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The Common Origins of Language and Action

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Abstract

The motor system organization shows some interesting parallels with the language organization. Here we draw the possible communalities between Action and Language, basing our claims on neurophysiological, neuroanatomical and neuroimaging data. Furthermore, we speculate that the motor system may have furnished the basic computational capabilities for the emergence of both semantics and syntax.

Motor system hierarchy

The motor system is organized according to a clear hierarchical structure from abstract motor plans/intentions to motor implementation parameters in dissociable cortical, subcortical and spinal regions (Graziano, 2006). In fact, human behavior is mostly constituted by goal-directed actions based on the synergic composition of simpler motor constituents chained together according to a precise "motor grammar".

The work of Nicholai Bernstein (Bernstein, 1996) sets the basic principles for the modern study of the motor system. The novelty of his approach resides in the integration of evolutionary biology and musculoskeletal biomechanics to explain goal-driven motor behavior. Bernstein's model introduces some new concepts, such as the centrality of action goals (Bernstein, 1967). According to this view, actions are performed to achieve a desired goal and, thus, to solve a given problem. More specifically, the mismatch between actual movement and the desired action outcome is used for learning. This apparently simple idea sets the theoretical background to study the cortical motor hierarchy. According to Bernstein, actions are composed of simple motor constituents that can be chained together, maintaining a degree of adaptive variability. In this view, the motor system can recombine or substitute motor elements to cope with a change in context, to achieve a goal.

Furthermore and of great relevance, is the concept of motor recursivity or the ability to repeatedly retrieve previously learned motor elements composing an action. The idea of motor recursivity clearly has important consequences on the relation between language and action. In fact, recursivity has been historically considered a defining feature of language (Chomsky, 1957). The motor system might indeed contain a primitive ability to compose single motor acts into more complex behavior via repeating short sequences, a number of times. However, while language recursivity expresses nested structures, repetitive motor behaviors depict, in their simplest form, only sequential structures. It should be stressed, however, that recursion may be found in the motor system at, at least, two levels: in managing the redundancy of degrees of freedom at subcortical levels and in designing and using tools or even tools to build other tools, at the highest level of goal-directed motor representation (Fadiga et al. 2006).

Accordingly, the motor system could be conceived as a goal-driven hierarchical structure to concatenate simple motor acts. This hierarchical goal structure as well as the rules, which connect individual motor elements, might be paralleled to the syntactic organization of language. Also, the adaptive variability enabling the attainment of a goal regardless of how the motor plan is actually instantiated, coarticulation and motor recursivity are features showing clear analogies with speech and language systems. Hierarchical syntactic-like structures fulfill the two properties required for motor goal representation: Goal representations can (a) be reactivated as single units whenever required, and (b) have their component movements reactivated one by one or reassembled to enable learning of novel behaviors.

On neurophysiological ground research has shown that in monkey area F5, a ventral premotor area, complex hand and mouth movements are represented (Rizzolatti et al., 1988). Typical Neurons of this region discharge during the execution of a given specific goal-directed action (i.e. grasping, manipulating, tearing, or holding), whereas they do not discharge during similar movements made with other purposes. More interestingly, they become active during movements that have an identical goal regardless of the effectors used for attaining it. In addition to their motor properties, however, several F5 neurons also show complex visual responses (visuomotor neurons). Two categories of these visuomotor neurons are present in area

F5: Canonical and Mirror neurons. Canonical cells discharge when the monkey observes graspable objects or executes grasping actions upon those objects (Murata et al., 1997). Mirror neurons discharge both when the monkey executes and observes another individual making the same action in front of it (Gallese et al., 1996). Visual and motor properties of canonical neurons show a strict congruence between the two types of responses (i.e. a neuron active when the monkey observes small size objects also discharge during precision grip). The most likely interpretation for the visual discharge of canonical neurons is that there is a close link between the most common 3D stimuli and the actions necessary to interact with them. Mirror neurons, instead, fire when the monkey acts on an object and when it observes another individual making a similar goal-directed action. Typically, mirror neurons show congruence between observed and executed actions.

