Using the NEF-SPA Approach to Build a Neurobiologically Plausible Large-Scale Brain Model for Speech Production and Perception

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Introduction

- Goal: A **computer-implemented neural speech processing model** for simulating natural speech behavior (word and sentence production/perception)
- A **spiking neuron network model** has been implemented using the **NEF-SPA approach**: Eliasmith 2013, Stewart & Eliasmith 2014) here for speech processing (Kröger 2023, Kröger & Bekolay 2025)
- This approach allows to instantiate a **quantitative biologically plausible model architecture** (cf. CMC model, Sibert et al. 2021, Laird et al. 2025)

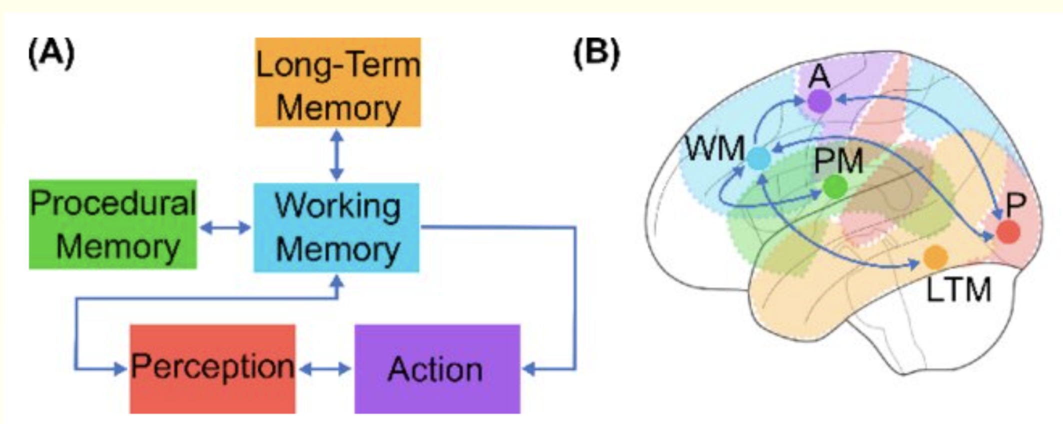


Fig. 1. (A) The Common Model of Cognition (CMC); (B) Proposed associations between components and anatomical brain regions (adapted from Sibert et al. 2021)

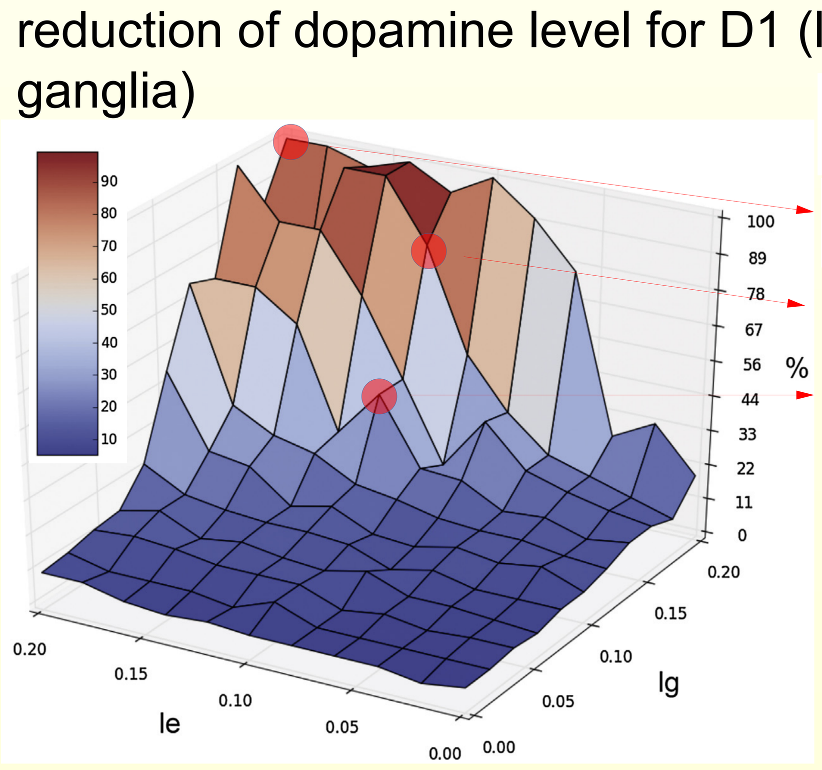
LTM / DM: long-term or declarative memory: temporal lobe, hippocampus
PM: procedural memory: basal ganglia (plus: cortico-cortical control loop)
WM: working memory: frontoparietal regions
P: perception: sensory cortices (plus subcortical regions)
A: action: motor cortex (plus subcortical regions incl. cerebellum)

