ACTION TO LANGUAGE VIA THE MIRROR NEURON SYSTEM

Mirror neurons may hold the brain's key to social interaction: each coding not only a particular action or emotion, but also the recognition of that action or emotion in others. The Mirror System Hypothesis adds an evolutionary arrow to the story: from the mirror system for hand actions, shared with monkeys and chimpanzees, to the uniquely human mirror system for language. In this volume, written to be accessible to a wide audience, experts from child development, computer science, linguistics, neuroscience, primatology, and robotics present and analyze the mirror system and show how studies of action and language can illuminate each other. Topics discussed in the 15 chapters include the following. What do chimpanzees and humans have in common? Does the human capability for language rest on brain mechanisms shared with other animals? How do human infants acquire language? What can be learned from imaging the human brain? How are sign- and spoken-language related? Will robots learn to act and speak like humans?

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Preface

There are many ways to approach human language – as a rich human social activity, as a formal system structured by rules of grammar, and as a pattern of perception and production of utterances, to name just a few. The present volume uses this last concern – with the perception and production of utterances – as its core. The aim is not to ignore the other dimensions of language but rather to enrich them by seeking to understand how the use of language may be situated with respect to other systems for action and perception.

The work is centered on, but in no way restricted to, the Mirror System Hypothesis (introduced by Arbib and Rizzolatti in 1997). This is the hypothesis that the mirror neuron system for the recognition of movements of the hands in praxic action – which is present both in monkey and in human in a number of areas including Broca's area (generally considered to be the frontal speech area) – provides the evolutionary basis for the brain mechanisms which support language. The Mirror System Hypothesis sees the ancestral action recognition system being elaborated through the evolution of ever more capable neural mechanisms supporting imitation of hand movements, then pantomime emerging on the basis of displacement of hand movements to imitate other degrees of freedom. A system of "protosign" emerges as conventionalized codes extend the range of manual communication, and serves as scaffolding for "protospeech." An expanding spiral of protosign and protospeech yields a brain able to support both action and language.

The arguments pro and con the Mirror System Hypothesis and the more general issue of how the studies of action and language can illuminate each other are developed in 15 chapters by experts in child development, computer science, linguistics, neuroscience, primatology, and robotics.

Part I of the book provides *Two perspectives* on the evolution of language. I discuss "The Mirror System Hypothesis on the linkage of action and languages," presenting the essential data and modeling of the mirror system for grasping in the macaque brain as well as related human brain imaging data to set the stage for the Mirror System Hypothesis on the evolution of the language-ready brain. Two controversial hypotheses are discussed: the view that the path to protospeech was indirect, depending on the scaffolding of protosign rather than evolving directly from primate vocalizations within the vocal domain; and the view that protolanguage was "holophrastic" and that the emergence of

language rested on the simultaneous fractionation of "unitary utterances" into words and the development of varied syntactic strategies to put the pieces back together again. Jerry Hobbs then offers a view of "The origin and evolution of language: a plausible, strong-AI account" which may be set against the Mirror System Hypothesis. He presents a computational approach in which abductive logic is realized in the structured connectionist networks of the SHRUTI model of language processing, and on this he bases an account of the evolution of language mechanisms. He uses the development of folk psychology to explain the evolution of Gricean non-natural meaning, i.e., the notion that what is conveyed is not merely the content of the utterance, but also the intention of the speaker to convey that meaning by means of that specific utterance. He also presents an account of syntax arising out of discourse, and uses that to argue against the holophrasis hypothesis.

