Conceptual grounding of language in action and perception: a neurocomputational model of the emergence of category specificity and semantic hubs

Max Garagnani
Freie Universität Berlin

Neurocognitive semantic theories propose that word meaning is grounded in the perception and action systems of the human brain (Barsalou, 2008; Pulvermüller & Fadiga, 2010; Glenberg & Gallese, 2012; Pulvermüller, 2013). These theories are supported by a growing number of experimental results, indicating that processing of words which belong to specific semantic categories leads to selective activation of modality-preferential areas (Pulvermüller & Fadiga, 2010; Meteyard *et al.*, 2012); for example, action-related words spark activity in dorsal motor cortex, whereas object-related ones activate ventral visual areas. Neuroimaging data, however, also show that a number of multi-modal areas are consistently activated by word and sentence comprehension processes, regardless of the stimuli's semantic category; this suggests the existence of general semantic centres (or "hubs") involved in processing the meaning of all word types (Price, 2000; Patterson *et al.*, 2007; Binder & Desai, 2011). The presence of both category-specific and category-general semantic areas begs for a unifying mechanistic account, able to explain the emergence of both in the cortex. We describe a computational model which provides such an explanation in terms of neural mechanisms underlying conceptual grounding in action and perception.

We implemented a spiking neural-network architecture closely replicating anatomical and neurophysiological features of frontal, occipital and temporal cortices of the human brain, and used it to simulate elementary aspects of language learning, focusing specifically on the semantic grounding of object- and action-related words. As the network underwent training, the presence of Hebbian mechanisms at work within specific neuroanatomical structures led to the spontaneous emergence of distributed lexico-semantic circuits (cell assemblies (Hebb, 1949)), linking "auditory-articulatory" patterns with semantic information coming from the "senses" and the "motor" system. During simulated word recognition and comprehension processes, reactivation of these cell-assembly circuits produced activity in the model-correlates of either dorsal primary motor or ventral visual areas, reflecting the correlated sensorimotor patterns that co-occurred during action- or object-related semantic grounding, respectively. Furthermore, areas which interfaced between the different modality-preferential systems (i.e., multimodal connection hubs) exhibited spontaneous emergence of substantial numbers of neurons of both types of distributed circuits, therefore becoming loci of general processes of semantic binding.

These computational results enable integrating key experimental observations about the presence of category-specific effects in modality-preferential sensory or motor systems with the emergence and "across-the-board" character of a range of semantic hubs in multimodal frontal, temporal and parietal cortex, consistently implicated in the processing of all types of meaning. By relating neuroanatomical structure and cellular-level learning mechanisms to system-level cognitive function, this work offers a neuromechanistic account of conceptual grounding able to explain the spontaneous emergence of different (category-general and category-specific) functional behaviours in distinct cortical areas during semantic processing, providing further computational evidence in support of an action-perception theory of semantic learning.

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