USING NENGO.AI FOR DEVELOPING MODELS OF SPEECH PRODUCTION AND SPEECH PERCEPTION

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www.speechtrainer.eu

Introduction

- Motivation: Why neural models?
- The NENGO.ai framework
- Our speech processing model (production and perception)
  - architecture of the modeled brain (modeling patients)
  - Scenarios: simulated tasks -> simulated behavior (modeling screenings)
  - speech movement generation
- Concluding remarks

Motivation: Why neural models?

Neural models

- can simulate macroscopic behavior if they are large-scale models
  - whole brain plus motor out and sensory in components:
  - CNS (whole brain) plus PNS towards vocal tract and ears
- can give clear definitions of neural dysfunctions
  - we can “destroy” neurons in specific parts of model
  - we study the resulting behavior of model: -> symptoms of speech disorders

Motivation: Why neural models?

Models are simplifications of reality and thus help to understand

- basic functional principles of neural processes, (here: for speech production and perception)
- relationship between neural processes and behavior and thus: e.g., how a neural dysfunction may change behavior (-> how a … leads to specific symptoms)?

The NENGO.ai framework

- "Neural ENGineering Objects" framework:
- www.nengo.ai
- Nengo is open source
- Python based: -> runs on: Windows, Mac OS X and Linux
- Profound scientific background:
  - Eliasmith, C. (2013). How to build a brain: A neural architecture for biological cognition. *Oxford University Press*.

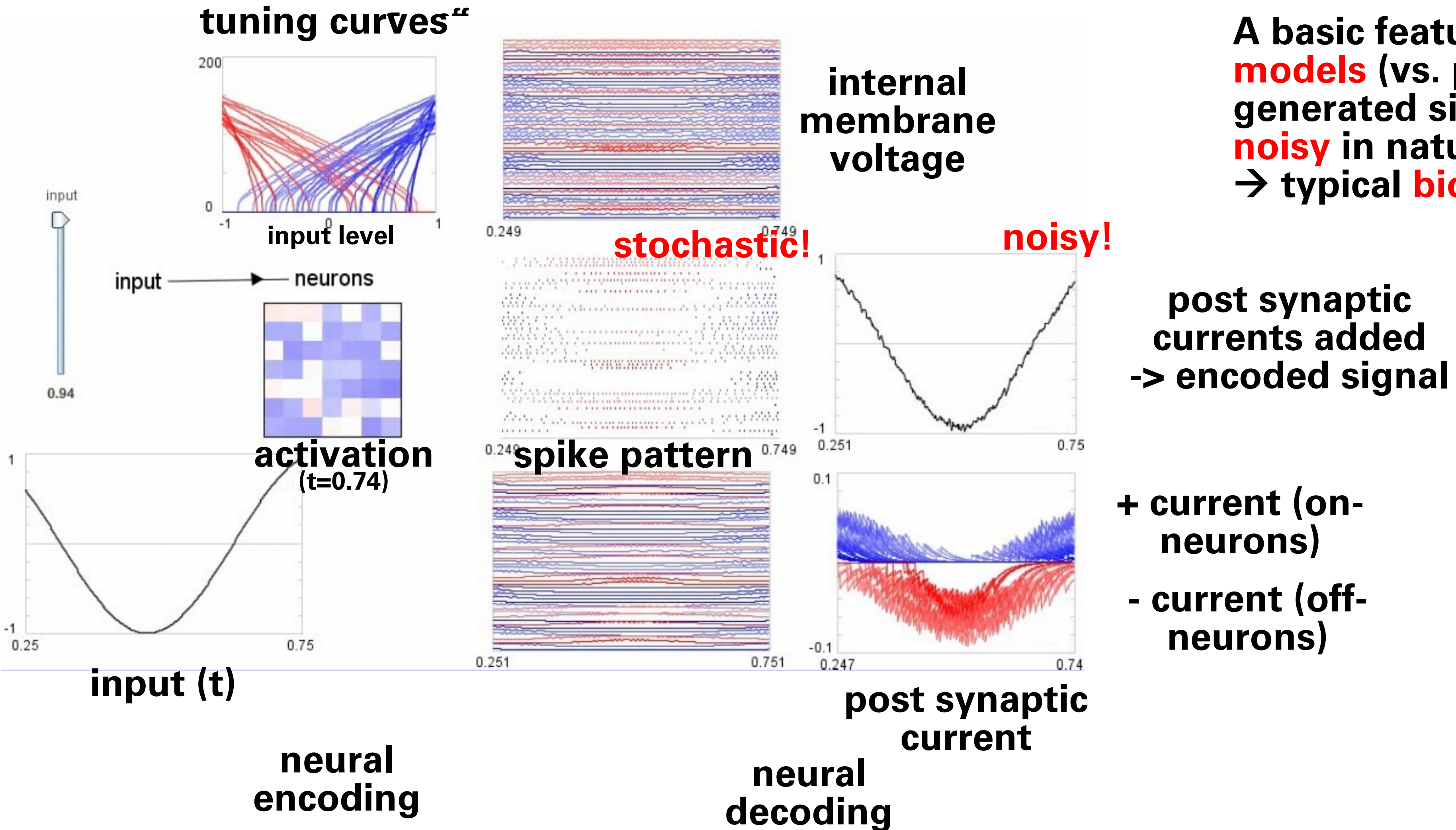
NENGO comprises

- basic neuron models (e.g., LIF-model) -> generation of spikes
- concepts or strategies for connecting neurons:
  - neuron ensembles, neuron buffers, short-term memories, associative memories, binding buffers, …
- strategies for coding functional **items** which need to be processed by the model (concepts, phonol. forms, motor plans)
- fully developed model for for neural process control over time (BG-Thalamus-complex: cortico-cortical control loop)
- strategy for connecting the periphery: -> large-scale model
  - sensory input: eyes and/or ears
  - motor output: arms and/or the speech articulators

Basis of our model: LIF neurons

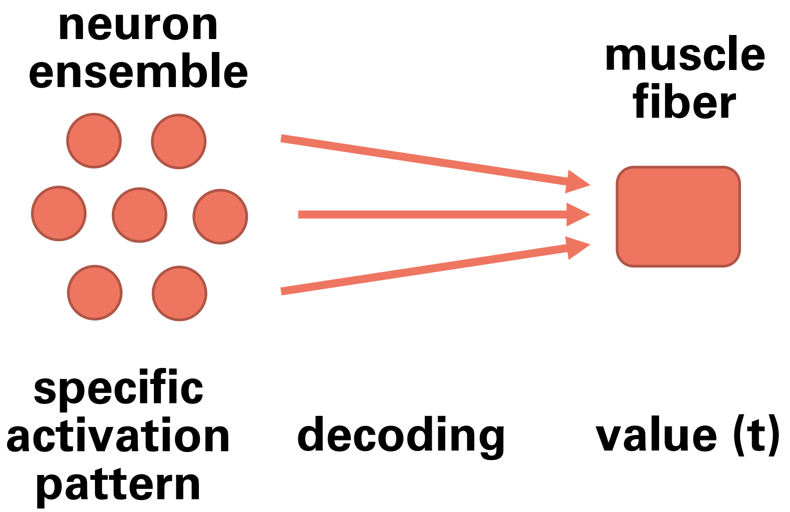
- 50 neurons -> lead to a sufficient coding of input values

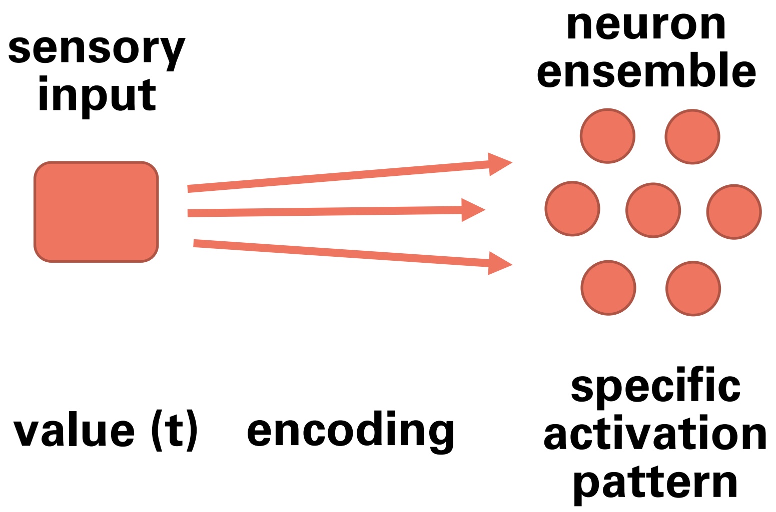
A basic feature of spiking neuron models (vs. parametric models): generated signals are stochastic and noisy in nature
→ typical biological signals



50-100 neurons -> neuron ensemble

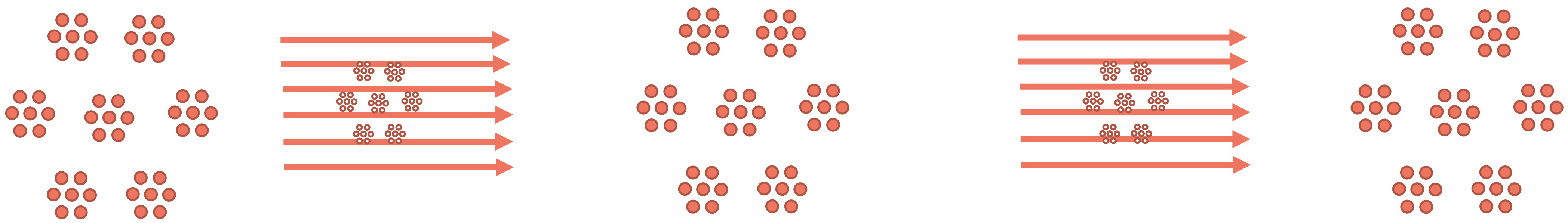
- represent **values**
  - e.g., muscular activation strength
  - or: sensory input value





50-100 ensembles -> neuron buffer

- Represent **<u>items</u>**:
  - motor plan of a syllable (complex!)
  - phonetic or phonological forms (sounds, syllables words)
  - lexemes (language-specific)
  - concepts (meanings) ((-> "thoughts"))



<u>neuron buffer</u> =
number of ensembles

neural connection =
<u>associative memory</u>

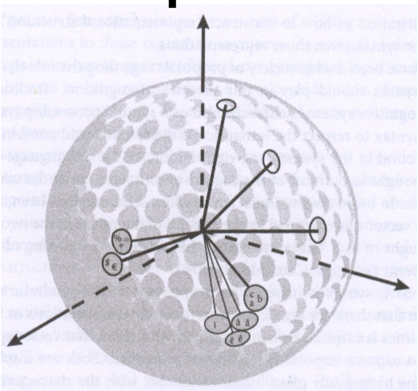
Semantic Pointer Architecture

- buffer represents complex information (**<u>items</u>** to process)
- mathematically: items are represented by vectors (called: S-pointers)
- SPA (Semantic Pointer Architecture is an important conceptual part of NENGO)

NENGO: S-pointer-networks

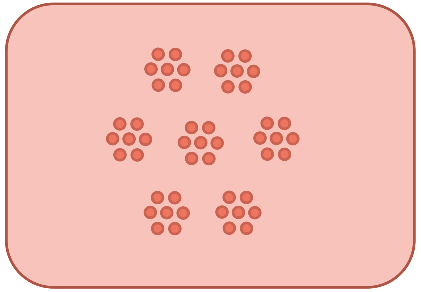
- … define an ordering of items:
- define the degree of similarity of items: e.g.,:
  - at concept level: <dog> - <cat> -> animals; <chair> - <table> -> furniture
  - at phonological level: /car/ - /cat/ -> begin with /k/; /far/ - /fat/ -> with /f/
- (mathematically: similar S-pointers point in a similar direction)

D-dimensional space



vector ordering in D-space

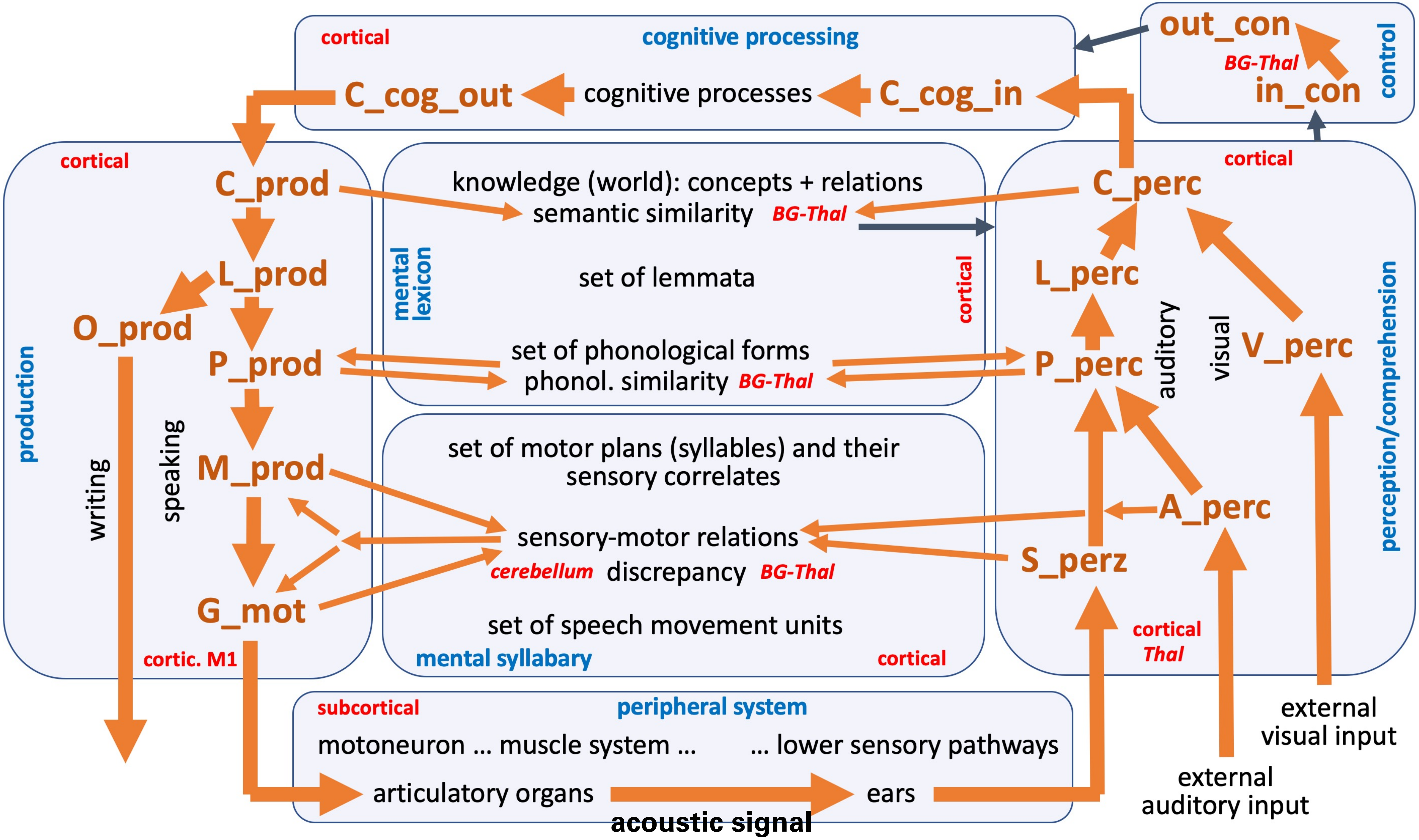
dog
cat
…
man
woman
…
table
chair



buffer A

Speech processing model: Architecture

- … is a large-scale neural model
- Perception / production pathways: a chain of buffers, connected by associative memories (arrows)
- Knowledge and skill repositories: mental lexicon, mental syllabary implemented as S-pointer networks (concepts, phonological forms, motor plans)



