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Structural and Functional Organizing Principles of Language: Evolving Theories

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1. Introduction

The overall goal of this paper is to evaluate theories that attempt to address the organizing principles of language and review the development of these theories toward the integration of language within an interactive network of higher-level cognitive functions. Commencing with an overview of traditional concepts of language as modular, distinct, and innate, we focus firstly on areas that highlight the foundation of modularity theory including various module definitions and criteria, and applications of modularity in information processing and biological systems. We also discuss challenges to the overall applicability of a modular system and limitations of modular models in dealing with adaptation, novelty, innate versus learned, domain-general and domain-specific features, and developmental and age-related changes of cognitive organization.

Prompted by the rapidly increasing amount of empirical data on the functional elements of the human brain, we then evaluate several major theories of cognition, including views that oppose modular organization and those that integrate modular and semi-modular views with topological modularity in simpler, and dynamic integration in higher-level cognitive functions.Within this framework, modular and non-modular components of linguistic knowledge, organizing principles of language viewed either as specific or derived from other systems, and concepts of language as one of the cognitive functions or the outcome of unique interactions among cognitive components are discussed.

Emerging theories that integrate interactive network models support a cognitive architecture as a mosaic of domain-specific and domain-general processes involving both functional segregation and integration within a global neuronal workspace. Within this anatomically distributed workspace, the language function represents unique interactions among cognitive components consistent with an organization that is task-dependent with a continuum between degrees of modular and shared processing. As a higher-level, learning-based, and effortful cognitive process language transiently enlists a less modular organization for an efficient network configuration in interaction with several cognitive systems and the domain-general cognitive control/multiple-demand network.

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2. Traditional Views of Language and Cognitive Architecture: Limitations and Challenges

Traditional explanatory models considered the language faculty (FL) as an organ of the body determined by genetic endowment (Universal Grammar, UG), experience, and possible design features, mainly centered around the concept of computational efficiency and conceptualized as third factor principles in subsequent theories. Some of these features, based on the initially assumed lack of difference in basic language capacity among contemporary humans, have also been considered language (UG) and/or even organism (third factor principles) independent (Chomsky 2005, 2011). Earlier concepts also held language as different and distinct from other cognitive functions with considerations of UG as a specific language module or a modularized knowledge or element of the FL (Hauser et al. 2002).

Modularity, originally an engineering notion of near-decomposability, refers to a system that is made of components whose workings are independent of each other and in which the modular structure allows parts to be modified without the whole system ceasing to function (Simon 1969). The concept of modularity including certain characteristic and/or necessary model features (Fodor 1983), and a modular design was considered central in biology (Marr 1982) with a general modular theory also proposed for perception and cognition (Coltheart 1999). The modular organization hypothesis has been also linked historically to the claim that aspects of the human mind are innately specified (Fodor 1983, reviewed in Twyman & Newcombe 2010).

The integration of modular organization in certain biological areas such as development has high explanatory value. However, a strictly modular view is controversial in the cognitive sciences as it precludes complex processes such as associative learning, attention, working memory, or general intelligence that cut across domains (Shettleworth 2012). The assumption that much of the cognitive processing is modular was challenged early on by fMRI data of brain activation (Wojciulik et al. 1998), and studies of neurodevelopmental language disorders that proposed relative modularity that is only achieved after an extensive period of developmental time (Bishop 1997, Karmiloff-Smith 2007). The widely different definitions of what constitutes a module remain controversial and the minimum criteria that are required for a system to be considered modular are unsettled (Twyman & Newcombe 2010, Kaltenbach & Stelling 2012). Important theoretical challenges also remain regarding function-centered decomposition of dynamic biological networks (Kaltenbach & Stelling 2012). The controversial issues include the integration of modular clusters in a larger-scale as modalities in the brain need to be both isolated and sufficiently connected for coherent functions (Gallos et al. 2012), questions as to how does a modular system deal with novelty (Anselme 2012), the innate and/or developmental nature of modularity (Thomas & Karmiloff-Smith 2002), the lack of one-to-one correspondence in function to structure mapping (Petersson et al. 2012), the relationship between domain-general and domain-specific cognitive processes (Meunier et al. 2010, Kitzbichler et al. 2011), the continuum between strictly modular processing and degrees of task dependent shared processing (Borowsky et al. 2007), and functional specialization as a matter of discrete units or as a matter of degree (Kanwisher 2010).

2.1. Universal Grammar: A Disputed Language Module

One of the most influential traditional theories of language assumed an innate faculty with a defining influence of neural circuitry shaped by biological determinants (Chomsky 1965, 1968, 1995, 2005). A few genetic events (summarized by Chomsky 2005), subsequently also interpreted as a single mutation scenario (reviewed in Jackendoff 2011), had been proposed to rewire the human brain and create an abstract cognitive mechanism responsible for the development of language. Within this framework a modular organization of cognitive functions was also assumed in which language constitutes its own module (Hauser et al. 2002). The traditional linguistics term of language refers to an internal component of the mind and/or brain (internal or I-language). The the FL in the broad sense (FLB) was proposed to include a narrower internal computational system (FLN) and at least two other internal systems (sensorimotor and conceptual-intentional) and cognitive resources or abilities necessary for the acquisition and use of language that together constitute UG (Hauser et al. 2002). FLN was considered to only include recursion and to be the uniquely human component of the FL and a biological capacity of humans that allows mastering of language without explicit instructions (Hauser et al. 2002). FLN by this definition cannot be compared to anything existing in the mind of other species, not even in other domains of the human mind (revisited in Boeckx & Longa 2011 and Traxler et al. 2012).

