



Review

Towards a Computational Comparative Neuroprimatology: Framing the language-ready brain

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Abstract

We make the case for developing a Computational Comparative Neuroprimatology to inform the analysis of the function and evolution of the human brain.

First, we update the mirror system hypothesis on the evolution of the language-ready brain by (i) modeling action and action recognition and opportunistic scheduling of macaque brains to hypothesize the nature of the last common ancestor of macaque and human (LCA-m); and then we (ii) introduce dynamic brain modeling to show how apes could acquire gesture through ontogenetic ritualization, hypothesizing the nature of evolution from LCA-m to the last common ancestor of chimpanzee and human (LCA-c). We then (iii) hypothesize the role of imitation, pantomime, protosign and protospeech in biological and cultural evolution from LCA-c to *Homo sapiens* with a language-ready brain.

Second, we suggest how cultural evolution in *Homo sapiens* led from protolanguages to full languages with grammar and compositional semantics.

Third, we assess the similarities and differences between the dorsal and ventral streams in audition and vision as the basis for presenting and comparing two models of language processing in the human brain: A model of (i) the auditory dorsal and ventral streams in sentence comprehension; and (ii) the visual dorsal and ventral streams in defining “what language is about” in both production and perception of utterances related to visual scenes provide the basis for (iii) a first step towards a synthesis and a look at challenges for further research.

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1. Introduction

This review includes some familiar tropes on the mirror system hypothesis (MSH) of the evolution of the human language-ready brain as a basis for expanding upon prior research. Since some readers will be familiar with the background material, Section 1.1 explains how this review relates to prior publications. The rest of this section then provides “background to the background” or otherwise sets the stage for what follows.

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Section 1.2 explains a parallel between vision and auditory pathways in the primate brain – both have dorsal and ventral streams radiating from the respective primary sensory cortices. The visual streams will play a key role for our base model of the macaque brain (and thus for our hypothesized brain for LCA-m, the last common ancestor of macaque and human) in Section 2.1; we will then build on this in assessing the implications of MSH for understanding the modern human brain in Section 4.1, and offer further notions based on the auditory and visual streams in Sections 4.2 and 4.3, respectively.

A number of the brain models in this review are based on modeling the interaction of biologically plausible neural networks localized in specific brain regions. Section 1.3 introduces a complementary approach, schema theory, based on the competition and cooperation of distributed processes called schemas. Once a schema-theoretic model of a cognitive process has been obtained, one may seek a (possibly alternative) description in which subschemas may be linked to the activity of specific neural networks in the brain. We consider two examples of schema-based models. For the first, reaching and grasping, such an implementation has proved possible (see Section 2.1); for the second, visual scene interpretation, it has not.

Most brain modeling focuses on one brain at a time, seeking to delineate neural processes in perception, memory, action, and so on. However, an emerging focus on social neuroscience (of which language as implicated in conversation is surely a crucial part) requires that we develop dyadic brain modeling – modeling the brains of two creatures as they interact with each other, so that the action of one affects the perception of the other and so the cycle of interactions continues, with both brains changing in the process. This is the focus of Section 1.4. Unfortunately, a theory of conversation is beyond the scope of this review, but we do offer an example of dyadic brain modeling in Section 2.2, suggesting how interaction between two apes may support the emergence of novel gestures.

Section 1.5 introduces the key notion of computational comparative neuroprimatology. The primates we consider are monkeys, apes, and humans. By comparing behavior and communication across diverse species of these primates, we can stimulate the development of schema-theoretic models both of what is shared across species (a candidate for hypotheses on the last common ancestor) and what is different (stimulating evolutionary hypotheses, and the challenge of teasing apart biological and cultural evolution). This comparative primatology becomes computational comparative neuroprimatology when computational models of brain mechanisms are thrown into the mix.

A human language (such as English and Swahili, but not music) is a system which combines a lexicon with a grammar which supports a compositional semantics, i.e., it supports an unbounded set of propositions whose meaning can be inferred from the meanings of words through the way the grammar combines them. (This is a useful approximation – for example, context clearly affects our understanding of what is said.) Since no nonhuman primate has language in this sense, it is a plausible assumption that somewhere in our evolutionary tree we had ancestors with a system more open-ended than the communication systems of other species yet far less flexible than modern human languages. Section 1.6 introduces the notion of “protolanguage” in the sense of such an intermediate system.

Finally, we note that linguists have developed many different ways of characterizing grammars. No satisfactory characterization yet exists, especially when the challenges of understanding performance and brain mechanisms are taken into account. Section 1.7 introduces construction grammar as a potentially useful framework for our research, while noting that it comes in many “flavors” so that, even here, the choice of an optimal framework for neurolinguistics is very much an open challenge.

1.1. How this review relates to prior publications

My concern with linking language to the brain goes back at least to Arbib and Caplan [28] and the follow-up edited volume [29], but the main impetus for the present review can be traced back to two papers that I wrote with Giacomo Rizzolatti [38,145] which introduced the Mirror System Hypothesis (MSH). Noting that

- (i) area F5 of macaque brains contains *mirror neurons* responsive both during action and execution of similar hand movements; neurons active only during execution but not observation are called *canonical neurons*;
- (ii) brain imaging (e.g., [89]) reveals a human *mirror system for grasping* – i.e., a brain region activated for both grasping and observation of grasping – in or near Broca’s area, an area traditionally viewed as involved in speech production;
- (iii) F5 seems homologous to (part of) Broca’s area in humans, and
- (iv) aphasia of signed, and not just spoken, languages may result from lesions “embracing” Broca’s area [137]

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