Part II of the book presents three chapters addressing the theme of *Brain, evolution, and comparative analysis*. Craig Stanford provides, in "Cognition, imitation, and culture in the great apes," a comparative view of humans and the great apes. The "culture of apes" is discussed, especially variations in behavior in chimpanzees in different areas of Africa. The capacity (or lack of it) for imitation in apes and the relation between "communication in the wild" and simple forms of "language" taught to apes in captivity leads to a discussion of which of the cognitive abilities that make human language possible are possessed by non-human primates; while an emphasis on social behavior is the basis for an evaluation of claims for Theory of Mind (Machiavellian intelligence) in non-human primates. Karen Emmorey provides a comparative analysis of language modalities within humans, focusing on "The signer as an embodied mirror neuron system: neural mechanisms underlying sign language and action." Like mirror neurons, signers must associate the visually perceived manual actions of another signer with self-generated actions of the same form. However, unlike grasping and reaching movements, sign articulations are structured within a phonological system of contrasts. She relates this to language evolution, showing how languages escape their pantomimic and iconic roots and develop duality of patterning, and probes the similarities and differences between the neural systems for production and perception that support speech, sign, and action. Finally for Part II, Mihail Bota joins me in the chapter "Neural homologies and the grounding of neurolinguistics" to use comparative neurobiology of the monkey and human to establish homologies between brain regions of the two species related to the mirror system as well as communication and (precursors of) language to ground claims as to the brain of the common ancestor of monkeys and humans of perhaps 20 million years ago, and thus evaluate the Mirror System Hypothesis on how such brains changed to become language-ready. Of particular importance to charting the similarities and differences between human speech and the vocalizations of non-human primates is a set of data on the macaque auditory system and on the role of anterior cingulate cortex in both motivation and vocalization to better distinguish mechanisms that support language from those that support quite different forms of communication.

Part III analyzes *Dynamic systems in action and language*. In "Dynamic systems: brain, body, and imitation," Stefan Schaal focuses primarily on technological approaches to

learning "motor primitives" by building up dynamical systems by using combinations of basis functions in the system description. Learning methods can set the weights of these combinations both to yield imitation of behaviors expressed in a form that uses all the relevant dynamic variables and to yield recognition of actions as well. The discussion is extended to superposition of movements and, briefly, to sequential and hierarchical behavior. A short discussion relates these concepts to "what the brain really does." With this we turn to speech as a dynamical system. Louis Goldstein, Dani Byrd, and Elliot Saltzman discuss "The role of vocal tract gestural action units in understanding the evolution of phonology," thus helping us think through the issue of to what extent speech production shares mechanisms with motor control more generally. Like Emmorey, they stress the central role of duality of patterning – the use of a set of non-meaningful arbitrary discrete units that allows word creation to be productive – in phonology. They analyze vocal tract action gestures in terms of dynamical systems which are discrete and combinable. They see the iconic aspects of manual gestures as critical to evolution of a system of symbolic units whereas phonological evolution crucially requires the emergence of effectively non-meaningful combinatorial units, with the two systems ultimately converging in a symbiotic relationship. Continuing in this vein, Jeremy Skipper, Howard Nusbaum, and Steven Small discuss "Lending a helping hand to hearing: another motor theory of speech perception." They describe an active model of speech perception that involves mirror neurons as the basis for inverse and forward models used in the recognition of speech, with special emphasis on audiovisual speech in which facial movements (e.g., of the lips) provide extra cues for speech recognition. According to this model, the mirror neuron system maps observed speech production and manual gestures to abstract representations of speaking actions that would have been activated had the observer been the one producing the action (inverse models). These representations are then mapped in a somatotopically appropriate manner to pre- and primary motor cortices. The resulting motor commands have sensory consequences (forward models) that are compared to processing in the various sensory modalities. This aids in the recognition of a particular acoustic segment of an utterance by constraining alternative linguistic interpretations. Brain imaging experiments are adduced in support of these ideas.