Alternative theories include those that argue that the language-specifically adapted sensorimotor systems should be part of FLN, traditions that consider the conceptual-intentional system as intrinsic part of FLN (Jackendoff 2011), and views that language is built on biological and cognitive foundations that pre-date the emergence of language (Chater et al. 2009, Christiansen et al. 2009). Although language is used to express recursive thoughts, their recursive nature is independent of language and likely preceded its evolution (Corballis 2011). Recursion may have evolved in order to solve other computational problems such as navigation, quantification, or social relationships (Hauser et al. 2002). Furthermore, as recursion is not unique to language, it cannot constitute FLN (Jackendoff 2011).

Theories that held FL as a distinct module among other cognitive modules, also considered UG as a specific and modularized knowledge/element of the language faculty. UG as a genetically determined language acquisition device that constrains the parametric options available for natural languages has been viewed as the key component that explains both the linguistic universals and the assumed quick and uniform path to language acquisition (Hauser et al. 2002). Based on the shared common core of human languages (Berwick et al. 2013), the poverty of stimulus for UG argues that invariant properties of the human mind, including the structure dependence of grammatical rules and certain constraints on question formation, reflect an innate human endowment (Berwick et al. 2011). The principles and neural mechanisms of UG have also been regarded not only as innate, but distinctly modularized and independent of (though connected to) other parts of cognition (Grodzinsky 2006).

UG however is a disputed notion (Elman et al. 1996, Boden 2006, Clark & Lappin 2011). Some argue that the simplest idea is that there is a universal set of cognitive capacities underlying human linguistic competence. Others question the reality of UG given that there is no consensus on the very notion of UG, and also question the species specificity, poverty of stimulus, ease of acquisition, and uniformity of the knowledge of language across a population (Dąbrowska 2004, Evans & Levinson 2009 reviewed in Irurtzun 2012). During language acquisition there is no need for UG to figure out what grammar/syntax underlies a particular language, the ability to learn signs also enables the learning of combinatorial signs or dedicated order of signs (Bouchard 2012). There are factors other than language-specific UG conditions that can canalize grammar very stringently: Properties of the perceptual and conceptual systems necessarily impose boundaries within a highly circumscribed course of language development and these properties are considered sufficient elements of language. Further challenging the existence or need for innately specified knowledge of language, a Bayesian framework for grammar induction showed that given certain innate domain-general capacities, a learner can recognize the hierarchical phrase structure of language without having this knowledge innately specified (Perfors et al. 2011).

2.2. The Computational View of Language

The basic design of language as a biological subsystem reveals a system of discrete infinity, that is unbound number of expressions. Language (the unified nature of language) has been proposed to arise from a shared species-specific computational ability that is grounded in a neuronally realized computational mechanism that yields an infinite array of structured expressions. At minimum, this computational mechanism is able to combine one linguistic representation with others, yielding new and larger linguistic objects. The computational mechanism includes some operation (Merge) that constructs new representational elements from already constructed elements which must then be transposed to linear representations, a constraint imposed on the sensorimotor systems input–output channel (words must be pronounced sequentially) and on language perception (listeners analyze sequentially ordered acoustic sequences) (Chomsky 1995). In this view, the FL as a computational device is capable of processing symbolic elements and externalizing and internalizing the output of such computations. The computational system is viewed as the outcome of interactions between a sequencer (activity performed by the basal ganglia) and working memory (the activity of diverse cortical structures) (Benítez-Burraco 2012). Accordingly, language acquisition depends on the interplay of the shared initial genetic endowment (UG, the language- and human-specific module), conditions imposed by the structure of the brain, cognitive preconditions (statistical analytical capacity), external influences (environmental stimulants), and certain general principles such as external laws of growth and form, and minimalization of computational complexity (Berwick et al. 2013).

2.3. Modularity in Information Processing

The ubiquity of modularity and hierarchical modularity across technological and biological systems prompted a search for dynamic, adaptive, or anatomical constraints that may drive the evolution of networks towards a modular architecture (Meunier et at. 2010). A system built of multiple and sparsely interconnected modules allows efficient adaptation. Evolution of such a modular system can take place by change in one module at a time or by duplication or mutation of modules without loss of function of well-adapted modules. The evolution of individual modules does not jeopardize the function of the entire system and results in robustness, a major advantage for any system evolving under changing selection criteria. High clustering of connections favor locally segregated processing of specialized functions (as in visual motion detection), while short path length supports globally integrated processing of generic functions (as in working memory) (Meunier et al. 2010, Sporns et al. 2010, 2013). Modular topology is associated with rich non-linear dynamic behavior including time-scale separation (fast intra-modular and slow intermodular processes) and high dynamical complexity due to the coexistence of both segregated and integrated activity. The feedback between structure and function including reinforcement of links between synchronized units and pruning of links between asynchronized ones, naturally drives the emergence of inhomogeneities and a modular network. Optimality at performing tasks in a changing environment, where different goals share basic sub-problems and where rapid adaptation to each of the different goals is enhanced, produces networks, modules, and modular units that specialize in these sub-problems. Thus a modular network is a topologically modular and nearly decomposable system made of component modules each of which comprises a number of nodes that are densely intra-connected to each other but sparsely connected to nodes in other modules (Meunier et al. 2010).

