, & Chothia, 1999, and the Gene Ontology [GO], Ashburner et al., 2000). Figure 2 shows a simplified functional ontology based on SCOP. Note that the hierarchy indicates the functions at a particular level of description, but does not encode the order or mechanisms that might be implemented. A putative functional ontology for cognitive function is provided, by analogy, below (this and the following ontologies are just schematics and should not be taken too seriously). In proteomics the construction of ontologies is informed by reference to structure, biological function, genetic encoding and protein-protein interactions. What are the guiding principles for ontologies of cognitive function?

We will adopt the common sense position that the construction of cognitive ontologies should integrate structural and functional information. In other words, the functional ontology should "rationalise" structure-function relationships, such that a given function predicts the brain structures engaged and the architecture of the ontology is predicted by neuronal infrastructure. Again we can take our lead from proteomics, in which protein–protein interactions can inform hierarchical ontologies of function. In terms of cognitive anatomy, it is the functional interactions (i.e., the effective connectivity) rather than the structural anatomical connections themselves that are important for the ontology. These functional interactions are usually inferred by coactivation in different brain regions. The key insight afforded by this observation is that relationships between activations should be reflected in the cognitive ontology. For example, if two areas do not coactivate then they should not be hierarchically linked in the ontology. In contrast, coactivation among all hierarchically subordinate areas should be observed if the functional ontology is properly specified. This principle is illustrated in Figure 3. If the functional ontology is properly specified, then a task that engages process 2 should engage all the cortical areas in its hierarchically subordinate processes (i.e., BA39, V5, V3, and V1). This perspective affords a way of assessing how "good" an ontology is. A good ontology will correctly predict activation patterns over all levels of task analysis. A poorly constructed ontology will give prediction errors that can be assessed empirically and used to refine the ontology (see below). Before returning to the single word reading example of the previous section we will consider briefly the nature of structure–function mappings.

(a) **Protein function**



(b) **Cognitive functions**

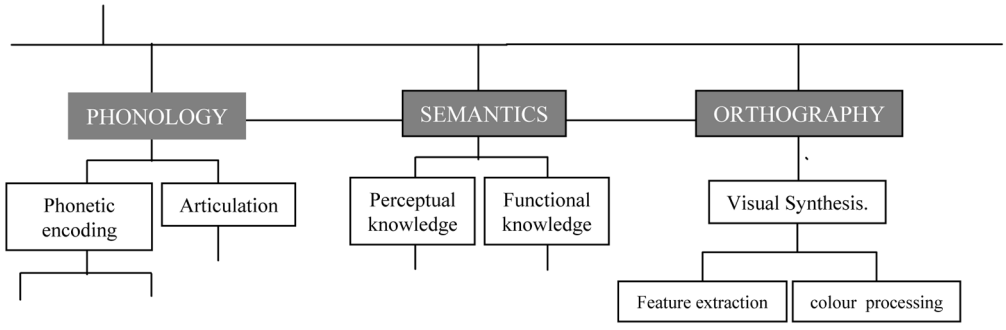
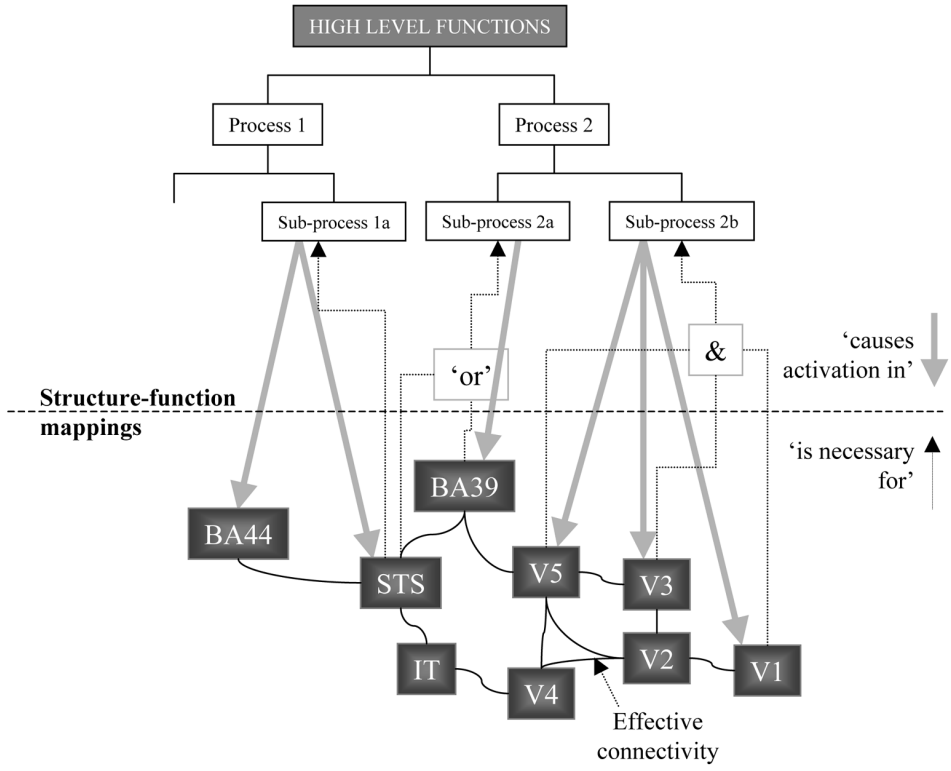