Method: Modeling Framework & Canonical Elements

- Neural Engineering framework **NEF** (Eliasmith 2013): *representation of "sensory and motor signals"* (ensembles), *transformation* (forwarding, synaptic coupling), *dynamics* (recurrent buffers: short-term storage, oscillators)
- Semantic Pointer Architecture **SPA** for representing cognitive items (words)
  - buffers: representation of higher-level items (distributed neural activity)
  - associative memories: transformation of items from "vocab" to "vocab"
  - action control module: action selection, decision making, ...
  - semantic pointer networks: distance/similarity measure for items
- A **trial-and-error procedure** is used for building a model architecture from **canonical elements** (comparable to evolutionary processes?)

Results: Architecture and Simulations

Simulation study 1: Syllable repetition task in case of Parkinson's disease (Senft et al. 2016): Non-fluent speech (syllable sequencing deficits) results from reduction of dopamine level for D1 (lg) and D2 (le) receptors in striatum (basal ganglia)



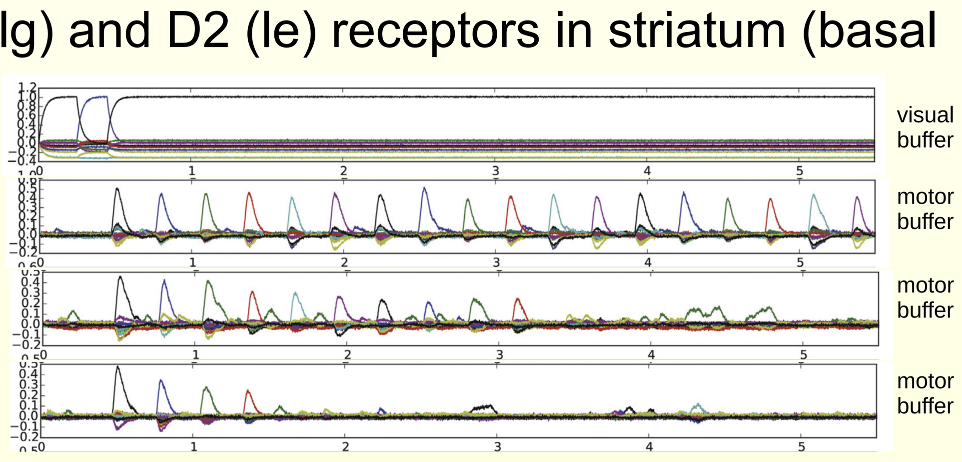


Fig. 2. Neural activation patterns of visual buffer (neutral and syllable /ba/) and motor execution buffer at different levels of le and lg (syllable sequence is /ba, da, ga, pa, ta, ka/). *D1/D2 receptors act on different functional elements and pathways in the basal ganglia.*

Simulation study 2: Picture naming, word repetition, word comprehension task in case of Broca's Aphasia (Kröger et al. 2020)

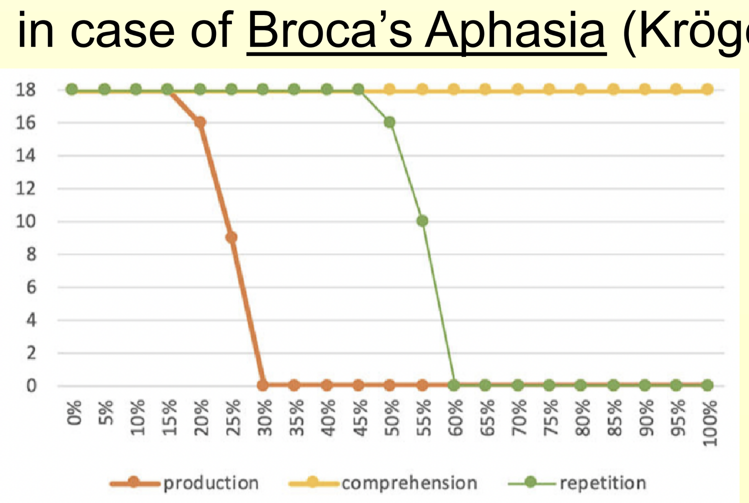


Fig. 3. Task execution deficits increase with percentage of neural ablation (= percentage of "dead" neurons within specific buffers). Here: ablation in phonological form buffer (Note: less stability in degree of ablation in case of ablating concept and lemma level buffers like in transcortical motor aphasia)