2.4. Modularity in Biological Systems

In biomedical research, mechanistic explanations dominate by which a phenomenon is explained by revealing the set of entities and activities that are spatially, temporally, and causally organized. The modular partitioning and hierarchical structure of the biological space emerged as a symmetry-breaking phase transition exemplified by metabolic networks, gene networks, protein interaction networks, or social networks (Lorenz et al. 2011). The biological norm has been considered to be a set of specialized modular systems and this type of organization presumed so ubiquitous that all functional systems were anticipated to be subject to the same organizational principles. In evolutionary and developmental biology, modularity, defined in general terms as a property of being made up of self-contained and independently functioning parts, is regarded as a key principle (reviewed in Shettleworth 2012).

Connotation for modules (Fodor 1983) has been defined as autonomous (operate independently of other systems and are independently disruptable), domain specific (responsive to a distinctive class of stimuli), innately specified, informationally encapsulated (impervious to information outside the modules domain, a feature considered to be at the heart of modularity, Fodor 2001), peripheral (as opposed to central decision making), fast acting (as a reflex), mandatory (not under conscious control), obligatory (acting regardless of circumstances) and hardwired. While innateness and modularity are different concepts, modules are often held innate in the sense that they develop similarly across individuals regardless of environmental input (Barrett 2012).

These definitions have been interpreted not as necessary conditions for the applicability of the term but rather as a general theory of perception and cognition and features that are characteristic of modules (Coltheart 1999). While it has been recognized that the notion of modularity ought to admit to degrees (Fodor

1983), it has also been postulated that if a system has most of the modularity properties, then it is very likely to have all of them, a mechanistic explanation derived from the computational information-processing paradigm. Of the various module-associated concepts, however, only the concept of autonomy corresponds to strict modularity in the sense of independent disruptability, or dissociability (it can be selectively disabled with no effect on other capacities of the same system) (Menzies 2012).

The most basic term of a module is a capacity that is functionally individuated in terms of its input and output conditions with domain-specificity as its most important property. The generalized and widely applied conceptualization of a module involves a set of related elements that maintain a strong connectivity within but a weak connectivity among other equivalent sets of elements. In this general sense, a module may include sets of functionally interrelated genes, interactions among regulatory elements, interrelated set of neuronal structures, or coordinated actions of biological structures (Benítez-Burraco 2012).

While the traditional analysis of complex biological networks relied on decomposition into smaller, semi-autonomous units (e.g. signaling pathways), with the recently increased scope of systems biology the different definitions of what constitutes a module or a modular structure and the function centered decomposition of dynamic biological networks sparked controversies (Kaltenbach & Stelling 2012). There are considerable debates about the extent to which any modular structure in a mature adult is inborn or emerges through experience (Thomas & Karmiloff-Smith 2002). Other views point out that biological systems are actually not all highly specialized and modularized and are rather varied in how they constrain processes (Gallistel & Gibbon 2000). Moreover, the modularity assumption does not apply universally in all domains, there is more depth to mechanistic explanations than box-and-arrow diagrams, and the spatial and temporal organization of mechanisms are often as significant as the causal organization (Gallistel & Gibbon 2000, Menzies 2012).

3. Organizing Principles of Cognition: From Modules to Global Neuronal Workspace

3.1. Modular Models of Cognitive Functions

Modularity has been traditionally presumed as being essential at both cognitive and neural levels, yet the notions of neural and cognitive modularity remain controversial (Marcus 2006). Of the brain mechanisms, commonly thought of as falling into two categories: specialized and general-purpose, the specialized mechanisms being frequently associated with the idea of modules (Barrett 2012, Barrett & Kurzban 2006). In this model, independent disruptability has been assumed to be a basic meaning of modularity as two sub-processes (mental or neural) can be modules if and only if each can be changed independently of the other (Sternberg 2010). Thus the notion of modularity, applied in a strict sense to the organization of the brain, envisions a system made of components whose workings are independent of each other with parts modifiable (Simon 1969) exemplified in the modular account of the visual system viewed as a computational system made of a collection of small independent sub-processes (Marr 1982).

The general application of the modularity concept to cognitive functions (Marr 1982, Coltheart 1999, Anselme 2012) resulted in the assumption of massive modularity for the human mind while other theories of modularity such as the (i) core knowledge modules position (Spelke & Kinzler 2007) distinguished limited number of core knowledge modules (object, action, number, geometry, and social partner representation), or in a version of core modules, six big traits (intelligence, openness, contentiousness, agreeableness, emotional stability, and extraversion) modules presumed to be domain specific, innate, and even shared across species (reviewed in Twyman & Newcombe 2010). Modules defined by these theories, however, do not conform to the module definition (Fodor 1983), few are encapsulated, and most are involved in various cognitive functions.