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knowledge (world): concepts + relations
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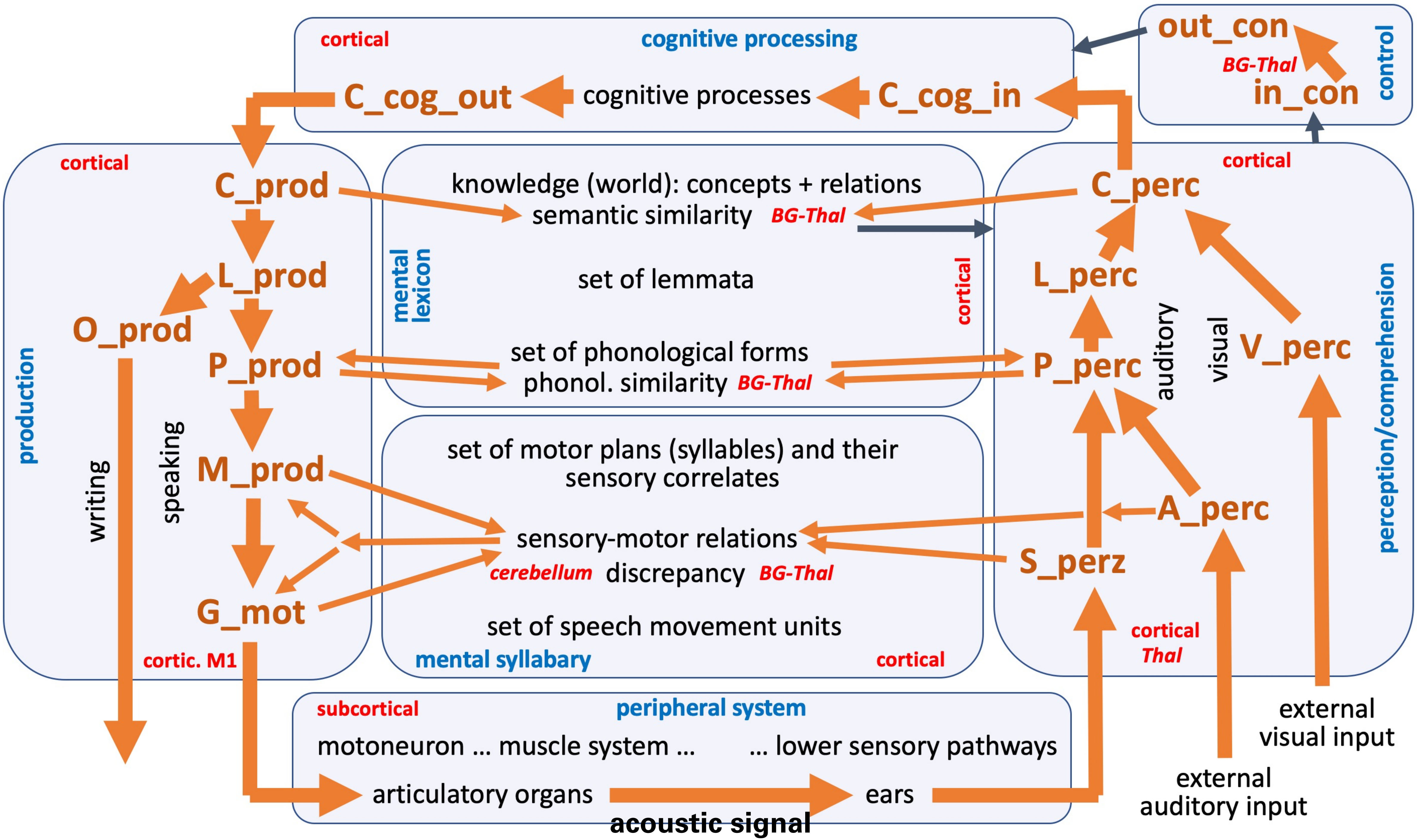
S_perz
perception/comprehension
cortical
Thal
subcortical
peripheral system
motoneuron ... muscle system ...
... lower sensory pathways
articulatory organs
ears
acoustic signal
external visual input
external auditory input

Speech processing model: Architecture

- in addition:
- action control by BG and Thalamus model
- internal feedback loops: semantic level, phonological level, sensorimotor level
- external feedback loop: motor-articulatory-acoustic-auditory



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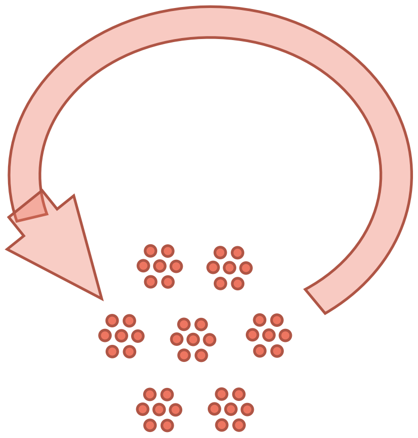
The cognitive processing level

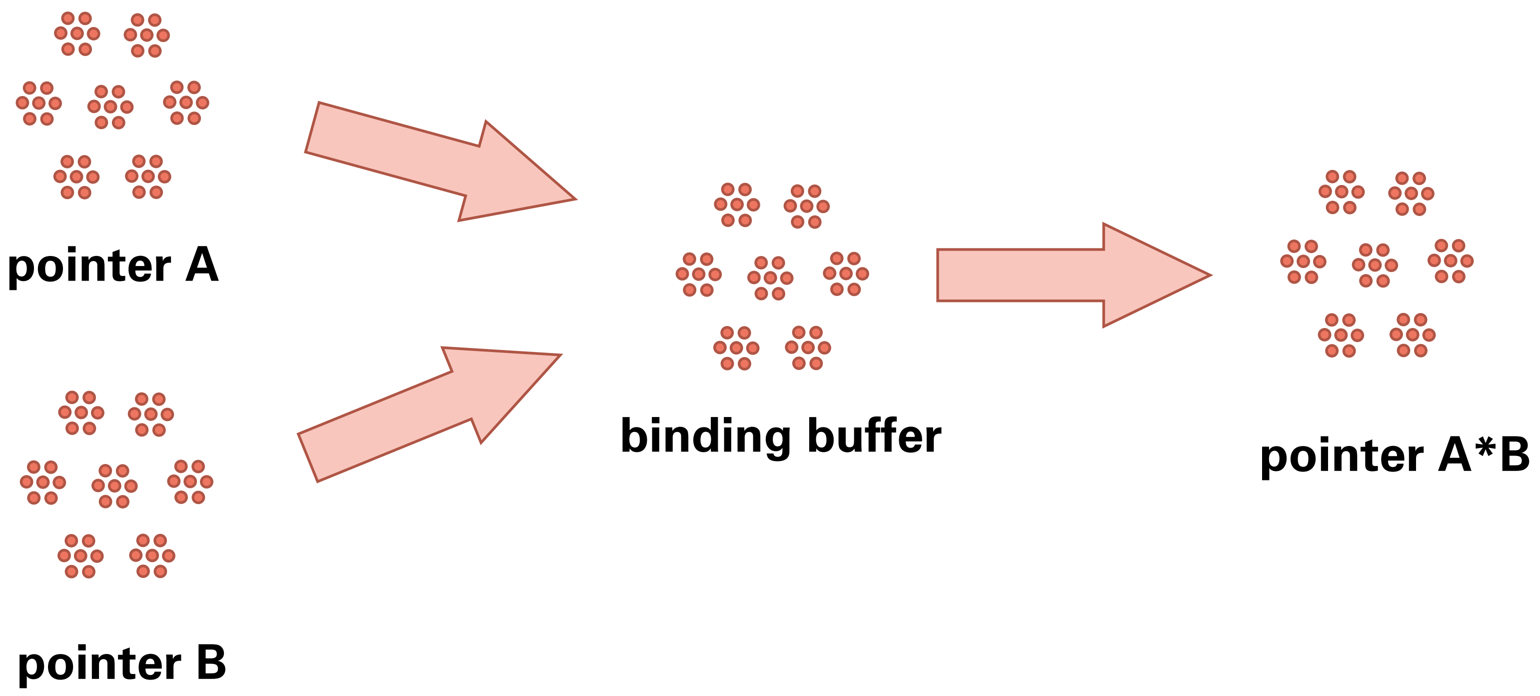
- Short-term memories, e.g., for memorizing word lists (-> serial recall task, perception + production tasks)
- realized as recursive buffers (neural within-associations)



recursive buffer

The cognitive processing level

- Binding / unbinding is realized by specific neural structures -> binding buffers vs. normal S-pointer buffers
  - at concept level: <dog> - <cat> -> animals; <chair> - <table> -> furniture
  - <dog>*<is_a> -> <animal>

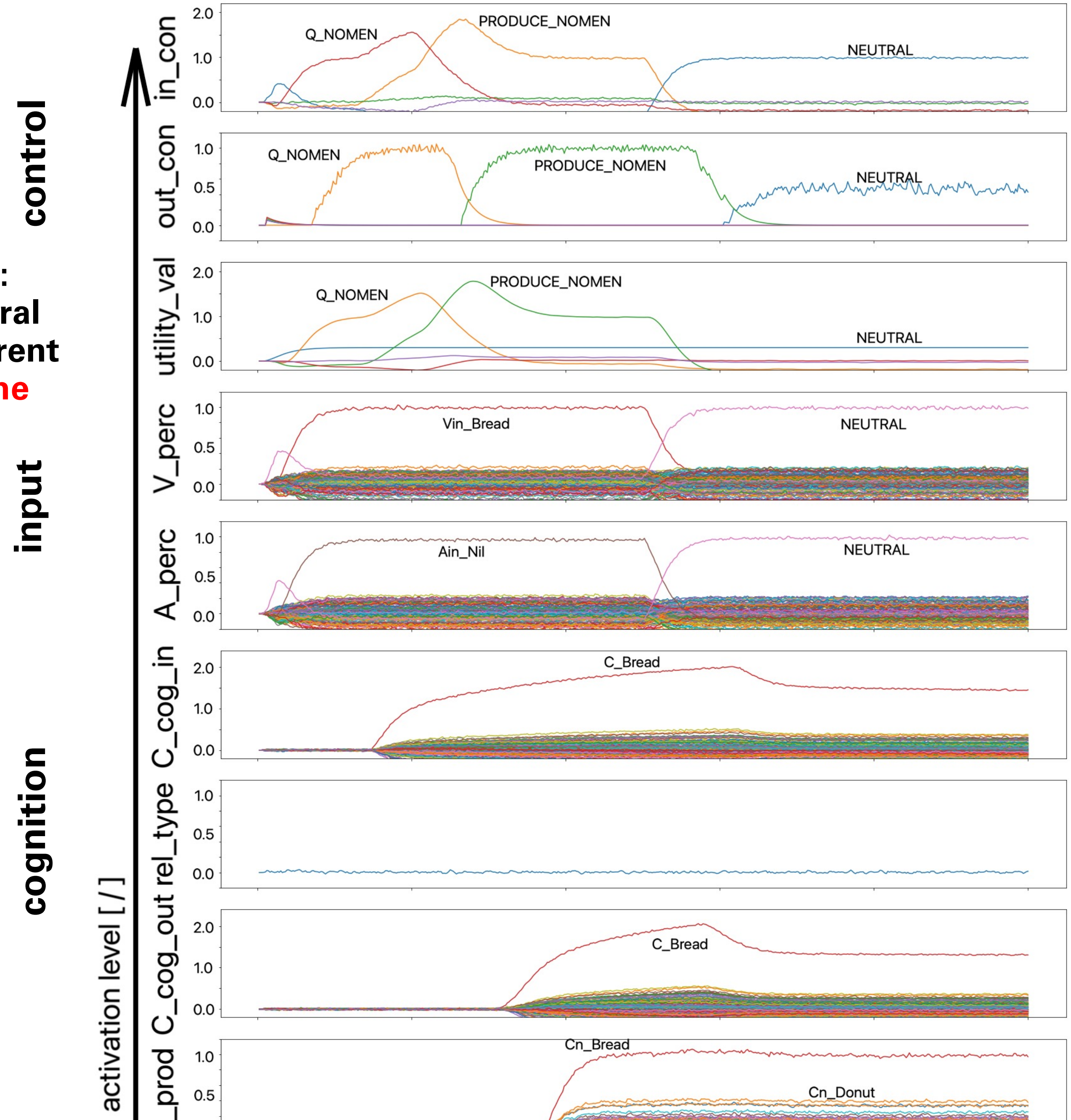


The definition of scenarios

- So far: the neural architecture of the model:
- In addition: we need to define the task which needs to be executed
- -> definition of scenarios
- Scenarios: speech tasks: (medical screenings)
  - Picture naming (visual input -> production)
  - word comprehension (auditory input -> naming of superordinate term)
  - word (logatome / syllable) repetition

