Material constraints enabling human cognition

"Most of our current neural networks are still much too far away from the structures of brain-immanent networks."

Professor Thomas Wennekers, Plymouth University

Developing neural networks to unlock the secrets of human cognition.

Why can we develop vocabularies consisting of tens of hundreds of thousands of words, yet our closest evolutionary relatives typically manage fewer than 100? This is just one of the vital, long-standing questions in cognitive science, linguistics and philosophy that is set to tackle:

- How can humans build vocabularies of tens of hundreds of thousands of words, whereas our closest evolutionary relatives typically use fewer than 100?
- How is semantic meaning implemented for gestures and words, and, more specifically, for referential and categorical terms?
- How can grounding and interpretability of abstract symbols be anchored biologically?
- Which features of connectivity between nerve cells are crucial for the formation of discrete representations and categorical combination?
- Would modelling of cognitive functions using brain-constrained networks allow for better predictions on brain activity indexing the processing of signs and their meaning?

To find new answers to these questions, the MatCo project is utilising novel insights from human neurobiology and plans to translate these insights into mathematically exact computational models—neural network models.

The cognitive capacities of humans and higher mammals—their ability to learn, think, experience and sense—may depend on their brains’ specific structural and functional features. If so, these neurobiological features must play a decisive role in explaining cognitive capacities.

Despite substantial progress in unifying and brain function in general, explaining how structural and functional features of neural tissue bring about cognition, language and thought has remained a challenge.

Neural network models

Neural network models are potential tools for improving our understanding of complex brain functions.

A neural network is a network of interconnected neuron-like devices whose connections vary widely. Depending on the purpose of the simulation, they may be used to analyse a ‘data set’ using a process that imitates biological neurons signalling to each other, providing us with a simplified model of the human brain processing information.

To unlock the secrets of cognition, these models must be neurobiologically realistic. Despite neural networks advancing dramatically in recent years and even achieving human-like performance on complex perceptual and cognitive tasks, their similarity to aspects of brain anatomy and physiology is imperfect.

The MatCo team propose that neural networks for modelling cognition must incorporate a broad range of features that make them similar to real neurobiological networks at different levels: the microscopic level of nerve cell function, the mesoscopic level of interactions in local neuron clusters and the macroscopic level of interplay between these clusters and even larger brain parts and the whole brain.

Neural models of cognition explored

In their paper, ‘Biological constraints on neural network models of cognitive function’ (Pulvermüller et al., 2021), featured in Nature Reviews Neuroscience, MatCo explore the different types of neural models of cognition and provide insight into how the biological plausibility of those models can be improved, i.e. how they can more closely mimic the functions within the human brain. Alongside the models themselves, MatCo has also identified a number of constraints that need to be applied to the models, as well as exciting future clinical applications of brain-constrained modelling.

Brain constraints

While increasing the neurobiological realism of the neural models is an important first step, a second crucial process is applying neuroscience constraints at different levels—the micro, meso- and macroscopic levels of description.

The novel proposed approach of ‘brain-constrained’ neural modelling aims at making ‘neural’ networks more neurobiologically plausible. The following seven subsections each deal with one specific aspect under which artificial neural models need to become more similar to real brains.

Integration at different levels

Previous modelling has mostly aimed to approximate neuronal function at the level of either single neurons (Gerstner and Naud, 2009; Teeter et al., 2018), neuronal interaction in local cortical circuits (Schwalger, Deger and Gerstner, 2017; Malagarriga, Pons and Villa, 2019; Ijssel and Bij, 1995; Potjans and Diesmann, 2014) or global interplay between cortical areas. To simultaneously apply constraints at different brain structure and function levels, these different levels must be addressed and integrated into a single model.

Neuron models

The functional units of the cortex and brain are neurons. All neural networks are composed of artificial correlates of neurons, but the level of detail with which neuronal function is simulated varies considerably (Gerstner and Naud, 2009; Teeter et al., 2018; O’Reilly, Munakata and McClelland, 2000).
“Models that bridge the gap between the microscopic and macroscopic scales are a valuable resource in neuroscience.”

Professor Friedemann Pulvermüller, Freie Universität Berlin.