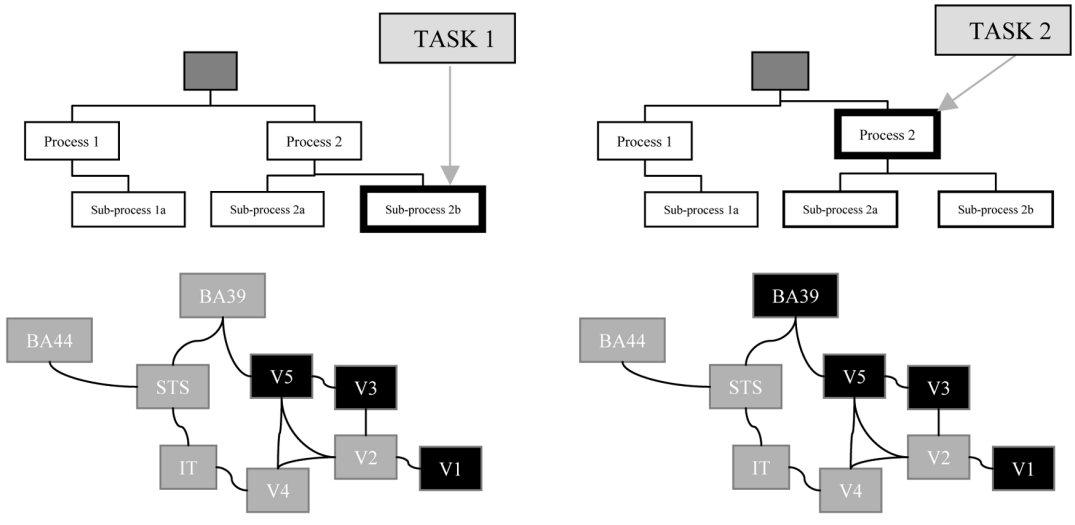
Figure 2. *Functional ontologies for Genes and Cognition. (a) A simplified ontology based on SCOP. (b) A putative functional ontology for cognitive function.*

Figure 3 (opposite). *Structure–function mappings. (a) A putative functional ontology illustrating the integration of cognitive processes and anatomical region. The grey arrows from cognitive process to brain region indicate the areas that might be engaged by each process. The dotted arrows from brain region to cognitive process indicate where performance might be impaired following damage. BA = Brodmann area. V = Visual area. STS = superior temporal sulcus. IT = Inferior temporal. (b) If the ontology above is correct, then a particular sub-process should activate its associated areas. In the right hand example, process 2 engages V1, V3, V5 (subprocess 2b), and BA39 (all highlighted black).*

