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A research program in neuroimaging for an evolutionary theory of syntax

Abstract: The Mirror System Hypothesis of Michael Arbib (2012), with respect to the cultural evolutionary origins of syntactic structure, allows to make a set of predictions about the neural mechanisms that govern the processing of modern human languages. Neuroimaging techniques may be employed to test these predictions and inform an evolutionary theory of language syntax. In this commentary, I will argue that future neuroimaging research needs in particular to: i) clarify whether linear sequential versus non-linear hierarchical structure differentially depend on mirror neurons as opposed to higher-order heteromodal cortices; ii) challenge current neuroscientific evidence on multilingualism: as it stands, syntactic processing appears to be mediated by the same neural mechanisms across languages, independently of cross-linguistic idiosyncrasies; iii) devise longitudinal studies of grammar acquisition in newborns and children; iv) recreate in the laboratory nearly-ecological conditions for the emergence of syntactic constructions through cultural and social interaction, and exploit the “experiment of nature” of pidgin and creole languages.

Keywords: Mirror neurons, syntax, hierarchical structure, multilingualism, grammar acquisition

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The theoretical framework of Michael Arbib’s Mirror System Hypothesis (MSH) of language evolution has been markedly deepened and broadened by the author over the past fifteen years, since its initial proposal in collaboration with Giacomo Rizzolatti (1998). In his recent book *How the Brain Got Language* (2012), Arbib has, in my view, brought his theoretical framework to full maturation. Many details of the MSH, which were previously left implicit or just roughly sketched, are now clearly spelled out, and in reading through the chapters of the book, one is confronted with a detailed unfolding of the possible evolutionary stages that endowed humans with language. As with other evolutionary processes that did not leave behind any fossil traces, it may well not be eventually possible to experimentally challenge all of the postulated evolutionary stages and mechanisms

but, at the least, two main tenets stand out: first, a coherent chain of events that can be rejected or further refined by the proof of intellect; second, of particular importance for the present commentary, a set of specific predictions that may be directly tested by empirical studies (with focus on functional and structural neuroimaging techniques).

The greatest advance with respect to the specific topic at stake here, namely hierarchical organization of behavior and language syntax, is the detailed spell out of the evolutionary stages that may have engendered a language-ready human brain, including the role of the mirror neuron system (MNS) in understanding of others' intentions; and, on top of that, the tentative enumeration of which linguistic properties may be mediated directly by the MNS, as opposed to other properties, including syntactic processing, that may require a broader neural system instantiating a wider range of cognitive and computational capacities. The search for a somewhat obvious association between the uniqueness of the human species in possessing language and anatomo-functional brain features that are exclusively found in humans, must take into account the prominent expansion of the frontal lobe and the related increase compared to non-human primates in working memory, executive functions, focused and divided attention, and planning (Norman and Shallice 1986; Stuss and Knight 2002), which are all fundamental components of cognitive hierarchical structuring.

Although obvious in general terms, the full elucidation of the evolutionary expansion of frontal lobe anatomy and function in humans can be quite problematic. This is particularly evident in the case of the posterior sector of the left inferior frontal gyrus, roughly corresponding to Broca's area. Whereas Rizzolatti and Arbib (1998) and Arbib (2012) posited cytoarchitectonic Brodmann Area (BA) 44 to be the human homologue of area F5 in the macaque, i.e. the area where mirror neurons were first discovered (di Pellegrino et al. 1992; Gallese et al. 1996), Petrides et al. (2005) identified, by means of cytoarchitectonic analysis and intra-cortical electrophysiological recordings in the macaque brain, a region lying rostro-ventrally to area F5, which they named area 44 and which they suggested to be the true homologue of human BA 44. Accordingly, both monkey and human areas 44 present a dysgranular layer IV (as opposed to an agranular layer IV in area F5), both are involved in the control of orofacial musculature, and both are replaced rostrally by the granular area 45, with which BA 44 forms Broca's area in humans (see also Petrides and Pandya [2009]). Thus, contrary to the MSH, the *pars opercularis* of Broca's area (BA 44) does not appear to be the human homologue of area F5 in the monkey, and it remains to be clarified whether the macaque area 44 also contains mirror neurons. This may represent a shift with respect to the MSH, but one that does not contradict a main tenet of *How the Brain Got Language*, namely that the mirror system alone cannot support language in

its entirety, and one that may allow for the resolution of some problematic issues that were pointed out by Tettamanti and Moro (2012) in relation to syntax and mirror neurons.