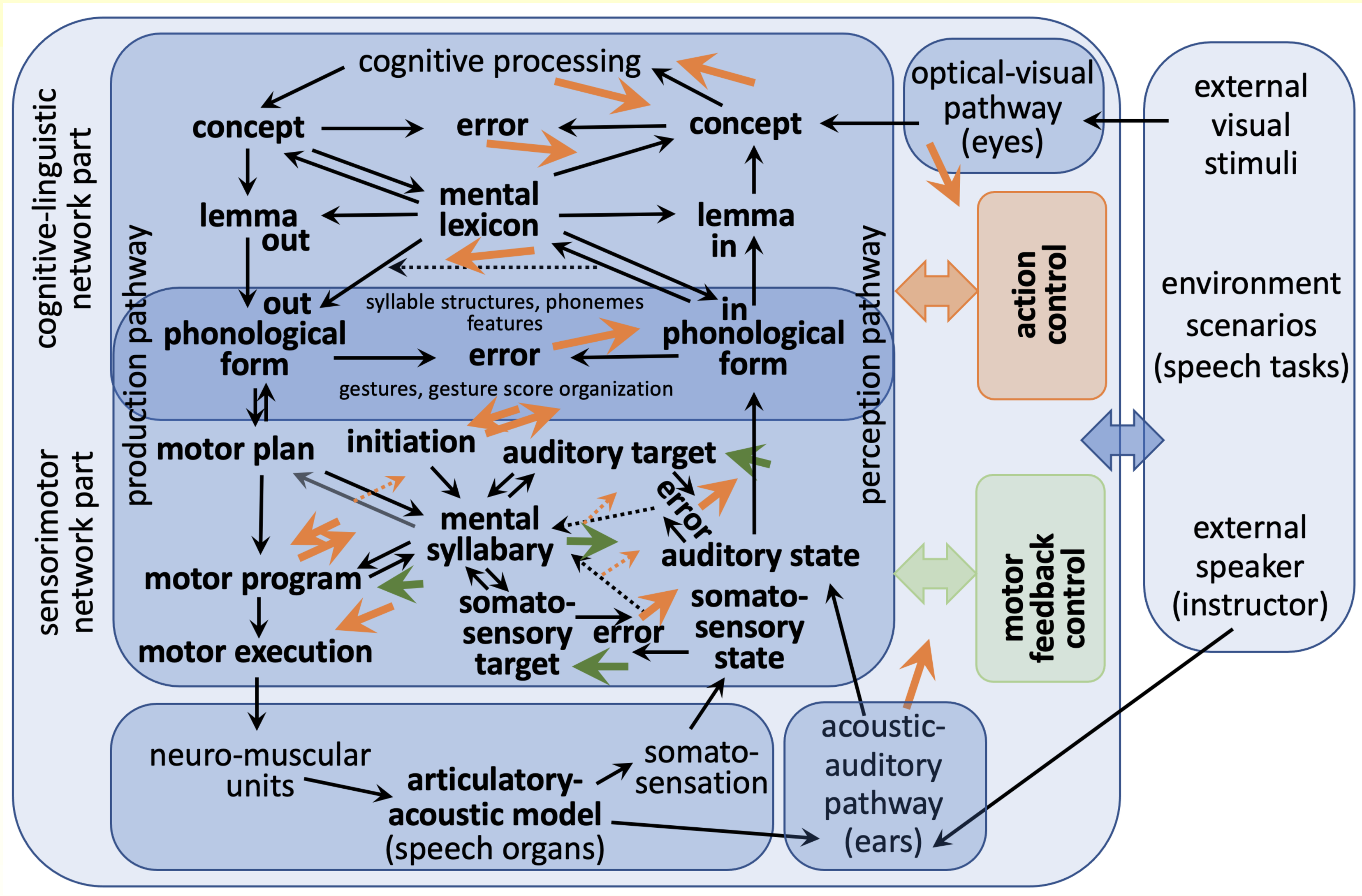


Fig. 4. Model architecture (case: word processing): **perception and production pathway** (WM (plus circuits) short-term buffers and associative memories) interacting with **mental lexicon** and **mental syllabary** (LTM: buffers for SPA vocabularies). PM (plus circuits) = action control (plus cortico-cortical loop: orange arrows), P = auditory, somatosensory & visual state buffers (plus processing), A = motor plan, motor program & motor execution buffers (plus processing incl. motor feedback control loop)