Among various additional theories, the (ii) functional modularity approach argues that the key property of cognitive modularity is functional specificity given that distinct domains of information require specific processes to operate on them (Barrett & Kurzban 2006). In this view, functional modules constitute a subsystem of the cognitive system each dedicated to specialized functions. (iii) Anatomical modularity is an additional thesis by which each functional module is implemented in a dedicated, relatively small, circumscribed neural hardware (Anderson 2010). In this paradigm, various kinds of cognitive modules have been distinguished: developmental, (neuro)functional, mental, or even virtual (a pattern of dissociability between aspects of the systems that does not correspond to separate neural systems) (Griffiths 2007). These modules have been generally assumed to be localizable within the brain and to be neurally specific. In contrast, it has also been proposed that there is no necessity for a cognitive module to be associated with a localized fixed neural architecture (Coltheart 1999). An alternative hypothesis to the functionally distinct, independent neurocognitive modules (e.g., in an extreme view, language module owes nothing to other cognitive devices) is the (iv) descent-with-modification view by which modules are shaped by evolutionary changes. Thus, from common origin ancestral cognitive or neural modules/capacities, relatively recent modules (such as language) may derive and draw on general cognitive resources, consistent with features of neurodevelopmental disorders and developmental language disorders (Marcus 2006).

Given the many invocations of the term modularity, also referred to as (v) innatist-modularity (inborn modularity without modification), the modularity definition is considered so vague as to be essentially untestable (Twyman & Newcombe 2010).

3.2. Challenges to Cognitive Modularity: Domain-Specific and Domain-General Processes

While cognitive modules clearly function in dynamic environments and have to deal with change-induced novelty and uncertainty, the novelty of stimulus is problematic for the modular concept as it does not satisfy the modules criteria for domain specificity. In order to overcome this problem, a potential for (vi) transient variations in domain-specificity (behavioral transitions from exploratory activity to habit formation) have been proposed (Anselme 2012). Explanations for information processing adaptation, however, remain controversial and the form in which such adaptation may take is disputed.

Brain mechanisms, if evolved through processes of descent with modifications are likely to be heterogeneous rather than limited to two specific kinds (modular and non-modular). As new structures evolve from older structures, adaptations represent a mix of ancestral and derived features of which the older ones are shared more widely across structures, while relatively recent ones (properties of specialized brain regions) are more narrowly distributed in a hierarchically organized fashion (Caroll et al. 2005). The mix of these mechanisms are also likely to be highly plastic, environmental factor dependent for development, and interactive with other systems (Barrett 2012). A structure recaptured in the (vii) dual process theory proposes two kinds of human cognitive domains: simple basic processes shared with other animals and slower developing uniquely human processes, a human cognitive architecture that is a mosaic of modular and domain-general processes (Shettleworth 2012). Based on this model, variations in developmental outcomes across individuals or environments may be standard for brain adaptations. Adaptations for language exemplify this theory producing highly variable outcomes in various languages (Evans & Levinson 2009).

Additionally, domains/modules are not persistent (inborn) and among the modules, for example, language is viewed as a mechanism that moves infants from an innate modular representation to integrated cognition in adulthood (Twyman & Newcombe 2010). Or in contrasting opinions, infant brains start out highly connected and only over developmental time do the networks become increasingly specialized with domain-general and domain-specific processes (Steele et al. 2012). The organization of brain networks overlapping with functional domains (executive and auditory/language processing) has been reported to also demonstrate aging related changes, a reduction in functional segregation and intra- and inter-module connectivity (Chen et al. 2011). Function related dynamic changes have also been noted to occur such as an increase in connectivity between working memory regions and language regions concomitant with processing load increase (Makuuchi & Friderici 2013).

While specialized (modular) mechanisms appear innate, domain specific, and/or isolated from other brain systems, the generalized mechanisms (non-modular) are considered developmentally plastic instead of innate, domain-general and interactive. Along these lines, the (viii) dual system view equates specialization with highly local, narrow, and stereotyped (modular) processes, while the general-purpose processes are defined as those outside modularity. Thus, features of developmental plasticity, interactivity, or the ability to respond to novel stimuli are taken as evidence that a brain process or region is not evolutionarily specialized (Barrett 2012).

3.3. Brain Networks: Structurally Distributed and Functionally Diverse Connectivity

The human brain has been subjected to extensive multiple scale studies from neurons, circuits, anatomically defined areas to functional networks. Anatomically localized and functionally specific brain regions (developed through the maturation of specialized groups of similar fate cells sparsely connected to groups of cells of different fates) and their connecting networks, considered as information processing systems, share some of the organizational principles of modular systems. As other complex systems, brain networks also demonstrate hierarchical structure, or modularity on several topological scales (submodules and sub-submodules) that ensure robustness, adaptivity, and ability for evolution of network function (Meunier et al. 2010). Brain organization studies based on data obtained in cat and macaque brain connectivity using fiber tracking have identified four hierarchically organized major sub-networks classified as visual, auditory, somatosensorimotor, and frontolimbic. Human anatomical network analyses of cortical regions reproduced some of these functionally localized areas such as auditory/language, strategic/executive, sensorimotor, visual, and mnemonic processing (Chen et al. 2008) and interpreted the data as a modular — though with modules loosely defined as groups of connected cortical regions — brain structural networks (Hagman et al. 2008).