Tettamanti and Moro (2012) noticed that the recursive hierarchical structure of human language syntax is only partially manifest in the physical linear word order of spoken, signed, or written language, and as such it is not entirely transparent to the bodily senses. They then argued that this prominent feature of language grammars, which is inherent to a wide range of transformational and non-transformational generative grammar approaches (Jackendoff 2003), speaks against the view that syntactic hierarchical structures are coded by the MNS, as suggested for instance by Pulvermüller and Fadiga (2010). Due to the perceptuo-motor neurophysiological properties of mirror neurons in matching observed and executed actions, the MNS can at most respond to those aspect of language processing that are readily available through hearing or vision, arguably not to “hidden” hierarchical syntactic properties (see Tettamanti and Moro [2012] for the detailed argumentation).

The association between the MNS and syntax has largely originated from consistent neuroimaging evidence of the activation of the left-hemispheric BA 44 by hierarchical syntactic processing tasks (for reviews, see Tettamanti and Perani [2012] and Tettamanti and Moro [2012]), and from the aforementioned idea that human BA 44 is the homologue of monkey’s area F5 hosting mirror neurons. Now, the discovery that human BA 44 has its proper homologous brain region in the macaque, as well as in the chimpanzee (Sherwood et al. 2003), potentially avoids the problem of implicating mirror neurons in syntactic processing, particularly if we postulate that the marked tissue expansion of BA44 in humans compared to monkeys (Petrides and Pandya 2009) is not driven by a major increase in mirror neuron cells, but rather to an increase of non-mirror, heteromodal cells. In this view, an expanded BA 44 would confer to the human brain increased higher-order computational resources to store and manipulate non-local dependencies, thus making it “language-ready” and paving the way for the emergence of fully grammaticalized languages.

Two corollary observations are worth mentioning. The first observation is that the argument of Tettamanti and Moro (2012) regarding the unattainability of syntactic structures to the perceptuo-motor system pertains to non-linear hierarchical relations, as opposed to sequential hierarchical relations such as found in simple linguistic phrases, or in motor and cognitive behavior (Tettamanti and Weniger 2006). Linear sequential hierarchies are transparent to the senses and can in principle be coded by the MNS. Thus, the strategic proximity of mirror neurons in the ventral premotor cortex and heteromodal neurons in BA 44 would allow the flexible combination of a rich variety of linear and non-linear

structural information as found in language. This functional specialization of the ventral premotor cortex (and frontal operculum) versus BA 44 is suggested for instance by activation studies contrasting, respectively, local and non-local syntactic dependencies (Friederici et al. 2006). These two brain regions act in concert with, respectively, the anterior temporal lobe and the posterior portion of the superior temporal cortex (Friederici et al. 2006), thus further stressing the contribution of non-MNS brain regions in syntactic computation and integration processes. The second observation is that the distinction between local and non-local syntactic dependencies, and as a consequence between the ventral premotor area and BA 44, may largely reflect, respectively, the type of syntactic information that can be extracted in early child language acquisition through generalization from lexically specific constructions and, typically later on during development, the maturation of non-perceptual, internal cognitive skills related to hierarchical structuring (Friederici et al. 2011), compatible with empirical (Bannard et al. 2009) and theoretical usage-based generative approaches such as Construction Grammar (Goldberg 2006) and related accounts (Jackendoff 2003).

In his spell out of the evolutionary stages of language, Arbib (2012) argues that the language-ready human brain was shaped by biological evolutionary pressure, but that full-fledged modern language properties, such as complex syntax, syntactic categories, adjectives, or conjunctions, were largely the product of cultural evolution. Complex language structure may have arisen through progressive fractionation of holophrastic symbols and signs, a slow process of spontaneous invention that was at least in part “scaffolded on preexisting understanding of object-action schemas” (p. 272). This is a compelling and original theoretical construct, with some predictions that can be derived and subjected to experimental verification. On the one hand, there is the panoply of past and modern human languages, each with characteristic lexical and phonological, but also syntactic and morphosyntactic features. As Arbib (2012) repeatedly points out, there is no such thing as *the* language: the diversity of languages, dialects, even of individual linguistic idiosyncrasies, is largely the product of shared social constructions and conventions. Language is an imprecise code that hinges on the capacity of understanding our conspecifics’ communicative intentions (Enrici et al. 2011). On the other hand, different languages that are far apart in their historical and geographical origins share common features that may have originated independently several times, such as the basic subject-object-verb order or rare grammatical properties such as evidentiality (p. 53). This suggests that complex language structure is not solely the product of cultural evolution, but is intrinsically shaped by the manner in which our brain is perceptually and computationally constrained in elaborating the physical world.