The role of Broca's area

Recent comparative cytoarchitectonic studies of human and monkey frontal cortex looked for the human homologue of monkey area F5, where mirror and canonical neurons were originally found. Area F5 is a typical premotor area characterized by no granular layer IV, analogously to human ventral premotor cortex (vPM). The pars opercularis (BA44, the posterior part of Broca's area) has a rudimentary layer IV and no large cell bodies in layer III. Human BA44, a disgranular cortex, shows important similarities with a monkey brain area in the fundus of the inferior branch of the arcuate sulcus. The pars triangular is (BA45, the anterior part of Broca's area), characterized by an important granular layer IV and very large cell bodies in layer III, is substantially a prefrontal region (Petrides et al., 2005). This structural difference between granular cortex (BA45) on one side and agranular (vPM) and disgranular (BA44) cortices on the other is also paralleled by recent connectivity studies in both humans (Frey et al., 2008) and monkeys (Petrides & Pandya, 2009). These studies demonstrate that the former (BA45) is anatomically linked to temporal areas, whereas the latter two (vPM and BA44) are mostly connected to the inferior parietal lobule and to the temporo-parietal junction. Therefore, human BA44 and vPM are the best candidates to host neuronal populations with mirror-like and canonical-like properties.

On the functional side, a growing body of neuroimaging evidence indeed indicates that vPM and posterior Broca's area (BA44) have properties similar to monkey area F5. Passive observation of graspable objects, in accordance with canonical-neuron properties in the monkey, was found to elicit motor and vPM activities in humans (Grezes, Decety, 2002). The vPM cortex also became active during the simple observation of tools (Grafton et al., 1997). Several other experiments studied brain activity when the participants observed actions of others, in search for mirror-like functions. Activations were present in BA44 and vPM cortex with a functional pattern analogous to that of mirror neurons in the monkey (Rizzolatti, Craighero, 2004). Moreover, frontal aphasics, without apraxia, failed in an action sequencing task, further suggesting the intriguing possibility that Broca's area could represent the hierarchy of action goals - seen or executed - rather than the basic motor program to execute them (Fazio et al., 2009). Similar results have been found in normals by temporary blocking BA44 function by transcranial magnetic stimulation (Clerget et al. 2009).

What action tell us about language

Thus far we have shown data supporting the representation of a hierarchical goal structure in the motor system. We described the complex and abstract integrative functions observed in monkey area F5 – containing mirror and canonical neurons – and we draw the anatomo-functional parallel between F5 and human Broca's area.

Interestingly, one might speculate that the emergence of a proto-semantics stems from the capability to build a pragmatic object representation - or the capability to convert purely perceptual objects into tools. The process of object to tool transformation requires several critical aspects. First, it needs the conversion of objects' complex geometrical features into hand-object interaction possibilities - affordances (Gibson 1979). Also, it requires the inclusion of the object into the body schema and the modification of motor internal models to account for the change in movement dynamics. In simpler terms the brain has to build a continuous and integrated sensory-motor representation of body-object interaction. Finally, but most crucially, the subject has to re-map the new potentialities for action afforded by the new body-object unity (Arbib et al., 2009). For instance, fingers have specific geometrical and biomechanical characteristics that allow precise grasping; a knife instead is a tool since it affords a totally new set of behaviors and thus offers an extension to human action possibilities. Human action extension offers the critical ability to build abstract semantic trees. In fact, the abstract defining feature of a "knife" or the pragmatic definition of "sharpness", enables the inclusion of another specific instance "broken glass", into the same superordinate category "cutting tools" via a functional/pragmatic description. In such a context, the process of object to tool conversion might have furnished the mechanisms to build a proto-semantics structure based on behaviorally relevant actions.

On the other hand one might speculate that the emergence of a proto-syntax might stem from the inherent hierarchical nature of the motor system. Indeed, the critical passage is between serial to hierarchical representations. Serial structures require an ordered representation of temporally organized events. However, human behavior cannot be accounted by serial mechanisms (Lashley, 1951). Hierarchical structures, instead offer the critical possibility of goal abstraction - as enunciated by Bernstein - as well as the capability to plan and predict action outcomes. In fact, an abstract action goal may be used to anticipate the whole tree-like structure associated to it and thus predict which specific sub-action will be executed. Furthermore this tree-like structure enables the simulation of actions or part of them to apply changes for the specific context we face every time we issue a desired goal. Only hierarchical syntax-like structures enable such behavioral flexibility as noted by Bernstein. Therefore, we suggest that the primitive hierarchical organization of behavior has *in nuce* all the required basic features that language needs, including recursivity, and sequence chunking.

In this respect it might be interesting to remember the idea, originally proposed by Leroy-Gourhan (1964), that the appearance during evolution of the capability to build and use tools might have represented the intermediate step linking action and language. As outlined before, tool fabrication may indeed have provided the capability of recursion to action representation. Tool design and tool use expand the complexity of motor plans and project actions in temporal dimensions other than the present. This is particularly true in the case of tools fabricated to build other, new tools. This forces the brain to postpone the ultimate goal following a complex, but quite flexible, hierarchy of subroutines/sub-goals. These spatial-temporally augmented degrees of freedom might have provided the brain with the first example of recursion for actions.

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