In more complex cognitive functions, to establish the association of anatomical brain structures with specific function ranging from synapses to entire brain regions, remains a challenging task (Fotopoulou 2013). The integration of modular clusters in a larger-scale has also been problematic as modalities in the brain that process different characteristics need to act in an isolated fashion for efficient computations, yet need to be sufficiently connected to perform coherent functions.

In order to overcome the limitations of the modular cognitive model (with modules variably defined as network areas based on connectivity features: high intra- and sparse interconnectedness), several types of alternatives have been proposed. The network view emphasizes that a complex system is shaped by the interactions among its constituents driven by universal selection criteria, such as high efficiency of information transfer at low physical connection cost (Sporns 2010). The functional integration-convergence model further emphasizes the significance of connectivity patterns among various interconnected, functionally diverse, and structurally distributed components of the nervous system (Fotopoulou 2013). Another alternative is the adaptive combination model supported by results of a study that challenge the existence of a geometric/reorientation module and hypothesizes that information (geometric and featural in this case) is utilized to varying degrees dependent on the certainty and variance that these two kinds of information represent (Ratliff & Newcombe 2008, Twyman & Newcombe 2010). Additionally, a recent combination of high-temporal resolution fMRI and network analysis tools have revealed both functional and topological fractal properties of brain networks, described as a two-layer structure (strong ties in a sea of weak ties) that fulfill the need for information flow within complex structures (Gallos et al. 2012).

3.4. High-Level Cognitive Functions Enlist a Global Neuronal Workspace

Adult human cognition shares simple basic processes with the cognition of other animals while additionally includes unique, slower-developing, usually slower acting, more explicit, and consciously accessible processes, among which the kind versus the degree of cognitive difference has not always been clearly defined. The relatively low level cognitive or perceptual processes based on features such as domain-specific, informationally encapsulated, fast, automatic, and anatomically localized, can be characterized as physiologically modular. In contrast, higher-level integrated, effortful, and conscious cognitive processes have been linked to anatomically distributed neuronal workspace architecture that may have emerged by breaking modularity of the background modular system (Dehaene et al. 1998), suggesting that modularity and/or non-modularity of brain network organization may be related to the type of cognitive processing that it can support (Meunier et al. 2010), and by this definition certain elements may be modular, while others are not (Barrett 2012).

Consistent with this theory is the basic modular architecture of the visual system (Magen & Cohen 2007) and evidence in favor of modular processing of verbal and spatial information in short-term memory (Guerard & Tremblay 2008). A contrasting non-modularity characterizes the central auditory function involving higher order performance (Musiek et al. 2005), the task-dependent activation of multiple/alternative pathways in prelexical and semantic processing, and the dynamically determined cortical network supporting language comprehension (Price 2010). Additionally, there is a continuum between strictly modular processing (in perceptual tasks) and varying degrees of modular and shared processing (in analytical tasks) that depends on the nature of the task (Borowsky et al. 2007).

Effortful cognitive performance that depends on the formation of a global neuronal workspace enlists — with increasing demand and faster performance — a more global, less clustered, and less modular networks with more long-distance synchronizations to allow the transient adoption of functional networks for less economical but more efficient configuration (Kitzbichler et al. 2011).

3.5. Functional Segregation and Integration: Continuum and a Matter of Degree

Neuropsychological theories that infer the functional role of certain brain areas on the basis of the consequence of damage to these areas (localizationist and anti-localizationist theories) served as the bases for two central principles of structure-function relations: functional specialization/segregation (specialized neurons form segregated regions responsible for discrete mental function) and functional integration/convergence (mental functions are based on connectivity patterns among various functionally diverse and structurally distributed components of the nervous system) (Friston & Price 2011, Fotopoulou 2013).

The segregation model derives from the long tradition of concepts for specialized organs and specialized brain modules and the logic of information processing systems that perform a series of formal operations (reviewed in Kanwisher 2010). Based on the theory that the mind is modular in its core conception, organized in computationally autonomous serially organized domains of function, brain damage was anticipated to result in a selective, encapsulated impairment of a component of cognitive processing without affecting other components. Earlier studies based on these assumptions aimed to identify behavioral dissociations to suggest new modular division in which cognitive information followed paths along serially organized modules each serving a different core cognitive function. In structure-function mapping studies (neuroimaging based mapping between neuronal activity and cognitive function), modularity of processing and processes was a key reference for establishing functional segregation as a principle of brain organization. The modularity theory also contributed to characterization of distributed brain responses in terms of functional integration or coupling among different brain areas (modular but coupled) (Friston & Price 2011).

The contrary concepts of distributed neural and cognitive processing have an equally rich tradition (Kanwisher 2010). It has been increasingly recognized that correlations between mental tasks and surrogate brain signals in functional neuroimaging studies have provided only indirect evidence (inferences about cognition based on neural activation). The initial and relatively simple imaging and statistical analyses resulted in simplistic localizationist and modular arguments about the role of certain brain areas in complex mental functions. From mapping of sensory functions into functionally specialized areas in the human cortex (spatial segregation) does not follow that similar kind of mapping would apply to complex cognitive and emotional functions.

