Perception-action circuits for word learning and semantic grounding: a neurocomputational model and neuroimaging study

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ABSTRACT

A neurocomputational architecture of the left-hemispheric areas of the brain is presented which was used to simulate and explain neural correlates of word learning and semantic grounding. The model's main distinguishing features are that (i) it replicates connectivity and anatomical structure of the relevant brain areas, and (ii) it implements only functional mechanisms reflecting known cellular- and synaptic-level properties of the cerebral cortex. Stimulation of the "sensorimotor" model areas (mimicking early stages of word acquisition) leads to the spontaneous formation of cell assemblies (CAs), network correlates of memory traces for meaningful words. Preliminary results of a recent functional Magnetic Resonance Imaging study confirm the model's predictions, and, for the first time, localise the neural correlates of semantic grounding of novel spoken items in primary visual cortex. Taken together, these results provide strong support for perceptual accounts of word meaning acquisition in the brain, and point to a unifying theory of cognition based on action-perception circuits whose emergence, dynamics and interactions are grounded in known neuroanatomy and neurobiological learning mechanisms.

Model architecture

At the microscopic level, the network implements physiologically realistic spiking neurons; at the system level, twelve areas of relevance for language and semantic processing situated in the frontal, the temporal and the occipital lobes (see Fig. **1.**A). Area-intrinsic, as well as between-area connectivity, was guided by neuroscience evidence. Six of the areas were in left-perisylvian cortex, relevant for language processing (Pulvermüller, 1999; Fadiga *et al.*, 2002; Pulvermüller & Fadiga, 2010): the model's 'auditory stream' includes the primary auditory cortex (A1), auditory belt (AB), and modality-general parabelt areas (PB), and its 'articulatory stream' comprises the inferior part of primary motor cortex ($M1_i$), inferior premotor (PM_i) and multimodal prefrontal motor cortex (PF_i). An additional six extrasylvian areas modelled referential meaning-related information about visual object identity (Ungerleider & Haxby, 1994), and about executable manual actions (Deiber *et al.*, 1991; Lu *et al.*, 1994; Dum & Strick, 2002; 2005). The 'ventral visual stream' includes the primary visual cortex (V1), temporo-occipital (TO) and anterior-temporal areas (AT) and the 'dorsolateral motor stream' the corresponding lateral primary motor ($M1_L$), premotor (PM_L), and prefrontal cortices (PF_L). Single-neuron properties, synaptic plasticity rule, and single-area model structure have been described in more details in previous publications (e.g., Garagnani & Pulvermuller, 2016; Garagnani *et al.*, 2017; Tomasello *et al.*, 2017).

The connectivity structure of the network reflects existing anatomical pathways revealed by neuroanatomical studies using diffusion-tensor, and diffusion-weighted imaging (DTI/DWI) (e.g., Rilling *et al.*, 2011; Thiebaut de Schotten *et al.*, 2012). These were modelled between adjacent cortical areas within each of the 4 'streams' (see black arrows in Fig. **1**.B) and between all pairs of multimodal areas (PB, PF_i, AT and PF_L) through the long distance cortico-cortical connections (purple arrows in Fig. 1.B). Additionally, non-adjacent 'jumping' links were implemented within the superior or inferior temporal and superior or inferior frontal cortices (blue arrows). Fig. **1**.C shows the micro-connectivity structure of one of the 7,500 single excitatory neural elements modelled (labelled '*e*'). Within-area excitatory links (in grey) to and from cell *e* are limited to a local (19x19) neighbourhood of neural elements (light-grey area). Lateral inhibition between *e* and neighbouring excitatory elements is realised as follows: the underlying cell *i* inhibits *e* in proportion to the total excitatory input it receives from the 5x5 neighbourhood (dark-purple shaded area); using analogous connections (not depicted), *e* inhibits all of its neighbours.