Part IV takes us *From mirror system to syntax and Theory of Mind*. Laurent Itti and I discuss "Attention and the minimal subscene," showing how perception of a "minimal subscene" linking an agent and an action to one or more objects may underlie processes of scene description and question-answering, linking the schematic structure of visual scenes to language structure. The approach integrates studies of the role of salience in visual attention with "top–down" attention, cooperative computation models of vision and speech processing, and theories and data linking sentence processing to eye movements. David Kemmerer then offers an integrative view of "Action verbs, argument structure constructions, and the mirror neuron system." Here the route from mirror neurons to syntax is via the constructionist framework which regards syntax as an extension of the lexicon. Construction Grammar provides the setting for discussing the major semantic properties of action verbs and argument structure constructions. This in turn sets the stage

for analysis of the neuroanatomical substrates of action verbs and argument structure constructions in support of the proposal that the linguistic representation of action is grounded in the mirror neuron system. The discussion is then broadened to consider the emergence of language during ontogeny, history, and phylogeny. Andrew Gordon looks at "Language evidence for changes in a Theory of Mind", with Theory of Mind viewed as the set of abilities that enable people to reflect on their own reasoning, to empathize with other people by imagining what it would be like to be in their position, and to generate reasonable expectations and inferences about mental states and processes. He analyzes a corpus of English and American novels in search of a "Freudian shift" and finds an increasing use of language about the unconscious in the decades *preceding* Freud. He thus concludes that a major shift has occurred in Theory of Mind, strengthening the case that its roots are cultural rather than biological.

The final part of the book, Part V, examines *Development of action and language*. Erhan Oztop, Nina Bradley, and I study "The development of grasping and the mirror system" from a modeling perspective comprising the Infant Learning to Grasp Model (ILGM), the Grasp Affordance Emergence Model (GAEM), and the mirror neuron system (MNS) model of the development of the mirror neuron system. The account has strong links to the literature on infant motor development and makes clear that the range of mirror neuron responses is highly adaptive rather than being "hard-wired." This paves the way for an understanding of how imitation builds on the mirror system. Iona D. Goga and Aude Billard provide a broad conceptual framework for the study of "Development of goal-directed imitation, object manipulation, and language in humans and robots." Social abilities, such as imitation, turn-taking, joint attention, and intended body communication, are fundamental for the development of language and human cognition. Inspired by this perspective, they offer a composite model of the mechanisms underlying the development of action, imitation, and language in human infants. A recent trend of robotics research seeks to equip artifacts with social capabilities. Thus the model also sets the stage for reproducing imitation and language in robots and simulated agents. They validate the model through a dynamic simulation of a child–caregiver pair of humanoid robots. Patricia Zukow-Goldring discusses "Assisted Imitation: affordances, effectivities, and the mirror system in child development." She takes a mirror-system oriented view of cognitive development in the child, showing how caregivers help the child learn the effectivities of her own body and the affordances of the world around her. The basic idea is that a shared understanding of action grounds what individuals know in common. In particular, this perspective roots the ontogeny of language in the progression from action and gesture to speech and supports the view that the evolutionary path to language also arises from perceiving and acting, leading to gesture, and eventually to speech. Finally, Patricia Greenfield explores "Implications of mirror neurons for the ontogeny and phylogeny of cultural processes: the examples of tools and language." Mirror neurons underlie the ability of the monkey and human to respond both to their own acts and to the same act performed by another, selectively responding to intentional or goal-directed action rather than to movement per se. Greenfield argues that this neural substrate

underwrites phylogenetic and ontogenetic development of two key aspects of human culture, tool use and language. She stresses that ontogeny does not recapitulate phylogeny, but that infant behavior is more likely to be conserved than adult behavior across phylogeny. The analysis of both ontogeny and phylogeny draws on comparison of chimpanzees, bonobos, and humans to derive clues as to what foundations of human language may have been present in the common ancestor 5 to 7 million years ago.

This multi-author volume gains unusual coherence through its emergence from a year-long seminar led by the Editor in which eleven of the authors met every 2 to 3 weeks to debate and build upon the Mirror System Hypothesis. We thank the Center for Interdisciplinary Research of the University of Southern California which made this seminar, and thus this book, possible.