The use of more refined methods to investigate the neural basis of the mind *in vivo* allowed insight into functions such as semantic processing and memory, and beyond these, into emotion and empathy. The concept that the human mind can be understood by examining exclusively cognitive functions has also undergone considerable criticism with increasing support for the view that mental abilities are defined also by emotions and motivations and are subject to intricate interactions with interpersonal, social, and technological environments. As a result, there is a recent change in emphasis from functional segregation to considerations of functional integration and to methods that allow the capture of dynamic large-scale operations in the brain. The possibility to observe structural connectivity, such as non-tasks specific large-scale distributed networks and (non-stimulus driven) self-organizing endogenous brain activity, reveal a neurocognitive organization that surpasses the classical modular and computational centered view of the mind (Fotopoulou 2013). There are still debated questions as how specialized regions of the brain are, how much of the mind is made up of specialized components, and importantly, whether the functional specialization is all or none or it is a matter of degree (Kanwisher 2010).

4. The Organizing Principles of Language

4.1. A Distributed and Hierarchical Language-Serving Network Structure

The brain regions that serve the capacity for language, collectively provide the semantic, syntactic, phonological, and pragmatic operations required for language comprehension and production. Previously developed language models such as the Wernicke-Lichtheim-Geschwind model that describe left-lateralized language functions give only limited view and interpretation of language processing in the brain. The language networks proved more extended than those defined (based on the earliest brain imaging research) as the classical language regions/modules (Broca and Wernicke areas) and include, as part of a prominent network-forming region, the lateral surface of the left frontal, temporal and parietal cortices and a number of other cortical, subcortical and cerebellar regions (reviewed in Fedorenko 2014). The division of labor between Broca's region (frontal cortex) and Wernicke's region (temporal cortex) does not correspond to language production versus language comprehension. Contrary to earlier reported functional distinction between language and other cognitive processes (Fedorenko et al. 2011), none of the language-relevant regions and none of the language-specific neurophyschological effects have proved language-specific as these are also triggered by other input

(Koelsch et al. 2002). For language as for other cognitive functions, the function-to-structure mapping as one-to-one correspondence is almost certainly incorrect (Petersson et al. 2012).

An analysis of the network structure for associative-semantic processing that also sub-serves many important cognitive functions, identified networks, sub-networks, and hub-status nodes with local clustering and discerned four major communities or sub-systems (Vanderberghe et al. 2012). In an attempt to identify cognitive elements involved in semantic circuitry and to capture the entire network (as opposed to individual functional components localized by methodologically limited neuroimaging studies and linear modeling) a group independent component analysis (ICA), providing both spatial and temporal information, identified a more complicated language distribution pattern, an elaborate network involving several additional spatially independent brain regions (eight task-related group ICA maps) sub-serving semantic decision. The authors of this work recognized the importance of information gained when analyzing cognitive functions in terms of underlying network structures, demonstrated that the semantic network comprises left, right, and bilateral sub-networks, concluded functional connectivity, and proposed a hierarchical cognitive model for semantic decision tasks, yet summarized this complex structure as modular with such broad functional (module) categories as verbal encoding and mental imagery and semantic decision making as sub-modules (Kim et al. 2011). In spite of revoking modularity in this study, the authors also propose each brain regions activation/function not as that of an isolated module(s), but rather as part of a network.

In these reports as in many others, the use of the terms module and/or modular have many connotations but few, if any, defined characteristics or specific criteria and critical attributes of modules (automatic, encapsulated, or neuronally specialized). Moreover, the terms modular and modules are often used as synonymous with various functional unit(s), however, with diversely defined content, and interchangeable with circuitry, networks, sub-networks and/or nodes, overlapping with the non-modular, dynamic network system concept.

4.2. Interactive Language-Related Abilities: The Role of Developmental Time

Interpretations of some the neurodevelopmental disorders have been viewed both as evidence for modular preservation of language or evidence for non-modular cognitive development (Brock 2007). Some of these disorders have been considered as conditions in which selective modules are impaired while others (language) appear normal (reviewed in Szalontai & Csiszár 2013). Williams syndrome with selective cognitive deficits but relatively preserved language, had been initially proposed as an example for modularity of language. Abundant subsequent evidence on alterations in brain development, language features, and interactions among cognitive capacities in Williams syndrome, however, point to contrary hypotheses. Genetic (Vanderweyer et al. 2012), and extensive developmental (Karmiloff-Smith 2007, 2012) studies revealed that in Williams syndrome, deficits profoundly affect synaptic activity, neuronal density, brain size and morphology, and functional connectivity. Among Williams-specific language features, spatial language deficits mirror deficits in nonverbal spatial cognition (Brock 2007). There is dissociation between grammatical rules and the mental lexicon in the production of inflected form for irregulars, as well as a correlation between performance on morphological tasks and phonological short-term memory (Pléh et al. 2003), and between semantic organization and reading levels (Lee & Binder 2014). Furthermore, the common basic auditory processing shared by prosody and music, is also affected (Don et al. 1999). While patients do process music and prosody through shared mechanisms, these are different from those in non-affected individuals (Martinez-Castilla & Sotillo 2014). The language phenotype in Williams syndrome, therefore, is not an indicator for a selectively spared (language) module, but the interactive result of multiple altered neural and cognitive processes during development (D'Souza & Karmiloff-Smith 2011).