Similarity plots: display the neural activity of different buffers **over time**

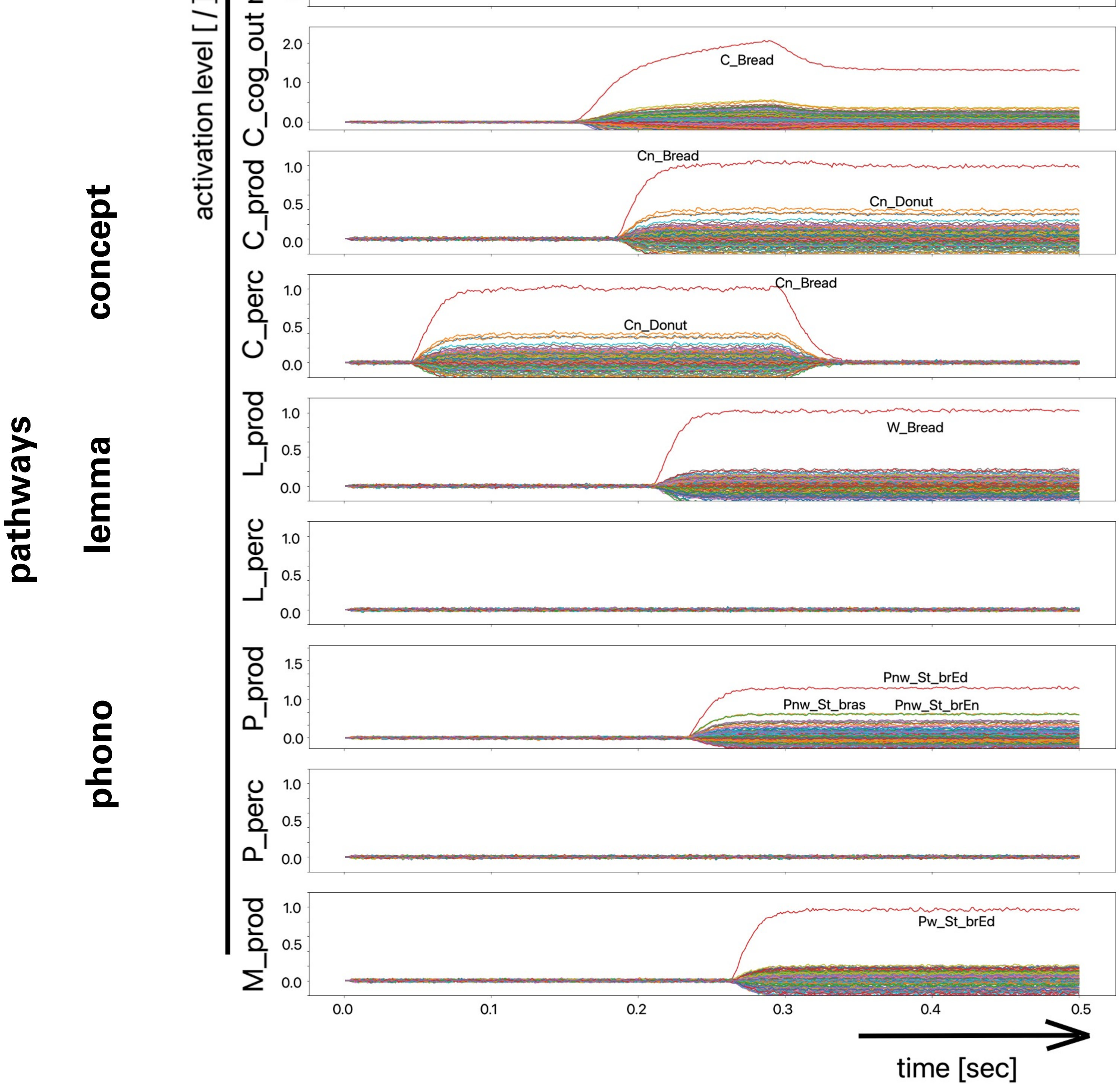
gives information about the function-ning of the model: we can see what is going on in each part of the model at each point in time



← priming: 100 msec: "look@pic and activate noun" +150 msec : "utter noun" c

Picture naming

Kröger et al. (2020)



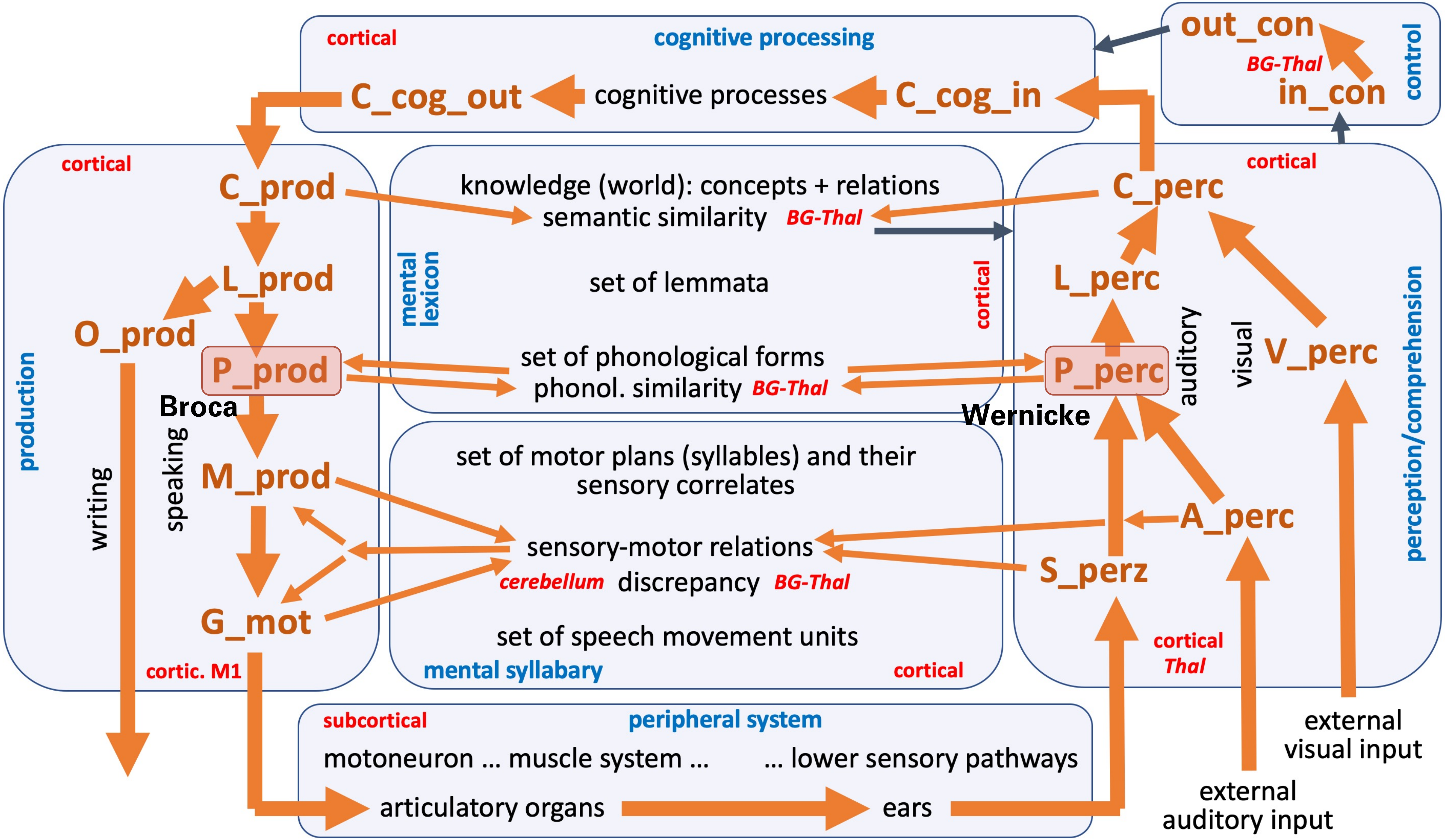
Kröger et al. (2020)

Example:
Simulation of disordered speech

- Goal -> modelling of different types of aphasia
- Want to see typical symptoms:
- Simulation of three tasks:
  - picture naming
  - word comprehension
  - logatome repetition
- So: we need neural damage at different parts of the model

Implementation of neural dysfunctions

- Lesions at different levels of the model:
  - Phonological state buffer -> Broca / Wernicke aphasia
  - Associative memories between phono-lemma buffer -> transcortical motor / sensory aphasia
  - Associative memories between lemma-concept buffers -> mixed aphasia
  - Neural association between phono-phono buffers -> conduction aphasia



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Broca
writing
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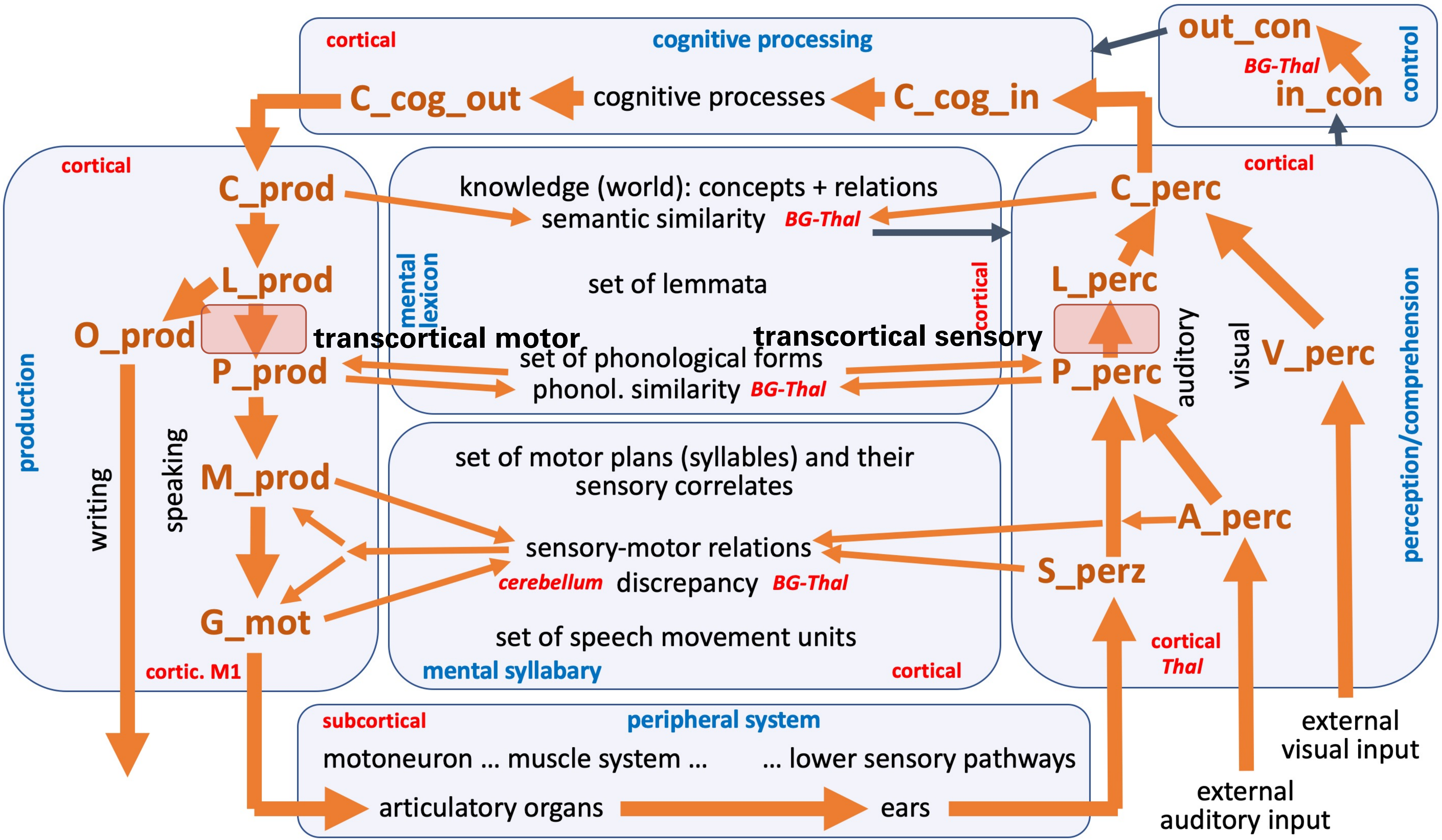