(a) Functional ontology



(b) Functional anatomy



Structure–function mappings

Clearly the construction of functional ontologies that are constrained by functional anatomy (see Figure 3) rests upon the definition of a structure–function mapping. These mappings are central to the cognitive neuroscience endeavour and require careful definition. A simple way to classify mapping is in terms of operational characterisation: There are a number of important concepts embedded in the schematic of Figure 3(a), which we will now describe briefly. First, the mappings from structure to function and function to structure are not symmetrical. These directed mappings correspond to the two most commonly employed ways of measuring structure–function dependencies: Namely, lesion studies that assess the functional deficit following structural damage and functional imaging studies that manipulate function and measure evoked responses (activations) in brain structures. These two approaches can be summarised as *is necessary for* (dotted arrows) and *causes activation in* (thick grey arrows). The first (structure–function) mapping is investigated by neuropsychology and, more recently, transient lesions using TMS (transmagnetic stimulation). The second (function–structure) mapping is used by functional neuroimaging and is usually taken to identify the set of regions that are sufficient for a particular function. For example, in the figure, BA39 is sufficient for subprocess 2a but it is not necessary because STS can also support this function if BA39 is damaged (Price & Friston, 2002). Notice that in Figure 3, the structure–function mapping can be one-to-many and many-to-one, in other words divergent and convergent. The many-to-one aspect represents a degenerate mapping and the one-to-many reflects a simple form of pluripotentiality. Together these constitute the complicated many-to-many function–structure relationships referred to in the introduction.

Single-word reading revisited

In Figure 4a and 4b we contrast conventional and revised ontologies for the results presented in Table 1. The problem with the ontology in Figure 4a is that it is not informed about the underlying functional anatomy, namely more than one function engages the same cortical region. Although, given the task, one could predict that the left posterior lateral fusiform would activate, it would be very difficult to predict the task a subject was engaged in, knowing only that the left posterior lateral fusiform was activated. In contradistinction, an integrated ontology (Figure 4b) allows one to predict that all tasks activate the left posterior lateral fusiform and furthermore that activation of this area means the subject is explicitly categorising a precept (e.g., for integrating sensory information with the requisite response). As above, this example is only schematic. Clearly, designating the left posterior lateral fusiform as a visual word form area, although tenable from the point of view of cognitive models of reading, does not do justice to a more integrated and holistic ontology.

Rules for "good" ontologies

We will conclude with some ideas about constructing "good" ontologies. Clearly, a good ontology should:

1. Have a hierarchical structure that predicts the coactivation of anatomical regions, where sets of coactivated regions should have demonstrable (effective) connections.
2. Enable cognitive processing to be predicted given any distribution of activations, based on which area, or set of areas, is necessary for that processing.

These criteria emphasise that function should be predicted from anatomical activation and conversely that anatomical activation should predict function. This can be embodied operationally in a cost function that reflects the prediction error in going from function to structure and back again. For example, such a cost function could be defined for a particular task in the following way. Identify all the cognitive processes involved in the task and compute the areas activated given the function–structure mapping. Using the structure–function mapping, identify all the processes for which the activated areas are necessary. The discrepancy between these processes, and those comprising the task, constitutes that cost