In specific language impairment (SLI), traditionally considered as a single impaired function within a normally functioning brain with intact cognition, affected children proved to have lower performance IQ (Botting 2005), an overall increased radiate white matter, altered intrahemispheric and corticocortical connections (Herbert et al. 2004), asymmetry in their language-association cortex (De Fosse et al. 2004), and abnormal development of brain structures that constitute the procedural memory system (Ullman & Pierpont, 2005). This complex phenotype in SLI does not support the involvement of a putative single language module. A developmental model of SLI proposes a higher order of complexity: As language emerges from multiple abilities (attention sharing, speech pattern detection, phonetic and phonemic discriminations, speech processing speed), contribution from lower level deficits in any or several of these abilities during development can contribute to the phenotype (D'Souza & Karmiloff-Smith 2011). Comparisons of adult and developing cognition including language revealed a strong role for developmental time in both typical and atypical development as infant brains start out highly connected and only during development do the networks become increasingly specialized. Understanding the concurrent and longitudinal constraints can cast a broader light on the role of development and relationships between domain-general (attention) and domain-specific (vocabulary, letter knowledge, phonological skills) processes (Steele et al. 2012).

4.3. Task-Dependent Recruitment of Perceptual and Cognitive Processes

Language used to be widely considered as different and distinct from other cognitive functions with its own specific organizational principles. Subsequent views, while considered some elements or principles specific to language (basic primitives, features, syllables that allow to begin to distinguish different types of patterned stimuli), recognized that some characteristics may become grammaticised over time. Furthermore, it was also recognized that interactive constrains on linguistic performance and structure arise from cognitive constrains on learning and real-time processing (Christiansen & Chater 2008, Newport 2010).

These organizing principles, while characteristic of language, are not unique to language and also include organizing principles for other functional domains (motor behavior). The basic language organizing principles recognized as shared with other cognitive domains include computation of mutual information, entropy, conditional probability, contingency or predictiveness between elements and computed over hierarchical rather than linear distance in a recursive fashion (Newport

2011). Consequently, a unique combination of cognitive functions constrains language and the localization of these cognitive functions arises not from the inherent localization of cognitive modules but from the interactions of multiple cognitive and perceptual processes involved in a particular function (Newport 2010).

The cortical network thought to be domain-specific for language processing has been shown to also process musical information suggesting that this network is less domain-specific than previously believed (Koelsch et al. 2002). While considerable research supported the view that faces and words are subserved by independent neural mechanisms located in the ventral visual cortex in opposite hemispheres, a current study demonstrated a co-mingling of face and word recognition mechanisms. This co-mingling is unexpected from a domain-specific perspective, but follows as a consequence of an interactive, learning-based account in which neural processes for both faces and words are the results of an optimization procedure with specific principles and constraints. A comparison of pseudoword and face identification revealed that both stimulus types exploit common neural resources within the ventral cortical network (sublexical orthographic representations within the left ventral cortex and continuity of reading with other visual recognition skills) (Nestor et al. 2012). Thus cognitive functions appear to arise not from localized cognitive modules (language or face perception) but from the interaction of multiple perceptual and cognitive processes that underlie a particular task (Behrmann & Plaut 2013).

A meta-analysis of comparative functional anatomy data for speech comprehension and production in healthy adult brain including activation patterns for prelexical speech perception, meaningful speech, semantic retrieval, sentence comprehension, and incomprehensible sentences, identified association with the use of prior knowledge of semantic associations, world sequences, and articulation that predict the content of the sentence. Speech production activated the same regions as speech comprehension and additional areas for word retrieval, articulatory planning, the initiation and execution of speech, and suppression of unintended responses (Price 2010). The observation that prelexical and semantic processing of spoken words extend into anterior, ventral, and posterior directions suggested that the same speech input can follow multiple different pathways in which the location of activation is determined by the task demands similar to alternative strategies and dual routes, featuring both a direct and an indirect route (noted earlier for phonological processing (Heim 2005)).

Collectively, results from these studies (without even addressing functional connectivity of the activated regions), strongly promote the view that the cortical networks supporting language comprehension are dynamically determined by the task and context.

