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Research paper

Dorsal and ventral streams in the evolution of the language-ready brain: Linking language to the world

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ABSTRACT

Many studies in neurolinguistics focus on the dorsal and ventral streams of the auditory system in language comprehension, but few address the production of language (whether spoken or signed). Moreover, almost no neurolinguistic studies addresses how language use is situated with respect to our perception of and action in the world around us, functions which depend (in part) on the dorsal and ventral streams of the visual system. The aim of this paper is to lay the foundations for an integrated account of situated language processing in the human brain that incorporates the dorsal and ventral streams for both vision and audition. Our further aim is to do so in a way which lays bare the challenges of offering an account of brain evolution in which the macaque brain is used as a surrogate for the brain of LCA-m (the last common ancestor of human and macaque). In particular, we assess the challenges to the mirror system hypothesis (MSH) of the evolution of the language-ready brain when data on auditory dorsal and ventral streams are taken into account. To this end, we compare two accounts of language comprehension and one account of language production (for the special case of describing a visual scene). It will be argued that much of syntactic and semantic processing is fed by ventral processes, that both operate at the level of words-as-signifiers, and that the dorsal path and its role in the perception and production of words-as-articulatory actions plays only a secondary role in such processing.

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1. Introduction

The relation between the ventral and dorsal streams for *vision* in macaque and human brains has long been a key component of my research, both in modeling the role of vision in the control of hand movements (Fagg & Arbib, 1998) and in developing the so-called mirror system hypothesis (MSH) for the evolution of language (Arbib, 2010: Mirror system activity for action and language is embedded in the integration of dorsal & ventral pathways). Subsequently, Ina Bornkessel-Schlesewsky and Matthias Schlesewsky and their colleagues have emphasized the ventral and dorsal streams for *audition* in macaque and human brains in addressing the neurolinguistics of sentence comprehension (Bornkessel-Schlesewsky & Schlesewsky, 2013: Reconciling time, space and function: A new dorsal–ventral stream model of sentence comprehension) and in seeking the neurobiological roots of language in primate audition (Bornkessel-Schlesewsky, Schlesewsky, Small, & Rauschecker, 2015). The present paper attempts to integrate these efforts, emphasizing that both the visual and auditory systems are crucial for the use (and thus for the evolution) of language because the language-using brain serves not only the processing of symbols (whether spoken, written or signed) of the language but also the linkage of utterances to what they are

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about, such as experiences with the external world. The "glue" for this integration is provided by an approach to language performance called Template Construction Grammar (Arbib & Lee, 2007, 2008) which is grounded in a particular challenge in "aboutness," the description of visual scenes.

1.1. The shape of things to come

"How did the human brain evolve from, e.g., that of the last common ancestor with chimpanzees (LCA-c) or macaques (LCA-m) in such a way that it was language-ready?" Here, the term *language-ready brain* emphasizes the hypothesis that the brain of early *Homo sapiens* evolved to a state that had the *potential* to support the acquisition and use of language long before early humans had first developed languages rather than far more limited communication systems (Arbib, 2005a). The counter hypothesis is that the human brain *has* language in the sense of an innate Universal Grammar of the kind characterized by Baker (2001).

But what does it mean to *have language*, whether or not such possession is innate? What demands does the use of language place on the human brain? The mere possession of an abstract syntax which governs the formation of "grammatically correct" sentences cannot be enough; language must serve social interaction with others in interacting with the physical world.

Any account of the evolution of the language-ready brain must assess the role of the auditory system in conveying speech signals during the comprehension of spoken language. Nonetheless, visual input is important for human language for its role in linking cospeech gestures with spoken language (Kendon, 2004; McNeill, 2005) and in sign language (Emmorey, 2002). However, our focus on vision here will be to examine how visual perception of the world around us informs both the comprehension *and production* of language (whether spoken or signed). Indeed, there is a body of literature that examines how language use relates to the perception of a visual scene (the visual world paradigm: Altmann & Kamide, 2009; Knoeferle & Crocker, 2006; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) which in no way depends on whether language presentation is visual or auditory.

Given this we approach the concern with the dorsal and ventral streams for both vision and audition in the context of neurolinguistic evolution as follows:

Section 1.1. provides brief background on the ventral/dorsal distinction expressed in the "what" versus "where/how" pathways in vision and the "what" versus "where" pathways in audition. Crucially, we note evidence for distinct dorsal pathways for spatial working memory, visually directed actions and navigation (other functions are not excluded). It thus seems reasonable to hypothesize that further subdivisions of the pathways may have occurred in the evolution of the language-ready brain.

Section 2 turns to the BSSR Hypothesis (Bornkessel-Schlesewsky et al., 2015) which roots language evolution in primate audition. Here the emphasis, following Rauschecker (1998), is on the reception of speech sounds in language, attending neither to the aboutness of language nor to its production.

Section 3 instead roots language evolution in visuomotor coordination. The Mirror System Hypothesis (MSH; see, e.g., Arbib, 2005a, 2012; Arbib & Rizzolatti, 1997; Rizzolatti & Arbib, 1998) starts with parity of production and comprehension of manual actions as its core, and traces a possible path from LCA-m via LCA-c to *Homo sapiens*. It hypothesizes stages which might have led from manual actions via gesture, imitation and pantomime to language. It includes a sketch of how grammar may have emerged, but is relatively silent [sic] on how auditory processing entered the mix.

Section 4 presents a model which is agnostic as to whether the signals of language are auditory-vocal or (as in signed languages) visual-manual, but stresses "aboutness": First it offers a model of how a brain might form a semantic representation of a visual scene and use this as the basis for generating a description of the scene); it then sketches work in progress to extend this model to incorporate sentence comprehension as well. By contrast, Section 5 presents a model (the B&S model, Bornkessel-Schlesewsky & Schlesewsky, 2013) which focuses on sentence comprehension and whose architecture is based on the structure of the auditory ventral and dorsal streams. This model (like the classic studies of Hickok & Poeppel, 2004; Hickok & Poeppel, 2007, and indeed most studies in neurolinguistics) ignores how language can be integrated with the way we interact with the world. Thus, the two models are to some extent complementary. Unfortunately, however, the details within the two models are often discordant. Section 5 thus concludes with suggestions to how the two models might be integrated to offer an account of "this is your brain on language. Section 6 then poses further research challenges for studying the evolution of the language-ready brain.

A note to the reader: This is a sequel to my PLREV paper (Arbib, 2016b). If you've looked through that, you will see quite a bit of overlap, but diverse updates and some truly new material (e.g., Section 2. Rooting Language Evolution in Primate Audition: The BSSR Hypothesis, and Section 5.2. Towards an Integration of B&S with TCG) and some fairly drastic updating of my ideas on the tradeoff between the dorsal and ventral streams in the Section 6.

We now turn to a brief summary of relevant findings about the dorsal and ventral streams for vision and audition before outlining the key arguments of the paper.

1.2. (Ventral + dorsal) × 2, briefly

We now summarize findings about the ventral and dorsal pathways for vision and audition to the extent that they provide background necessary to what follows. There is no attempt at scholarly completeness. A key point is that each pathway is *not*

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