These two opponent – but possibly coexisting – views should lead to different predictions regarding the specific neuroanatomical representation of individual languages if subjected to systematic cross-linguistic comparison. If languages differ in having lesser or greater grammatical complexity (Dixon 1997; Baronchelli et al. 2012), we should expect that grammatical processing in a specific language or in a specific class of languages is mediated by a characteristic blend of, or load on, cognitive (e.g. different load on working memory) and computational functions (e.g. “branch left” versus “add morpheme”) and dedicated neural circuits, and should therefore emerge in neuroimaging studies in the form of a unique neural fingerprint. If in turn, the cognitive and computational mechanisms do not differ eminently across languages or language classes, we should rather expect that the activation patterns revealed by neuroimaging are largely overlapping.

In order to properly address the MNH that syntax is mainly the product of cultural evolution, a paradigmatic shift in neuroimaging studies is in need. So far, most neuroimaging studies on complex syntactic properties have concentrated on the investigation of abstract hierarchical rule learning – leading to an evolutionary challenging debate on possible abilities homologous to humans in non-human primates (Saffran et al. 2008), dolphins (Herman et al. 1993), and birds (Stobbe et al. 2012) – and of sentence processing (Tettamanti and Perani 2012). With some notable exceptions, the focus of these studies has hinged on the dissection of an isolable syntactic component and on its inherent neurobiological basis from a rather universalistic perspective, i.e. with no particular consideration of the specific idiosyncrasies of the language investigated. Many more cross-linguistic comparisons will be required in the future, if we aim to resolve the outlined question of whether grammatical processing is supported by unique neural fingerprints in specific languages, compatible with the cultural evolution hypothesis, or by largely overlapping neural networks, compatible with the biological evolution hypothesis. The cross-linguistic comparisons should be theoretically motivated by considering specific typological syntactic parameters, such as in comparing morphologically isolating (e.g. Mandarin) versus polysynthetic (e.g. Oneida) languages, or fixed (e.g. English) versus flexible (e.g. Dyirbal) word order languages, while controlling as much as possible for non-relevant linguistic parameters, such as semantic content.

The traditional cognitive neuroscience research field for the comparison of activation patterns across languages has been the study of the neural correlates of bilingualism or multilingualism. Have neuroimaging studies on multilingualism so far provided any evidence in support of language-specific syntactic representations in the human brain? Two decades of neuroimaging on multilingualism have consistently demonstrated that multiple spoken languages are largely

represented in overlapping left-hemispheric perisylvian networks, with modulatory influences determined by language age of acquisition, proficiency, and daily exposure (Perani and Abutalebi 2005). As these parameters of language use should ideally be fully equated in order to address the question of biological versus cultural evolution of grammar, the most relevant observation here is that early, highly proficient bilinguals present closely matching functional and electrical responses for grammatical processing across the two languages (Weber-Fox and Neville 1996; Wartenburger et al. 2003; Rossi et al. 2006). The arguably most comprehensive cross-linguistic comparison in bilinguals was performed in a neuroimaging study by Kim and colleagues (1997), with 12 participants being highly proficient in language pairs among French, Korean, English, Japanese, Spanish, German, Turkish, Hebrew, Croatian, Italian, and Chinese. This study, which did not specifically focus on syntactic processing but rather required a generic internal sentence generation task, also showed that language-specific activations in Broca's area are found in late but not in early bilinguals. Even a language acquisition neuroimaging study specifically focusing on non-local hierarchical syntactic dependencies in two languages as diverse as Italian and Japanese, found a closely overlapping involvement of Broca's area (Musso et al. 2003).