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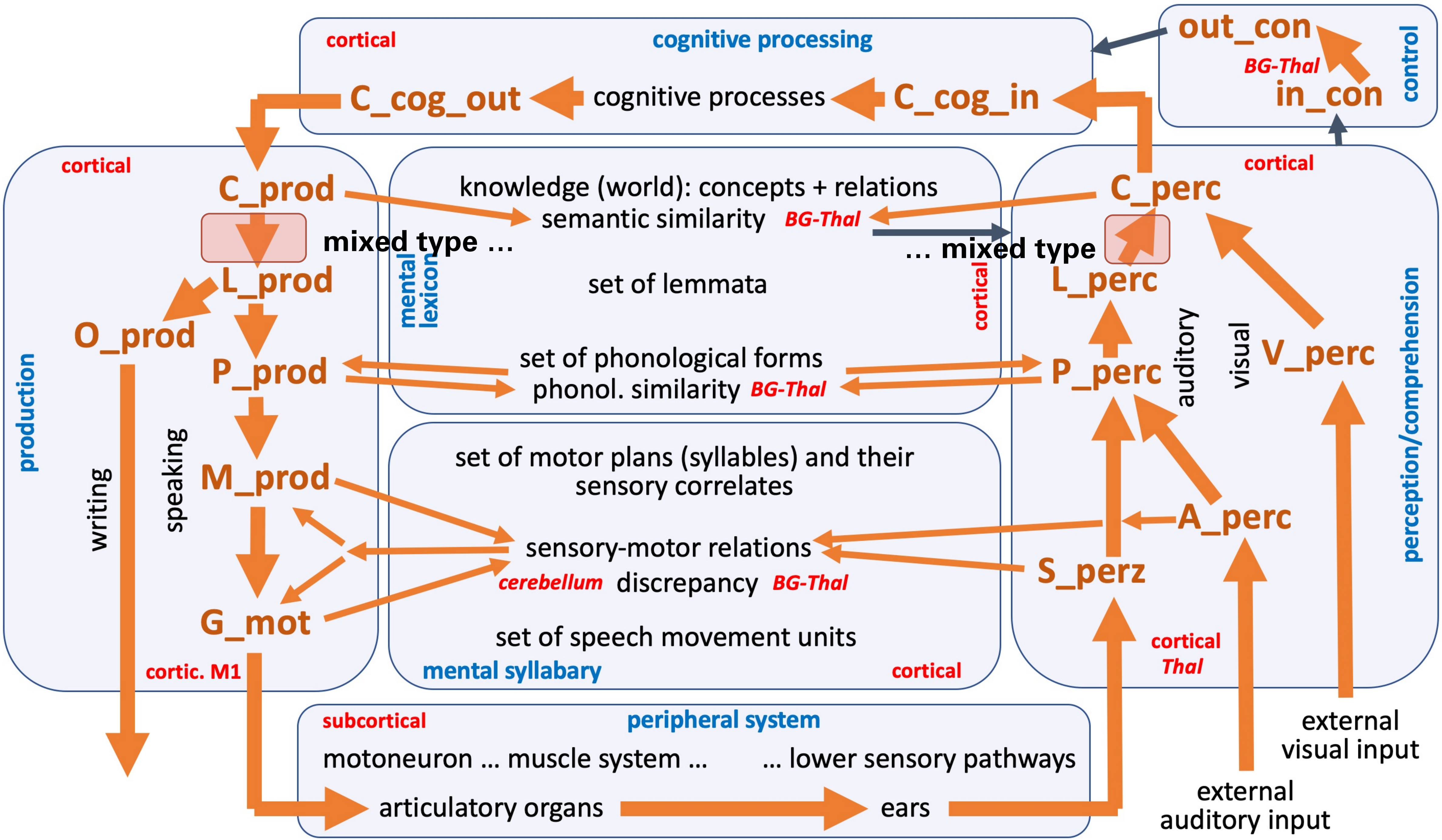

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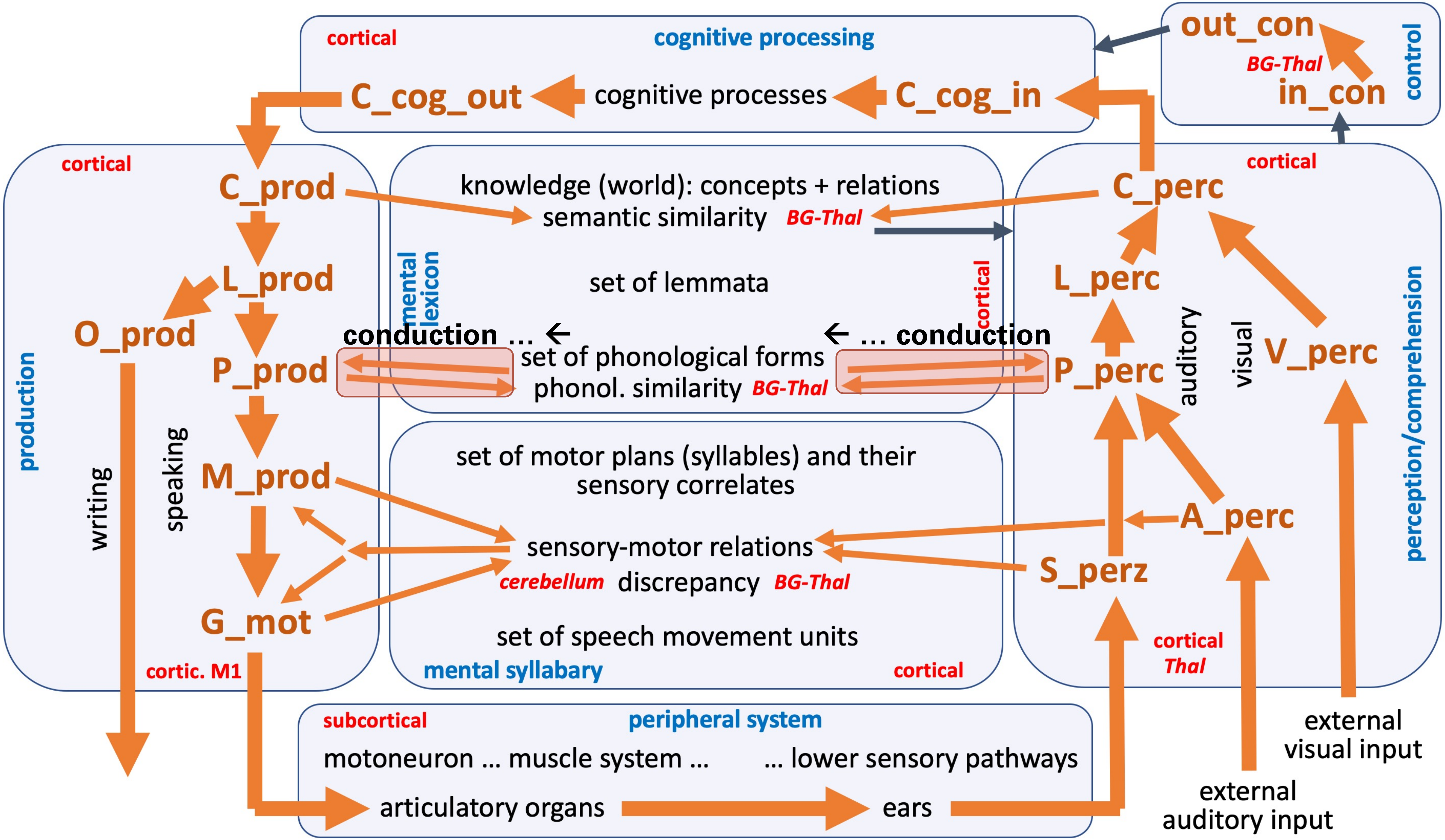

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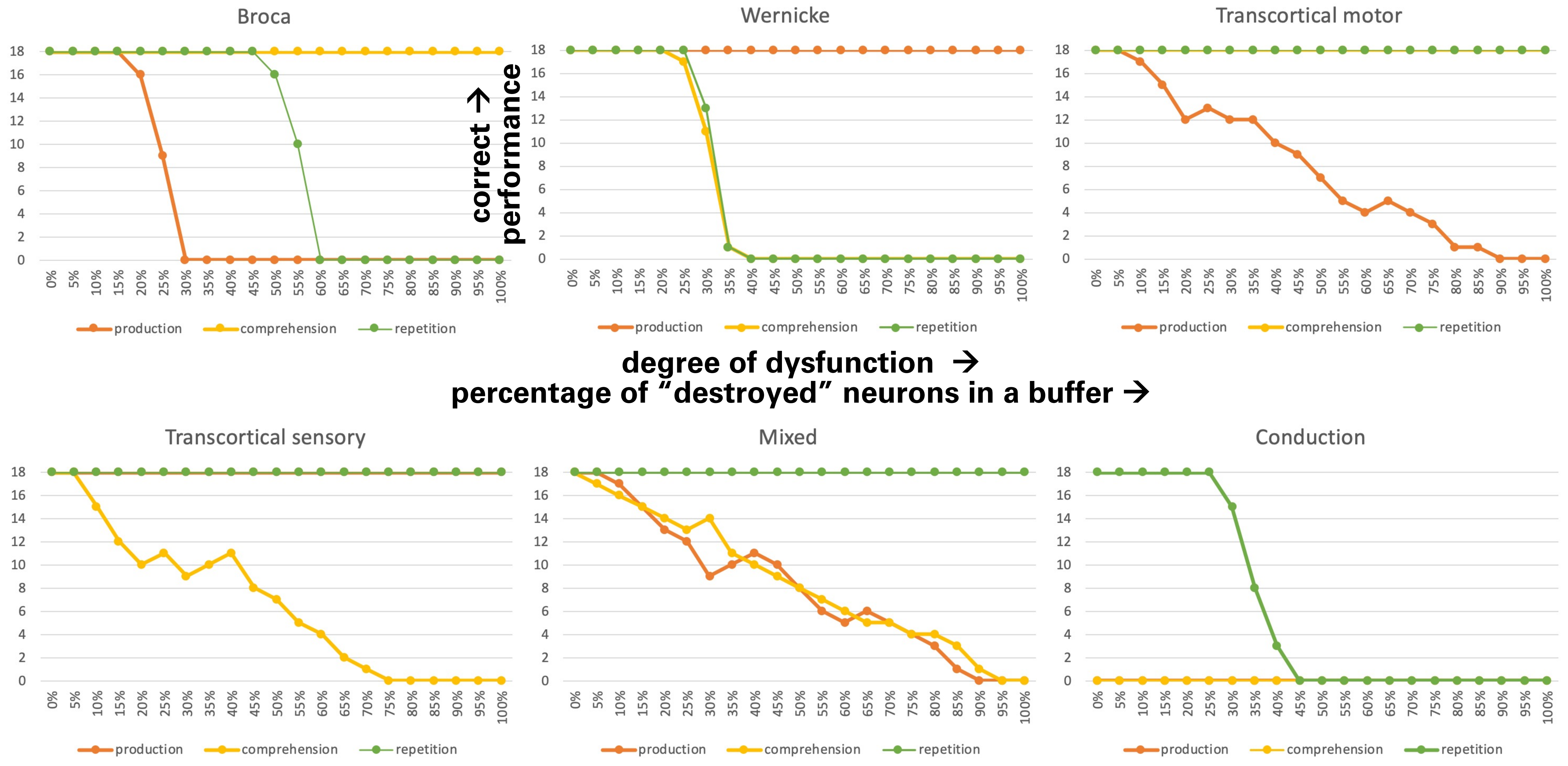
Neural dysfunctions

- Lesions are realized by ablation (“die off” / “die back” process) for a percentage of neurons of a buffer
- -> a percentage of neurons is “destroyed” / “switched off”
- -> decrease in task performance



Kröger et al. (2020)

The definition of scenarios

- So far: simple tasks and implementation of neural dysfunctions
- we want to demonstrate the power of the neural model:
- We tried to simulate more complex tasks:
  - to simulate overburdening -> may lead to speech errors
- Further speech screenings:

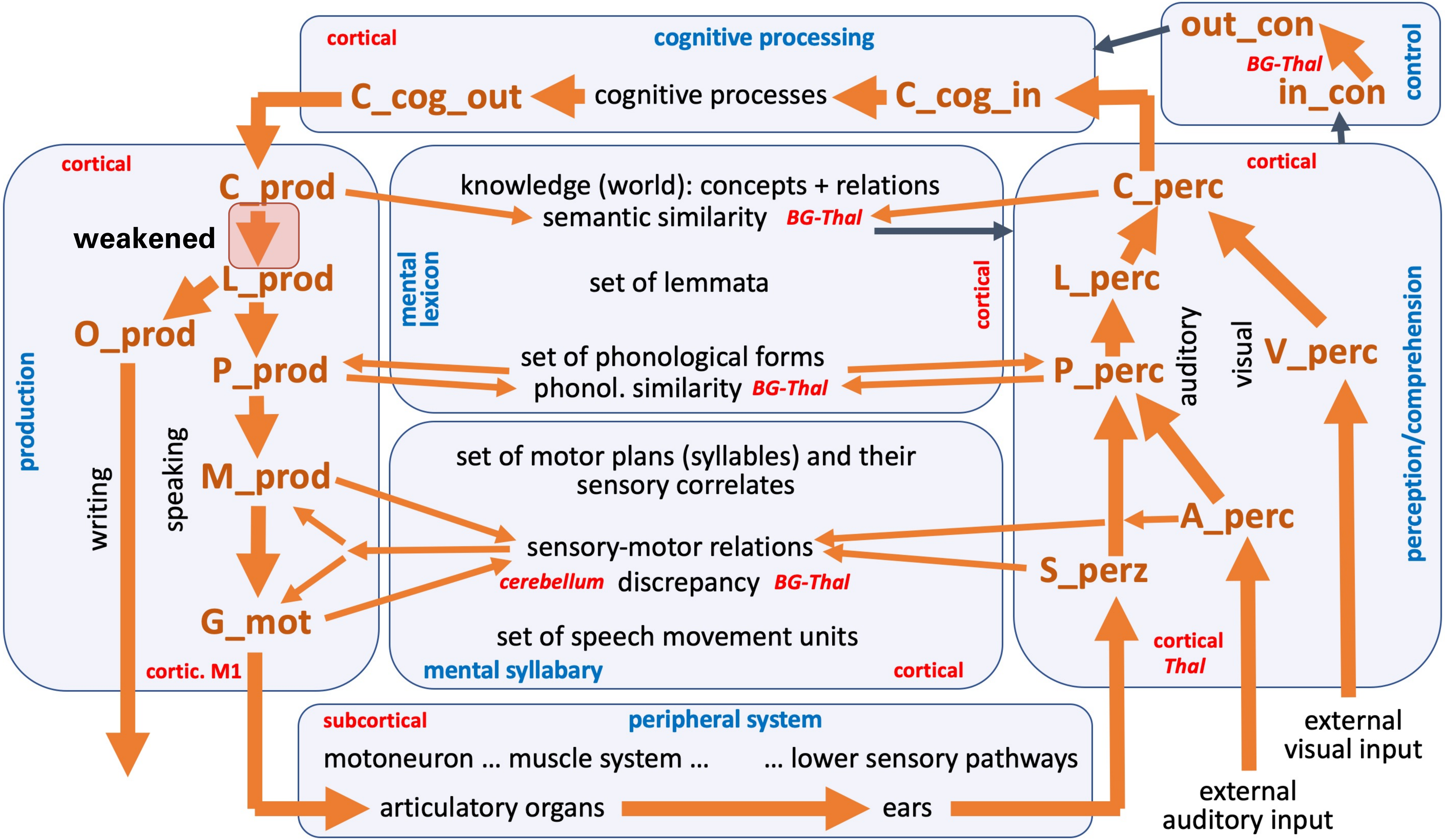
Result:

- Typical symptoms occurring in different subtypes of aphasia can be modelled correctly
- E.g.;
  - decrease performance of speech production -> Broca
  - ... perception -> Wernicke
  - ...