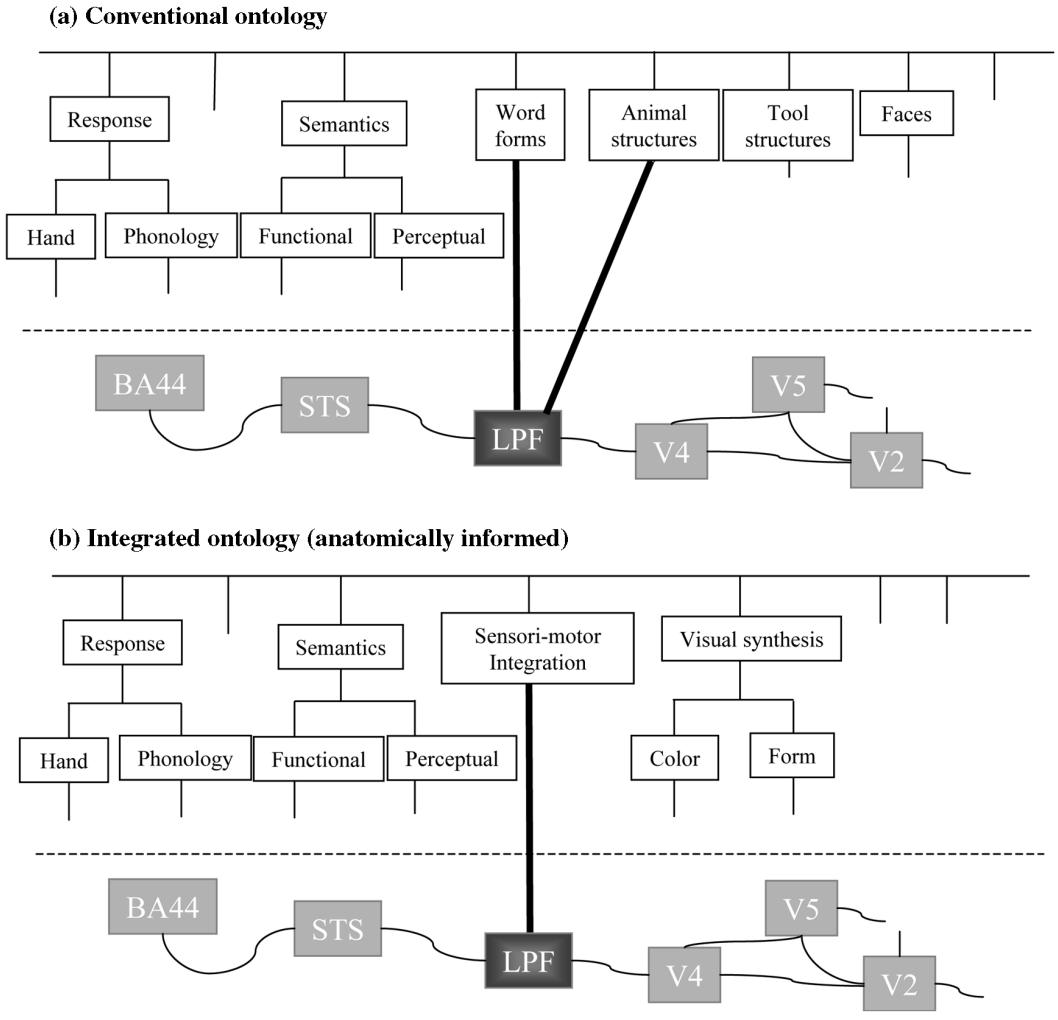


Figure 4. *Conventional and revised ontologies. (a) A conventional ontology that is not formed by the underlying functional anatomy. Here, more than one function can engage the same cortical region. (b) An integrated ontology where functional labels are constrained by the anatomical response. Here, activation in an area predicts the process that is engaged.*

function for that task. A good ontology will minimise this cost function over all tasks. Similar devices have been used in computational anatomy to define the hierarchical organisation of visual cortices using only anatomical connectivity information (e.g., Young & Scannell, 2000).

Note that this strategy relies on knowing which areas activate, given a particular set of processes (determined by neuroimaging) and which regions are necessary for each process (determined by the lesion-deficit model). This approach to cognitive ontology therefore rests upon an integration of neuroimaging and neuropsychological techniques, a pleasing point on which to end.

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