Though the "localizationist" question of language-specific representations is ill-posed, since a neuroscience of multilingualism should not solely focus on how two or more languages are represented in the brain, but rather on how these languages are acquired and how they are processed (Abutalebi et al. 2009), it is nevertheless possible that the incapacity to evidence language-specific neural fingerprints for syntactic processing so far, is due to technical limitations of neuroimaging techniques, such as low spatial resolution. If so, newest technical advances in functional magnetic resonance imaging, such as sub-millimeter spatial resolution, multivariate pattern classification, or connectivity analysis, may alter our current view on multilingualism. Integrating supramodality by comparing modality-specific representations in bimodal speaking and signing bilinguals will also be crucial in future studies (Abutalebi et al. 2009). As it stands, we are forced to accept that, at least the highly conserved syntactic patterns across languages are the product of biological, rather than cultural, evolution. Alternatively, we are forced to develop alternative explanations as to why, in spite of typological syntactic distinctions between languages, largely overlapping neural networks are observed as a result of cultural evolution: this may bear some analogies with the evolutionary recent specialization of the word form area for both printed and Braille reading (Dehaene and Cohen 2011), although the computational requirements of reading seem much less multifaceted than those of syntax.

A second important aspect of Arbib's view on the cultural evolution of syntax is the hypothesis that language grammar arose through social and cultural inter-

action, mainly as a result of agreed constructions. Although these cumulative processes developed at an extremely slow rate and escape any possible dynamic observation – on the one hand because of the irremediable lack of fossil traces of language evolution, on the other hand also because the time extent of tens of thousands of years exceeds the temporal constraints of scientific experiments as we conceive them in the laboratory – Arbib (2012) repeatedly points out that we can nevertheless base our research on the idea that the same language-readiness of the human brain is at work at present day when adults learn a foreign language or when children acquire language. However, neuroimaging studies on adult syntactic rule acquisition (e.g. Tettamanti et al. 2002; Bahlmann et al. 2008) have particularly suffered from the problem highlighted by Arbib that contemporary humans, as opposed to our proto-linguistic ancestors, do not have to invent language structures as they are already widespread in culture and society. Participants in these studies were required to learn syntactic structures that were imposed on them by the experimenters, and in some cases the acquisition process largely occurred outside neuroimaging measurements (Friederici et al. 2006; Bahlmann et al. 2008). A major problem is that grammatical learning by contemporary humans is fast, much too fast to allow dissecting the acquisition of single syntactic constructions. Therefore, such studies can be at most relevant for the investigation of the neural correlates of foreign language acquisition; they can not inform us on the evolutionary origin of grammar, whether it emerged through either cultural agreement or biological pressure. To directly tackle the evolutionary hypothesis, future neuroimaging studies will need to boost longitudinal research in newborns and young children with the hope to resolve the neural basis of incremental syntactic structure formation. Alternatively, novel experimental strategies to study adult language acquisition must be developed, for instance by devising longitudinal acquisition programs based on models of child language acquisition (see e.g. Bannard et al. 2009) that can be imposed on adult participants following strictly controlled timetables within the magnetic resonance scanner, or using electro- or magneto-encephalography. Or, using either virtual simulations or hyperscanning to study multiple subjects, each in a separate magnetic resonance scanner, interacting with one another, more ecological (from an evolutionary point of view), but strictly controlled, experimental paradigms could be developed, in order to let participants invent artificial grammatical constructions, and eventually full-fledged languages, through mutual interaction, akin to the cultural evolutionary scenario put forward by Arbib, but in a much more compressed time frame.

Finally, we must carefully consider the opportunity to investigate with neuroimaging techniques the offered “experiment of nature” of emerging sign languages or pidgin and creole languages. Though again limited by not being an

entirely spontaneous process that exclusively relies on independent invention freed from internal and external influences of pre-existing language structure, the longitudinal investigation with neuroimaging techniques of individuals of isolated communities as they develop a pidgin language may provide us with a deeper understanding of the neural subtleties that underlie a quasi “proto-language” devoid of meaningful word order, functional morphemes, grammatical categories, and complex syntax. Language creolization may in turn help us in understanding the functional and structural plastic brain changes that enable the progressive emergence of an expanded grammar and syntactic structure over subsequent offspring generations.

In summary, several research questions can help improving our understanding of the evolutionary origins of language. Does the recently identified dysgranular area 44 in the macaque also contain mirror neurons, as does the granular area F5 where they were first discovered? Is the processing of non-linear hierarchical relations in humans mediated by heteromodal neurons in BA 44, as opposed to mirror neurons? Will technical advances in functional magnetic resonance imaging provide counter-evidence of cross-linguistic, language-specific neural fingerprints for syntactic processing? Can we recreate in the laboratory nearly-ecological conditions for the emergence of syntactic constructions through cultural and social interaction? How can we exploit the “experiment of nature” of emerging pidgin and creole languages? Hopefully, some of these questions will prove relevant for the research framework sketched by Michael Arbib’s fascinating book.

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