Further goal: demonstrate the power of our model

- Can we model more complex tasks?
- Can we model overburdening situations?
- Further speech screenings: (-> demonstrating realism of model)
  - E.g.: Picture naming in case of lexical access problems ("tip of the tongue" case):
    - Problem to find a correct lexeme (in case of full concept activation!)
    - facilitation (help) by introducing phonological and semantic cues -> increase in performance

Kroeger BJ, Stille C, Blouw P, Bekolay T, Stewart TC (2020) Frontiers in Computational Neuroscience, 14:99. www.speechtrainer.eu **-> publications**



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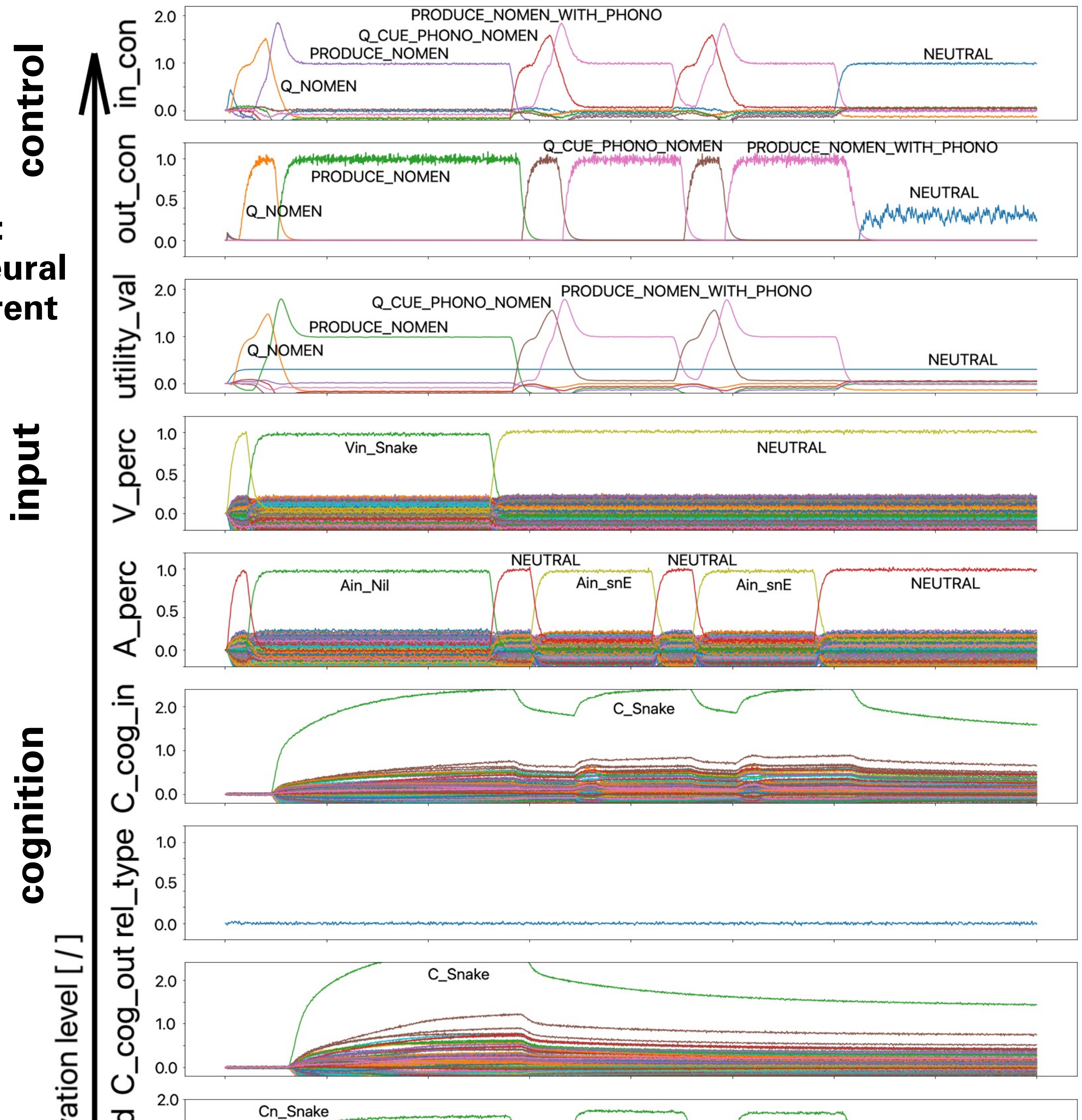
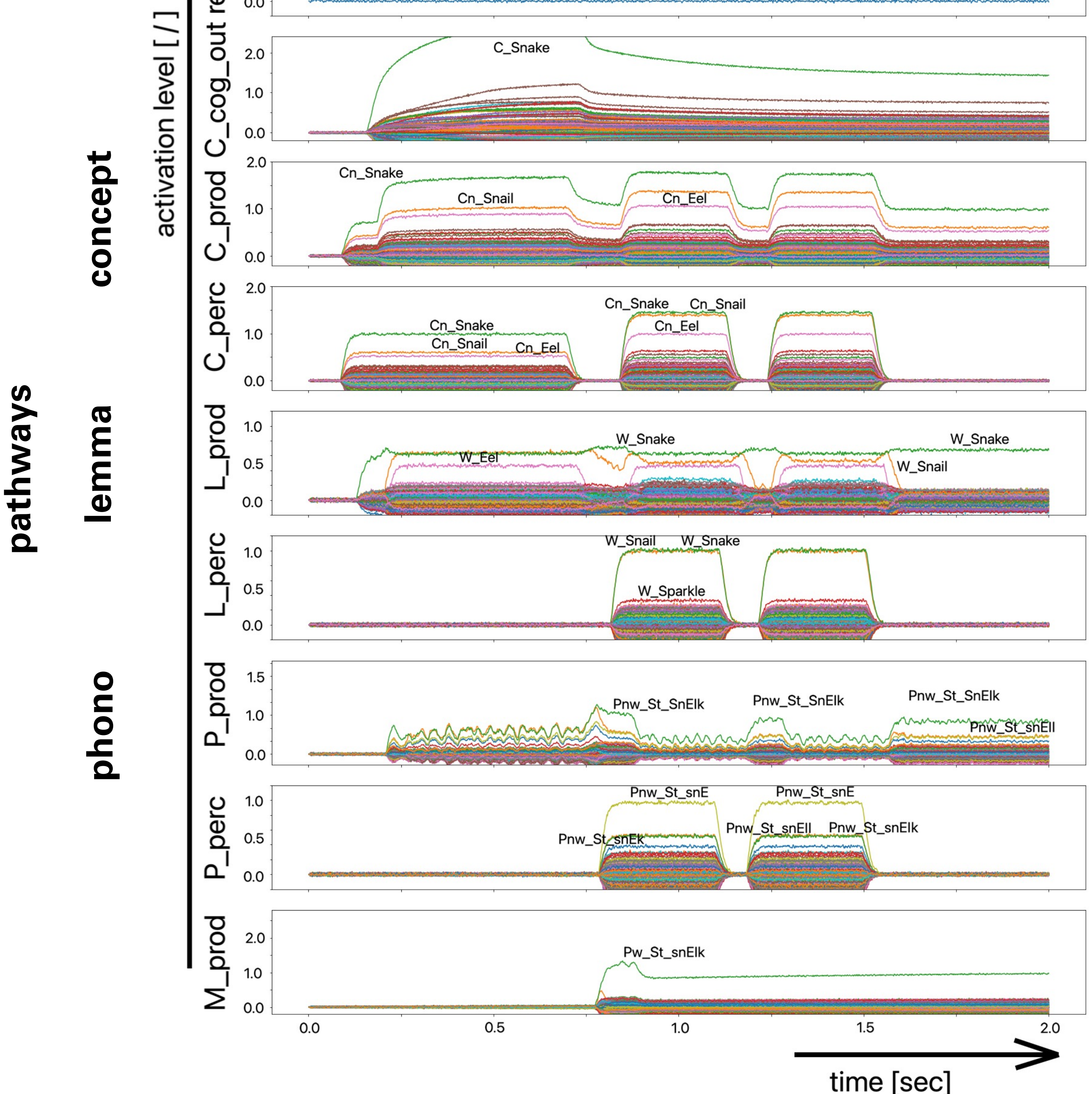
Similarity plots: representing neural activity of different buffers



← priming: 100 msec: "look and think" + 600 msec : "utter noun"
+ later: "listen to cues" + "utter noun"

Picture naming plus phonological cue

Kröger et al. (2020)



phonological cue in!

Kröger et al. (2020)

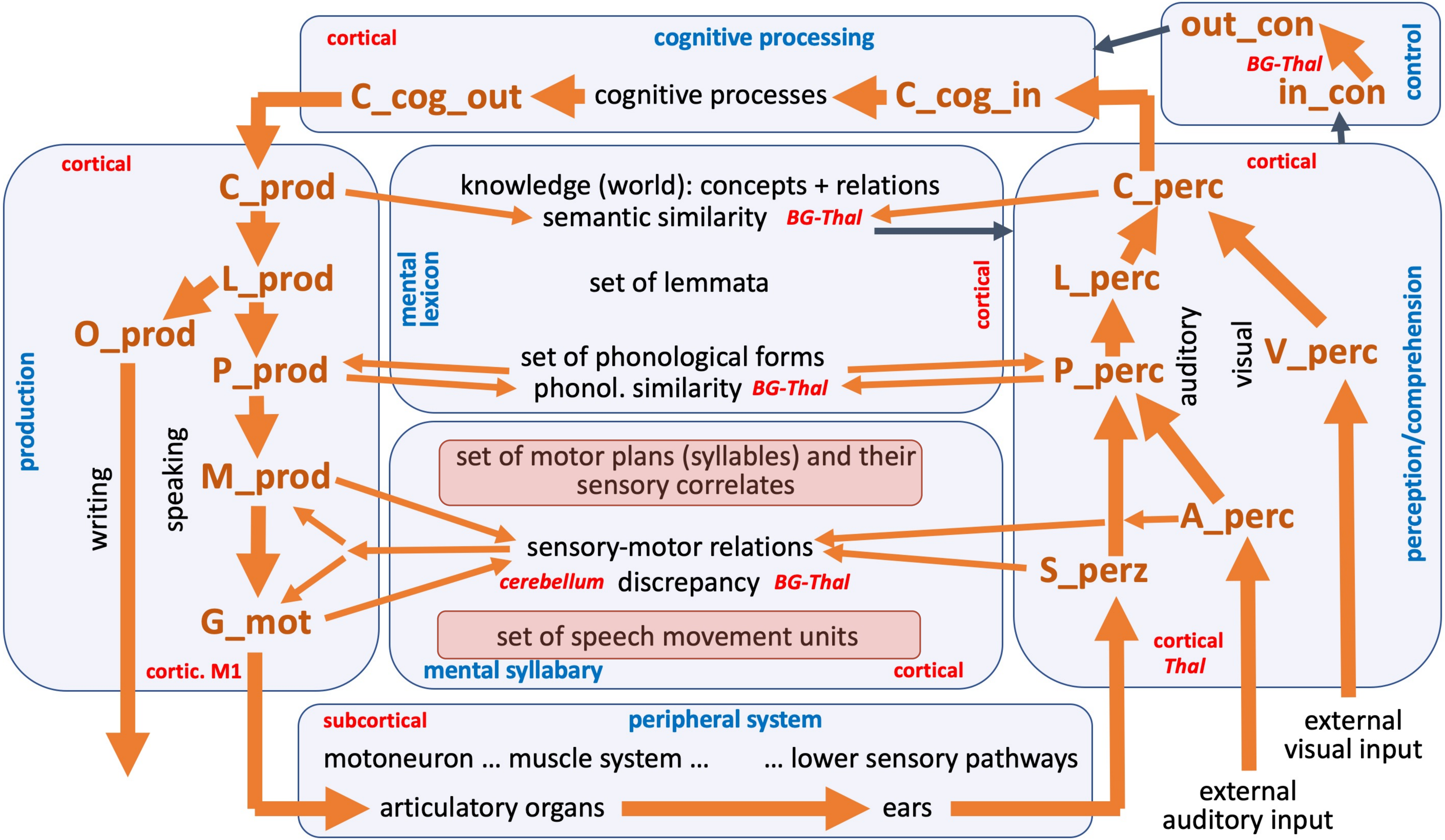
Conclusion: cues are helpful

- 2 different types of cues are helpful: semantic / phonological
- Starting with 20-45% of correct word naming (because of neural dysfunction)
- increase to about 55-70% as result of cues
- (this type of scenario sometimes is used in lexical access screenings)

Kröger et al. (2020)

The sensorimotor part of the model

- Results shown so far -> cortical / lexical part of the model
- Now: how to model the sensorimotor part?
- How to generate articulatory speech movement patterns using a spiking neuron model?
- How to generate speech gesture scores (speech movement unit / speech action scores)?