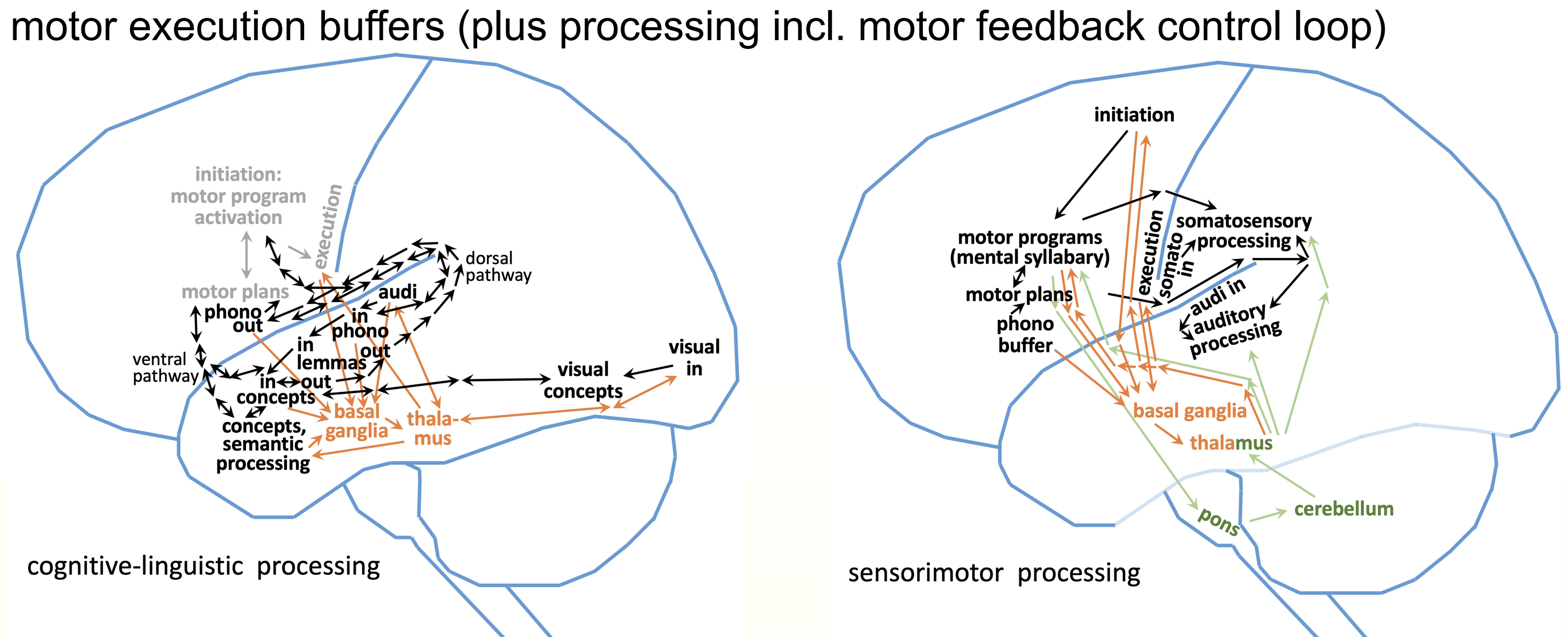


Fig. 5. Brain regions associated with components or elements of the model

Discussion and Conclusions

- Generation of **avatars**: cognitive, sensory and motor components exist; Ability to simulate **behavior** (beside providing data of neural activity)
- In accordance with **CMC** (DM, WM, PM, P, A modules)
- Insertion of **neurofunctional deficits** (dopamine level reduction, ablation of neuron populations in specific buffers, ...) for generation of (behavioral) **symptoms of speech disorders** (aphasia, dysarthria, apraxia, stuttering, …)
- Simulation of **learning** as for modeling *speech acquisition* (growth of model), and for *speech rehab* (restructuring of model) is difficult
- Current **AI models**: profit from less predefined structure and infinitely long developmental time window (high "plasticity" for learning). But: **ontogenetically**: "animals" have to function directly after birth; thus: "animals" need **phylogenetically** *predefined structure* (given by *evolution*)

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