4.4. Domain-General Cognitive Control and Functionally Specialized Language Regions: Division of Labor

Abundant evidence shows that the network-forming language system with somewhat varying functional definitions (the lateral surface of the left frontal, temporal and parietal cortices and a number of other cortical, subcortical and cereballar regions) (Fedorenko & Thompson-Schill 2014), interacts with several cognitive systems including the visual system, social cognition supporting system, and, importantly, the working memory/cognitive control network/mechanisms (Fedorenko 2014). Some of these cognitive mechanisms are also known to be shared between language and other functions such as musical ability with highly similar structural and expressive features (Perrachione at al. 2013). The cognitive control network/multiple-demand system, also referred to as task-positive network, or fronto-parietal attention network (including parts of the dorsolateral prefrontal cortex, parts of the insular cortex, regions along the precentral gyrus, presupplementary and supplementary motor area, parts of the anterior cingulated, and regions in and around the intraparietal sulcus), is domain-general and flexible according to task demands and is implicated in a broad range of goal-directed behaviors. While its role in complex behaviors is not fully understood, the cognitive control system has been implicated in attention, working memory, cognitive control, structure building, timing/sequencing, attentional episodes, and conscious awareness (Fedorenko 2014). The cognitive control network is spatially and functionally distinct from the language system, however, it responds to linguistic input (both to pseudowords or processing of natural sentences) as much as the language system. While domain-general regions are engaged during language comprehension, dissociations from the language network also exist, indicating that the cognitive control regions may not be essential for language comprehension. Yet these interactions may still function in facilitating efficiency or speed of comprehension, providing workspace and alternative routes, or support predictive processing (Fedorenko 2014). The involvement of domain-general processes not only in language comprehension, but also in language acquisition is supported by the impairment of implicit sequence learning in SLI (Lukács & Kemény 2014).

5. Conclusion

The theory of modularity as a general principle with traditions in informatics has been historically applied to aspects of human cognition. Modularity views have been specifically influential in characterizing the organizing principles and structural and functional elements of language. Application of strict modularity, however, has been controversial as it precludes complex cognitive processes. With recent advances in brain activation analysis and systems biology interpretation of these results, the various and controversial definitions of what constitutes a module or a modular organization have sparked profound theoretical debates. Criteria for a cognitive modular system remain inconsistent and range from the definition that emphasizes topological modularity (dense intra- and sparse inter-connectedness) (Meunier et al. 2010), to a system with independently disruptable components (Menzies 2012, Sternberg 2010), to a property of being made up of self-contained and independently functioning parts (Shettleworth 2012), to the most basic use of the term as a capacity with functionally individuated input and output conditions (Menzies 2012).

Alternative models of modularity and alternatives to modular organization have been suggested in order to resolve some of these controversies and address the limitations inherent in modular system organization. Examples of these models include the functional and topological two-layer structure for information flow integrating modular clusters in a large scale (Gallos et al. 2012), introduction of the feature of transient variations in module domain-specificity (Anselme 2012), the modular-but-coupled theory (Friston & Price 2011), and the descent-with-modification modularity involving evolutionary changes (Marcus 2006).

Specialized modular mechanisms are considered innate, domain specific and isolated, in contrast, non-modular mechanisms are generalized, developmentally plastic, domain-general, and interactive, overall, more suitable to capture the working principles of the cognitive system. Theories that embrace generalized mechanisms take into consideration the effect of the variance of types of information (Ratliff and Newcombe 2008, Twyman & Newcombe 2010), the dynamic interaction of multiple neural and cognitive processes and the role of developmental time (D'Souza & Karmiloff-Smith 2011, Karmiloff-Smith 2012), the significance of connectivity patterns among functionally diverse and structurally distributed components of the central nervous system (Fotopoulou 2013), and equate specialization with local, narrow, and stereotyped functions, and general processes as those outside modularity (Barrett 2012) with a view of the cognitive architecture as a mosaic of modular and domain-general processes (Shettleworth 2012).

The large-scale operations in the brain have been interpreted with a recent emphasis on dynamic functional integration rather than segregation. Structural connectivity data, including distributed networks and endogenous brain activity, have revealed a neurocognitive organization that surpasses the classical modular and/or computational centered view (Fotopoulou 2013) and suggest a brain network organization that is determined by the type of actual cognitive processing (Meunier et al. 2010). A task-dependent continuum has been also noted between modular processing and varying degrees of modular and shared processing (Borowsky et al. 2007), and functional specialization has been formulated as a matter of degree (Kanwisher 2010). Higher-level and effortful cognitive processes proved to be linked to an anatomically distributed neuronal workspace architecture (Dehaene et al. 1998) that and enlist with increasing demand, a global network configuration with long-distance synchronizations and transient adoption of functional networks (Kitzbichler et al. 2011).

Theories of language organizing principles are profoundly shaped by the facts that none of the traditionally defined language-relevant regions and none of the neurophyschological effects proved language-specific, there is no one-to-one correspondence for cognitive function and structure (Petersson et al. 2012), the principles of language organization are not unique but shared with other cognitive domains (Newport 2011), and are the developmental time-dependent result of interactions of neural and cognitive processes (Karmiloff-Smith 2012), the language-serving network is more elaborate than previously anticipated and involves connectivity of several newly recognized and spatially independent brain regions (Kim et al. 2011), language associated cognitive functions arise from the interaction of multiple perceptual and cognitive mechanisms, cortical networks while not domain-specific for language (Koelsch et al. 2002) reflect a learning-based mechanism in which neural processes are the results of an optimization procedure (Behrmann & Plaut 2013), with a multiple pathways activation pattern determined by the task demands (Price 2010).

Together with the activation of the language network, the domain-general multiple-demand system also engages (Fedorenko 2014), and while not essential, it may facilitate efficiency or speed by providing workspace and alternative processing routes. As cognitive function of any region depends on the areas that it interacts with (Price 2010), the functional association of language regions can only be revealed in the context of their interactions with other brain regions and with the understanding of the task-dependent modulation of these regional interactions.

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