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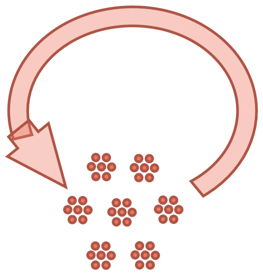
The sensorimotor part of the model

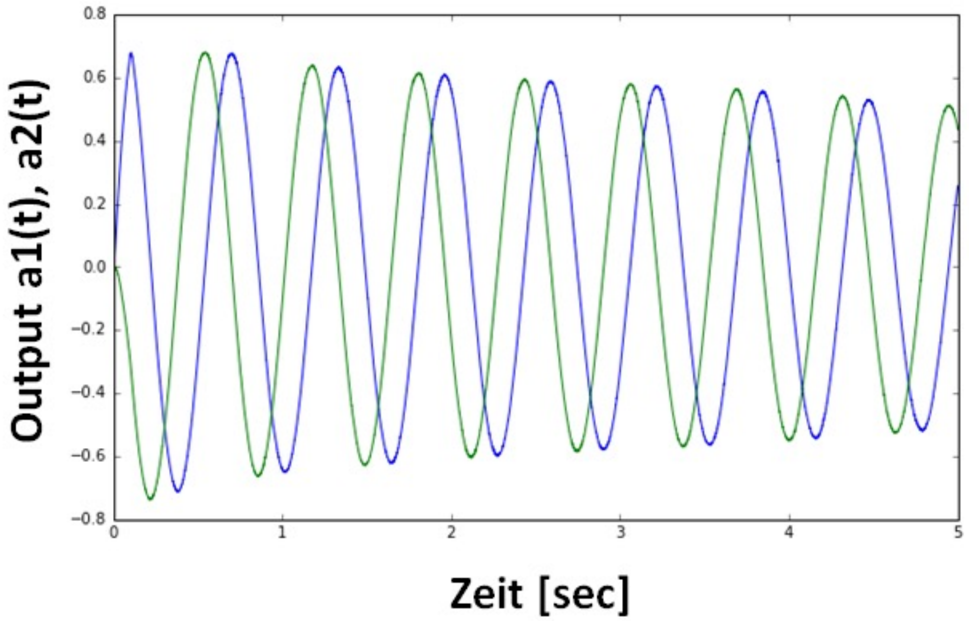
Idea: Basic concept for the production side: realized using

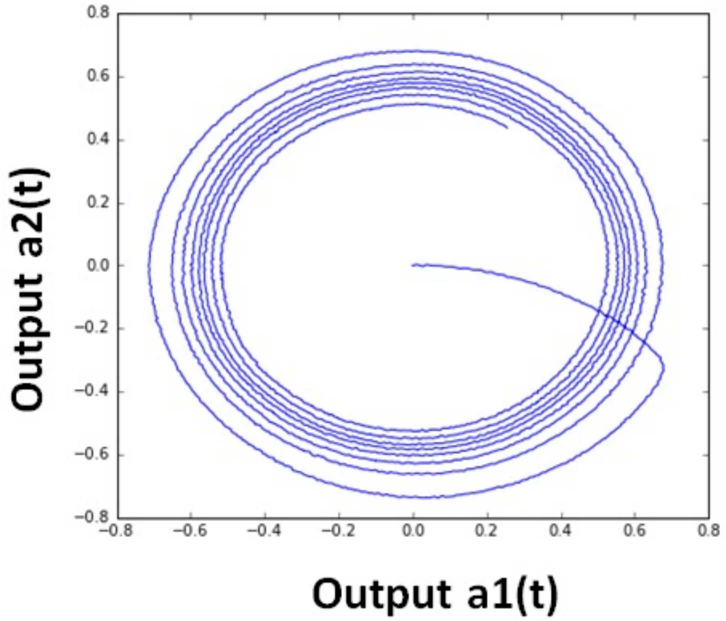
- motor plan (= gesture score) realized as neural oscillator
- gesture (= speech movement unit SMU: vocalic, consonantal, velopharyngeal, glottal) -> neural oscillator

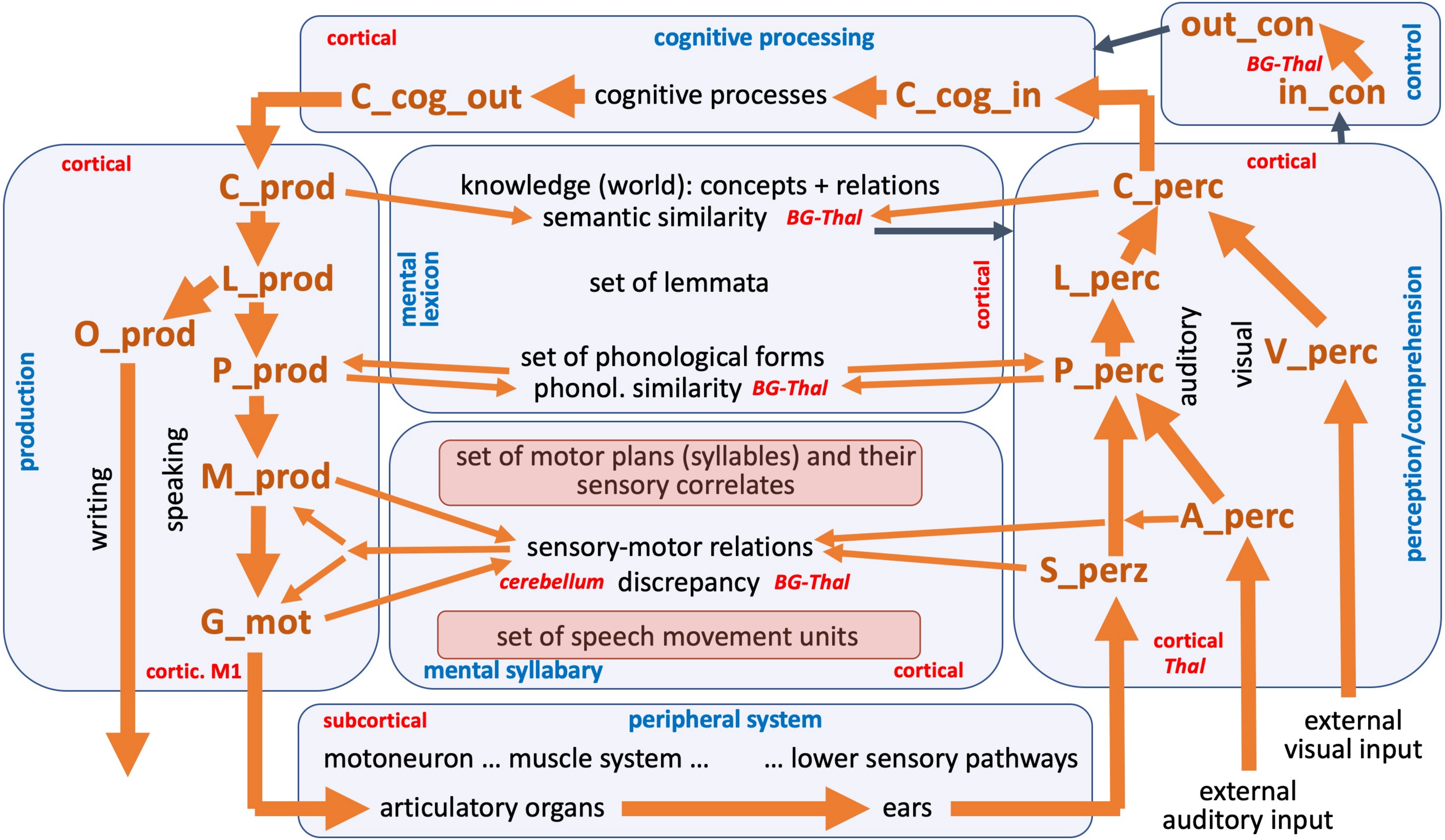
Neural oscillators are buffers:



- Buffers with recursive neural connections -> short-term memories or oscillators
- activation transfer from 50% of the neurons to the other 50% of the neurons of the buffer and back ...







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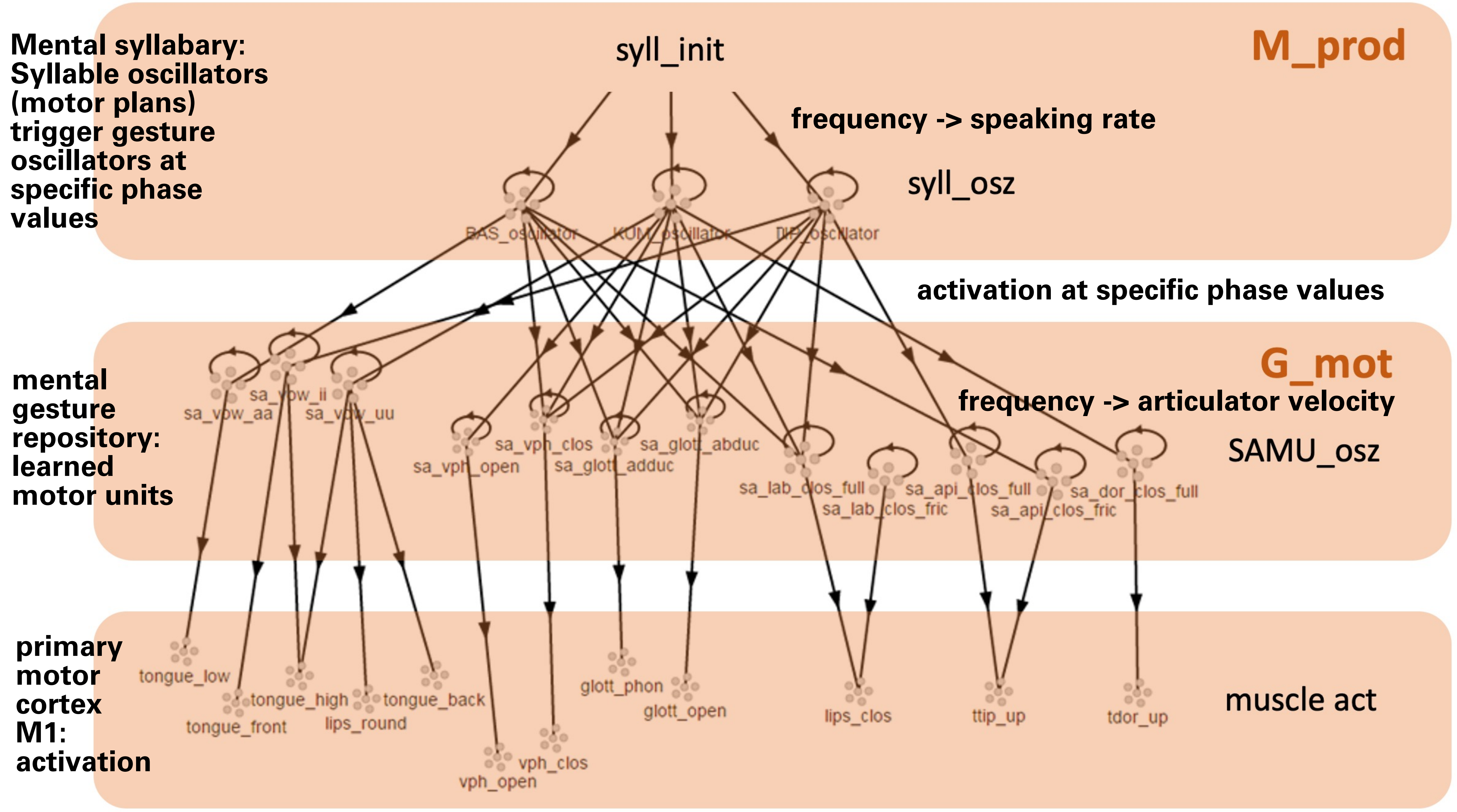
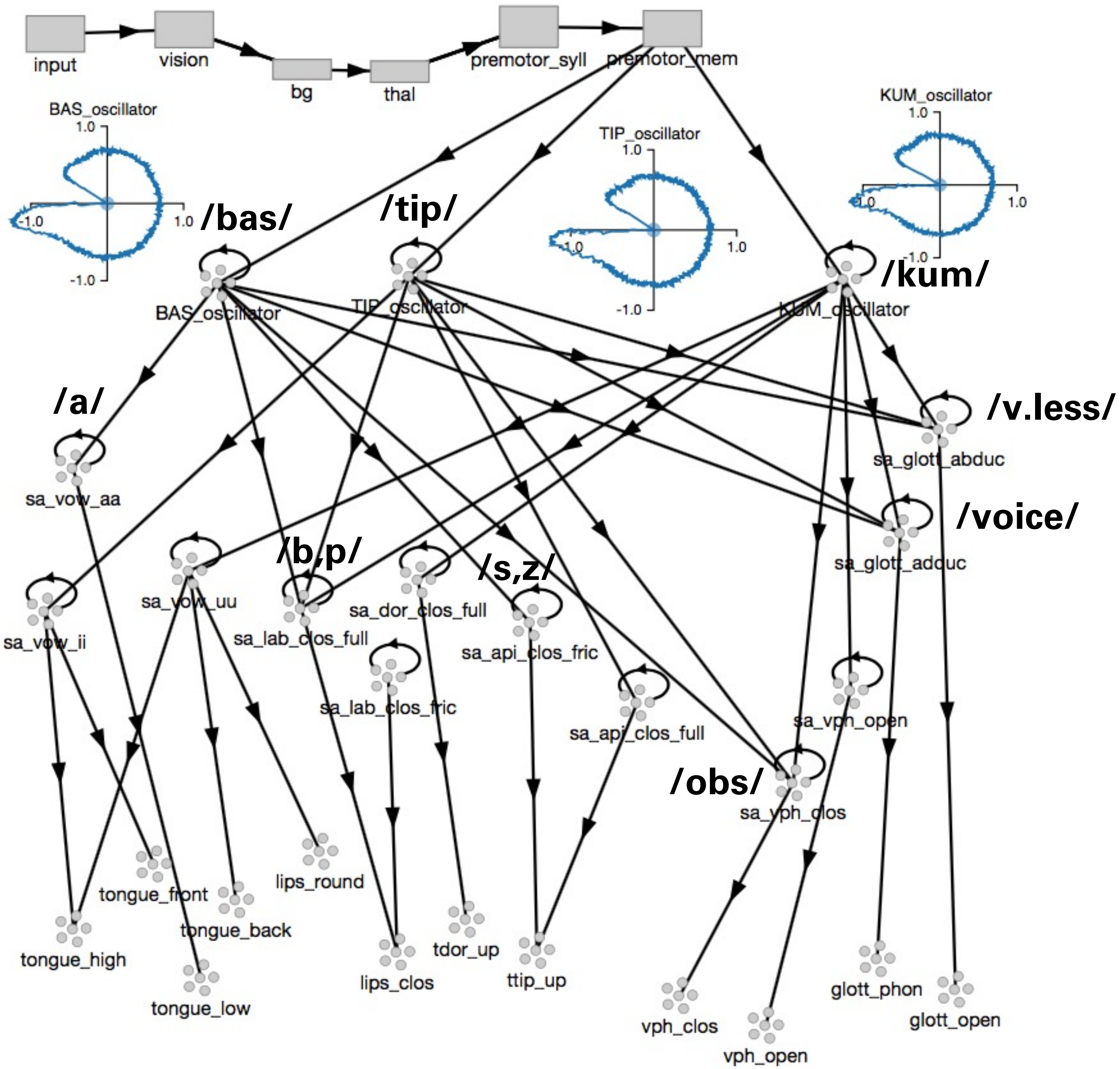
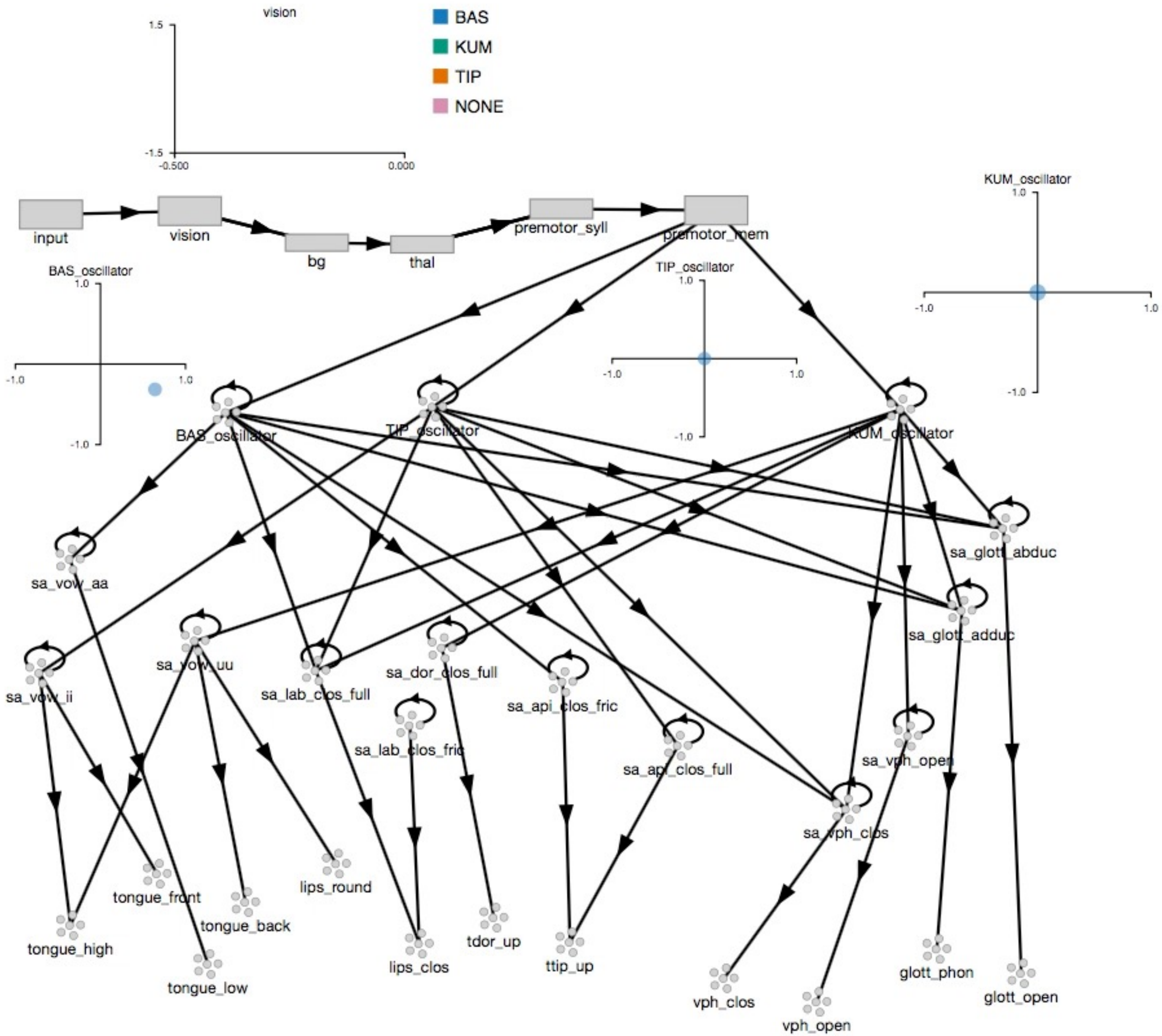