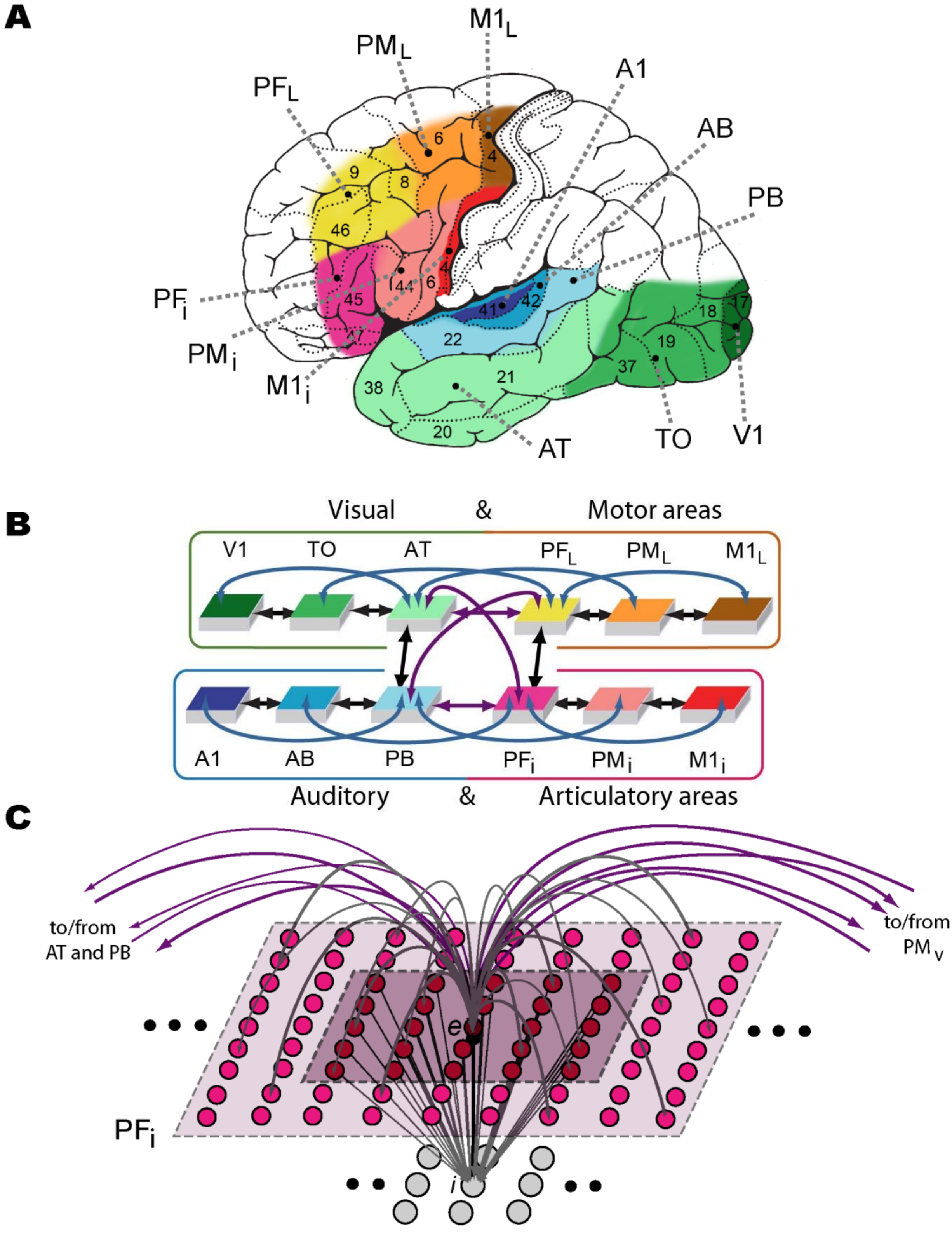

Figure 1

Results

As a result of training, cell-assembly circuits (CAs) emerged in the network. The graphs in Fig. 2.A-B below plot the number of CA cells per area that emerged, averaged across 13 different network instances. CA belonging to the two different semantic types exhibit similar distributions over the perisylvian cortex, with highest CA densities in the multimodal areas PF_I and PB. By contrast, extrasylvian motor and visual areas appear to exhibit a double dissociation: action-related word learning yields CAs including cells in lateral promotor and even primary motor cortex of the model, but weakly developed or virtually absent in visual areas TO and V1. Conversely, learning words with an object-related meaning seems to produce circuits biased towards the visual system. Finally, CA circuits for both action- and object-related words appear to include comparably large cell densities in multimodal extrasylvian areas AT and PF_L.

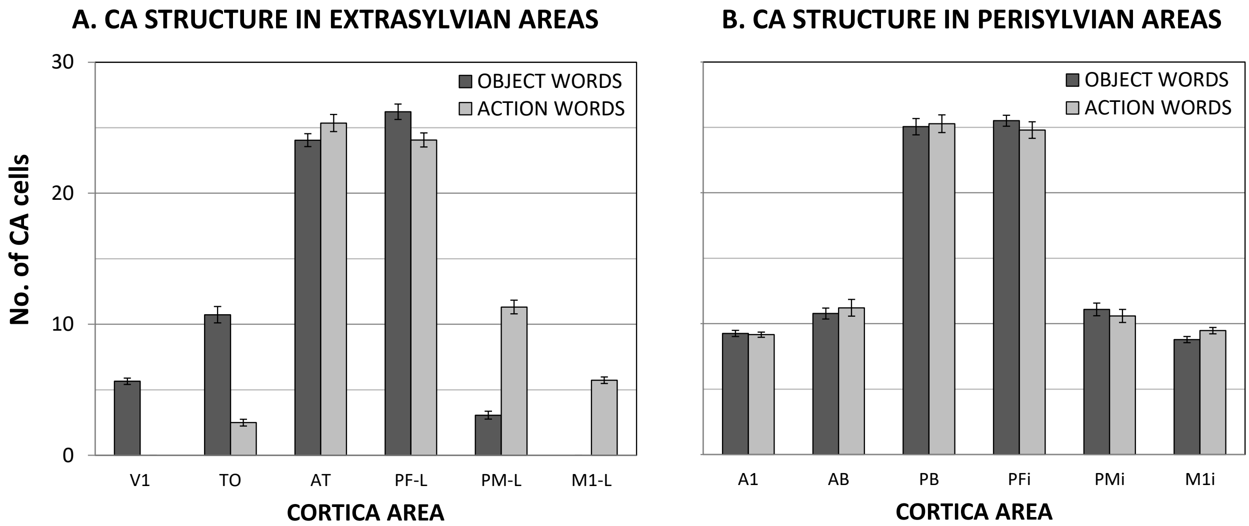

Figure 2

Conclusion

Linking cellular-level mechanisms with system-level behaviour, this work offers a novel neurobiological account of semantic grounding in the brain able to reconcile and explain existing data about different roles of distinct cortical areas during word comprehension processes, providing further computational evidence in support of an action-perception theory of semantic learning and processing.

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