The most detailed neuron model is not always the best choice for a given research question. While relatively basic neuron models yield excellent descriptions of neural activity (Gerstner and Naud, 2009), the greatest computational resources required by sophisticated neuron models currently limit their applicability to large-scale simulations of within-area and across-area interactions relevant to cognition.

Synaptic plasticity and learning

The inclusion of learning mechanisms is a crucial ingredient of biologically plausible brain models. The implementation of both local and global learning mechanisms in brain models typically lack this feature. To model multiple learning systems in the brain, the implementation of both major forms of learning, supervised and unsupervised, is crucial.

Supervised learning presents a challenge because feedback that informs the individual or network whether the performance was appropriate, wrong or erroneous. The choice of algorithms used in supervised learning simulations has been guided not only by biological plausibility (O'Reilly, 1993; Mollick, 2020), but also by the computational efficacy of gradient descent learning (Ran国防部 for Neuron and Synapses, 2019). Below we will discuss the learning mechanisms at the local and global levels in terms of their biological plausibility.

Inhibition and regulation

Brain networks are regulated by cortical activity controlling emotions, thoughts, memories, language, and consciousness (Maas et al., 2020). The mechanisms by which control is exerted depend on the level of regulation. At a more local level, inhibition and regulation mechanisms are specific to a single cortical area. For instance, each area or nucleus can be realised as a separate ‘layer’ of model area, including a predefined number of artificial neurons. This level of regulation is only made possible when the brain models include details of cortical connectivity, including connections among different cortical areas. Biological realism include the range of brain parts and regions covered by the model, in the networks modelling language and conceptual processing, it is important to model a range of cortical areas known to be relevant for language and meaning.

Within-area local connectivity

Pyramidal cells are the most common excitatory neurons in the cortex. One of the primary functions of these cells is to control the connectivity between cortical regions. The pyramidal cells are regulated by inhibitory mechanisms. Inhibitory interneurons are located in subcortical structures. Each area or nucleus can be realised as a separate ‘layer’ or model area, including a predefined number of artificial neurons. In the networks modelling language and conceptual processing, it is important to model a range of cortical areas known to be relevant for language and meaning.

Between-area global connectivity

The connections between areas of the cortex follow some general rules. Most connections are reciprocal. Adjacent areas are almost always interlinked, and second-nearest neighbours are connected in many cases (Braitenberg and Schütz, 1998; Young, Scannell, and Burns, 1995). However, longer-distance links are sparser, and much effort has been spent mapping them precisely using invasive and non-invasive techniques (van Albada et al., 2020; Eichert et al., 2019; Rujova, 2016; Fernández-Miranda et al., 2015, Rilling 2014; Petrides et al., 2012; de Schotten et al., 2012; Ardesch et al., 2019; Barbeau, Descoteaux, and Petrides, 2020).

If two areas are interlinked, their connections are in most cases, reciprocal and show topographic projections and local connections that are highly preserved. Between-area connections are carried by long axon branches of Cortical pyramidal cells. These axon branches pass through the white matter and can reach neurons in distant areas, where they branch and make contact with a local neighbourhood of neurons.

Essential brain constraints on artificial neural networks come from the connectivity structure of brain areas. Many networks that include autoassociative layers or areas (Willshaw, Buneman and Longuet-Higgins, 1969; Palm, 1982; Hinton and Shallice, 1991; Hopfield and Tank, 1985) include full connectivity between different areas. Within these areas, which is not in line with the sparseness of intrinsic local cortical connections identified in the neuroanatomical studies. Hetero-associative networks lack the within-layer connections identified and, therefore do not seem biologically realistic either.

The brain constraint of sparse, local and partly random connections with a neighbourhood bias has been realised in some neural networks. Nonetheless, for most neural networks available today, the implementation of connectivity constraints still leads to an increase in biological realism (van Albada et al., 2020).

Conclusion

The work of the MatCo project offers very practical applications for neuroscience. One such application addresses the brain’s ability to learn and use new connections for function and meaning. The MatCo project will develop models replicating structural differences between human and non-human primate brains. The results will shed light on the biologically constrained networks.

FUNDING

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 883115.
Material constraints enabling human cognition