Mental syllabary: Syllable oscillators (motor plans) trigger gesture oscillators at specific phase values
syll_init
M_prod
frequency -> speaking rate
syll_osz
BAS_oscillator
KUM_oscillator
TIP_oscillator
activation at specific phase values
G_mot
frequency -> articulator velocity
mental gesture repository: learned motor units
sa_vow_aa
sa_vow_ii
sa_vow_uu
sa_vph_open
sa_vph_clos
sa_glott_adduc
sa_glott_abduc
sa_lab_clos_full
sa_lab_clos_fric
sa_api_clos_full
sa_api_clos_fric
sa_dor_clos_full
SAMU_osz
primary motor cortex M1: activation
tongue_low
tongue_front
tongue_high
lips_round
tongue_back
vph_open
vph_clos
glott_phon
glott_open
lips_clos
ttip_up
tdor_up
muscle act

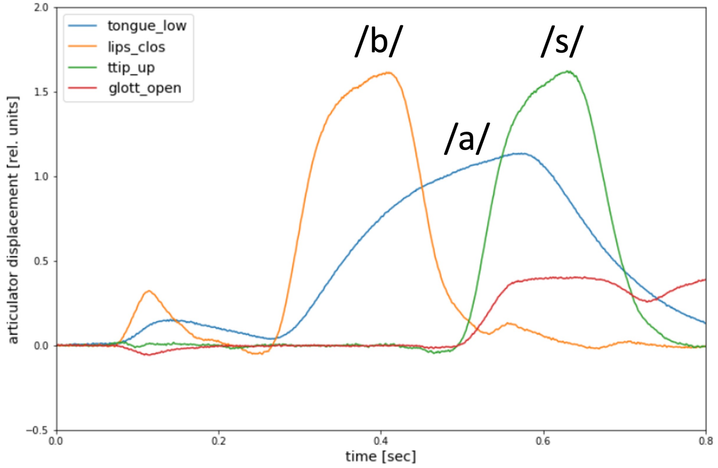
Example word: /bas kum tip/

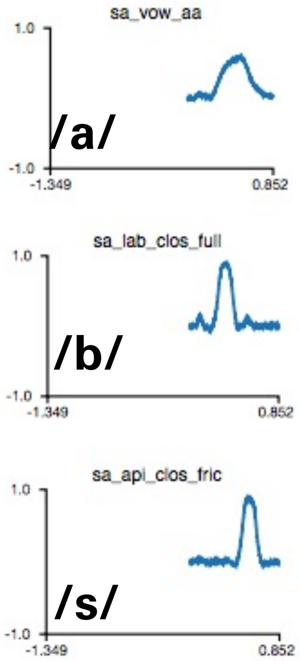
picture is generated by Nengo_gui →

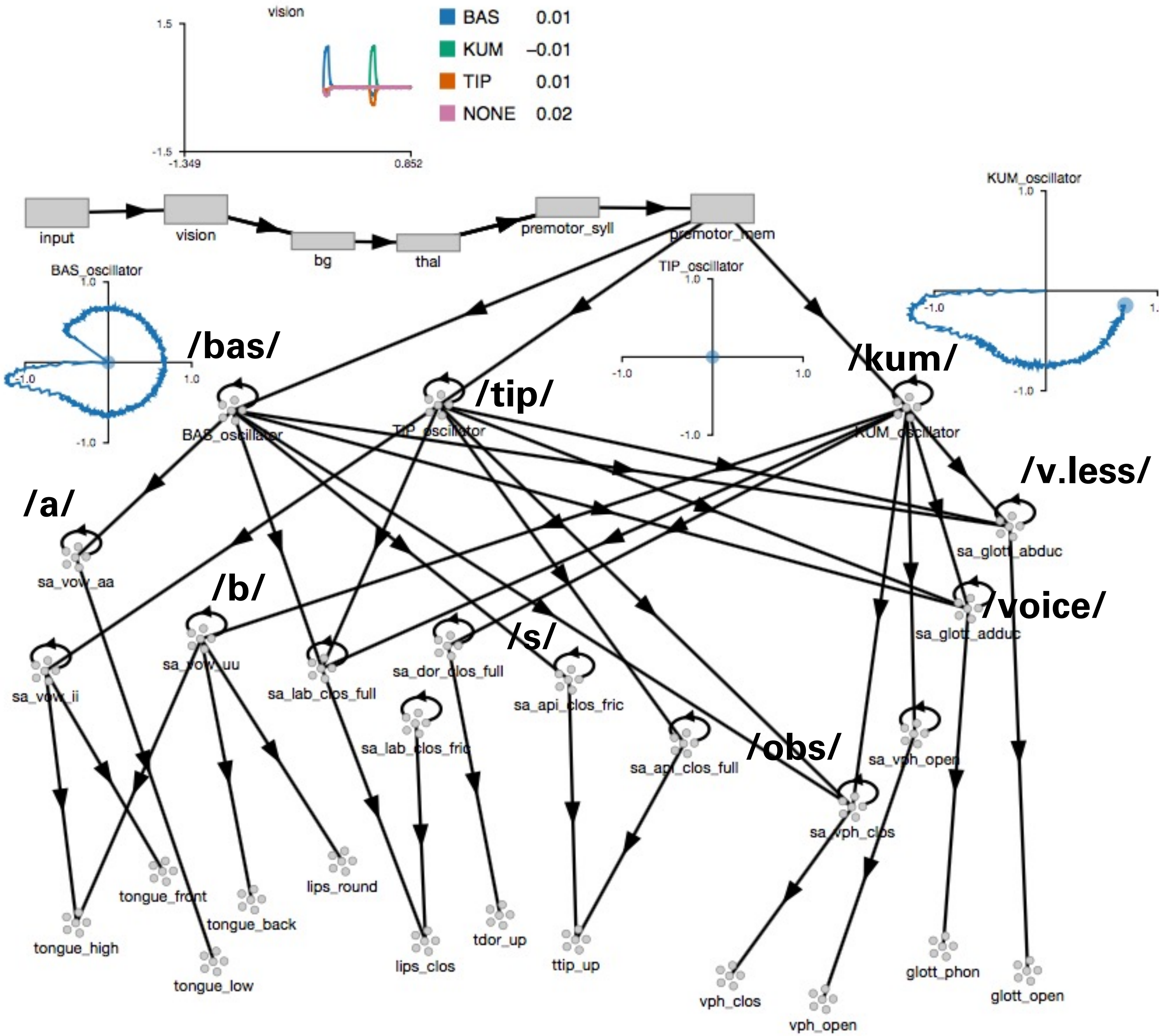



vision
1.5
-1.5
-0.500
0.000
BAS
KUM
TIP
NONE
input
vision
bg
thal
premotor_syll
premotor_mem
BAS_oscillator
1.0
-1.0
1.0
-1.0
TIP_oscillator
1.0
-1.0
1.0
-1.0
KUM_oscillator
1.0
-1.0
1.0
-1.0
BAS_oscillator
TIP_oscillator
KUM_oscillator
sa_vow_aa
sa_vow_uu
sa_vow_ii
sa_lab_clos_full
sa_dor_clos_full
sa_lab_clos_fric
sa_api_clos_fric
sa_api_clos_full
sa_glott_abduc
sa_glott_adduc
sa_vph_open
sa_vph_clos
tongue_high
tongue_front
tongue_back
tongue_low
lips_round
lips_clos
tdor_up
ttip_up
vph_clos
vph_open
glott_phon
glott_open

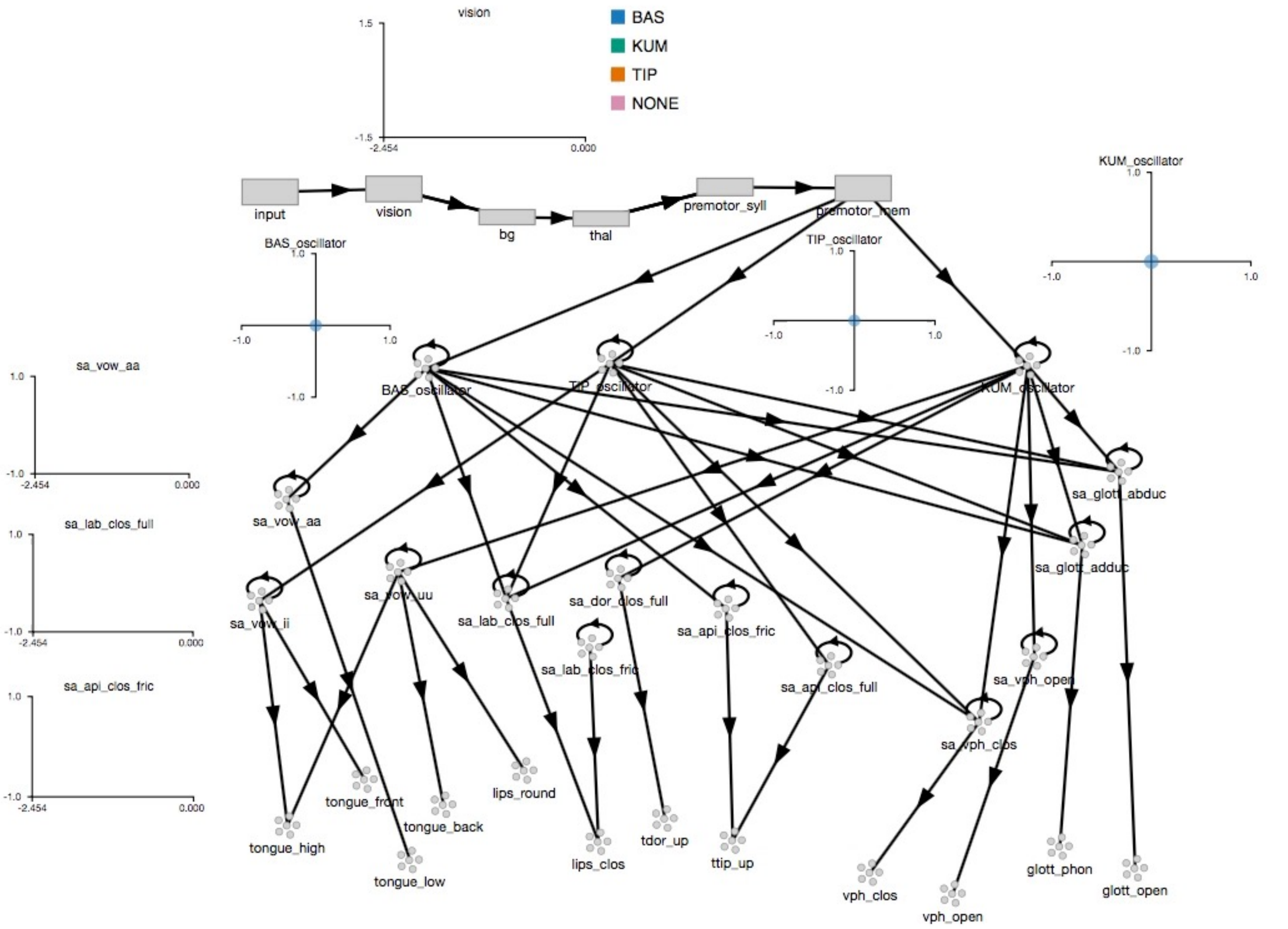
Syllable /bas/





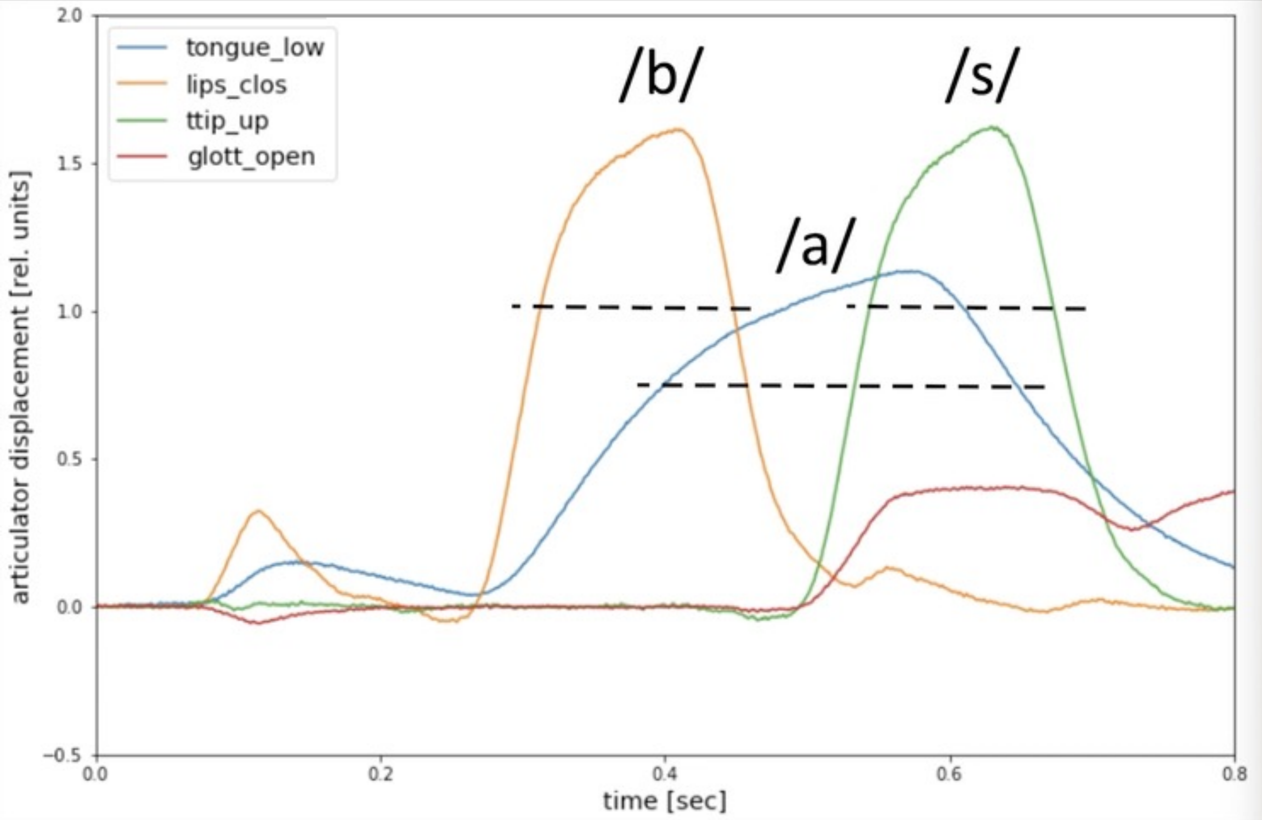


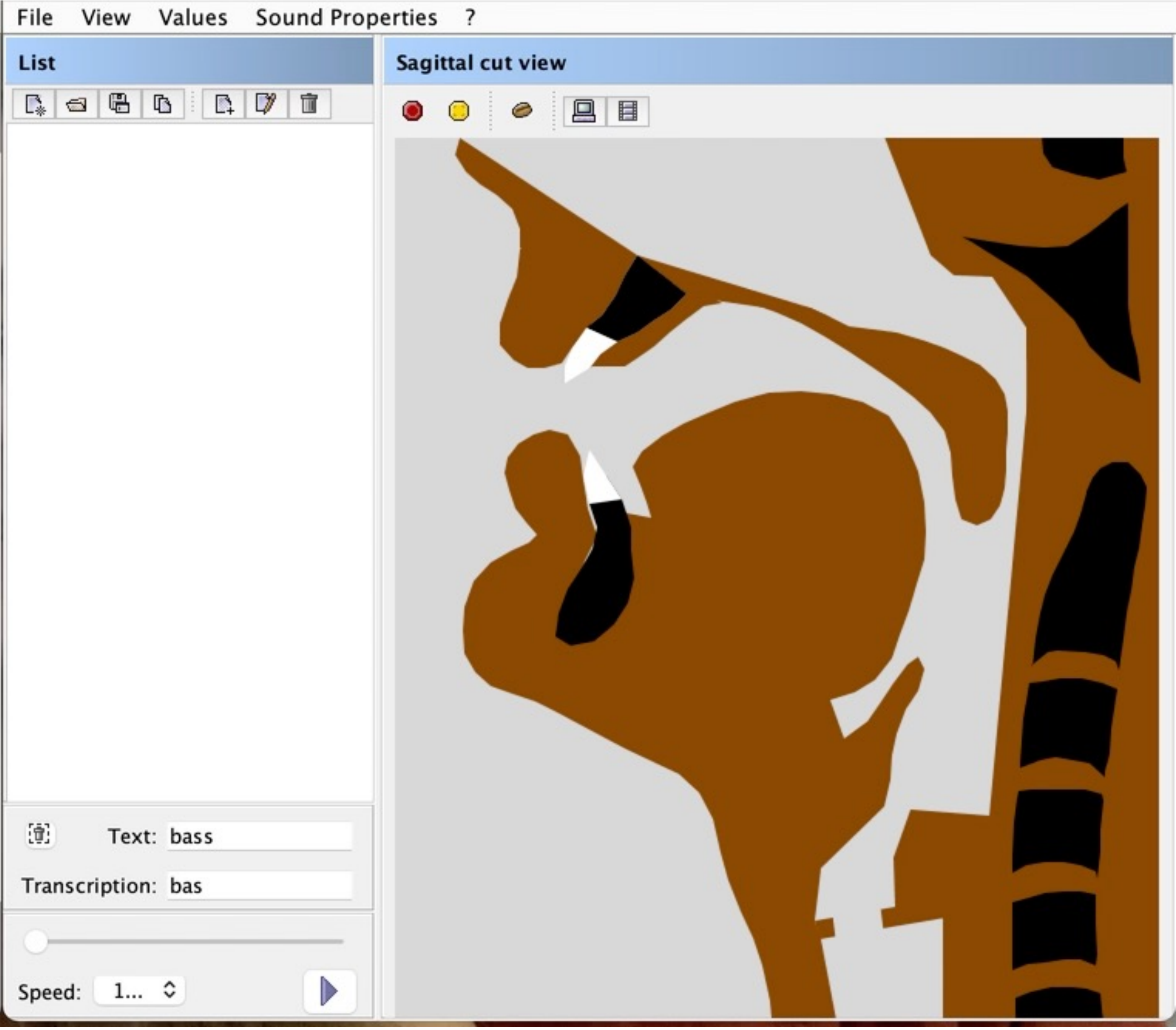
Gesture oscillators: degree of neural activation
-> degree of realization of a gesture
-> "abstract" movement trajectory



Gesture oscillators: degree of neural activation -> degree of realization of a gesture -> “abstract” movement trajectory

2D-articulatory model





Why oscillators?

- Oscillators define time intervals (<-> duration of one oscillation cycle)
- Oscillators are able to define timing of actions:
  - actions may start at specific points in time within an oscillation cycle -> phase values

Application of our approach: Modeling different speaking rates

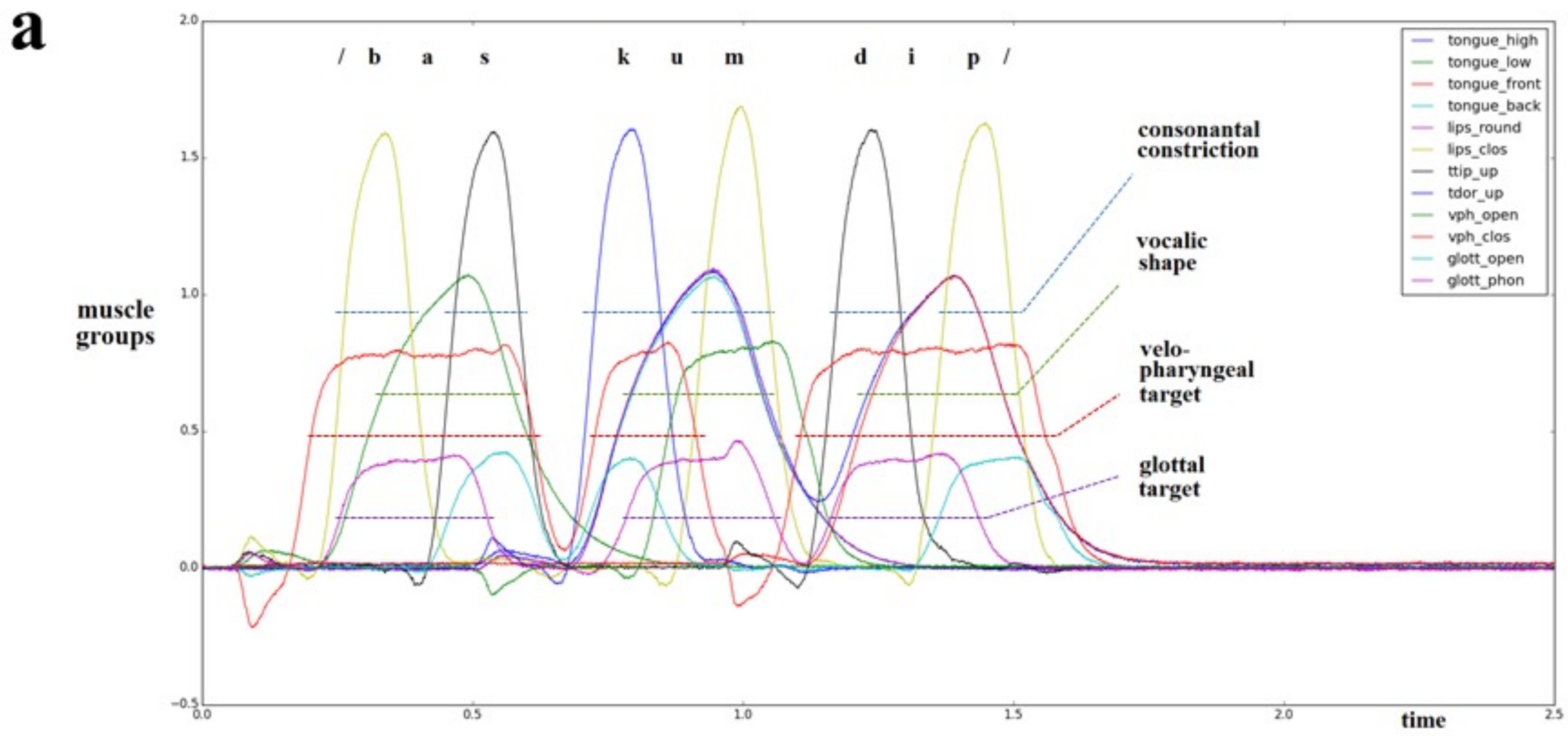
- phase values (coded in the motor plan / syllable level) stay constant
- oscillator frequency for gestures stays constant (coding vocalic and consonantal articulator velocities)
- oscillator frequency of syllable oscillators (motor plan level) is allowed to vary!! -> (increases with increasing speaking rate)

Kroeger, BJ, Bekolay T, Blouw P, Stewart TC (2020) Proceedings of the International Seminar on Speech Production ISSP2020. Yale University, New Haven, CT.
www.spechtrainer.eu -> publications

Results

- constant phasing of actions leads to correct production of speech sounds at each speaking rate:
- slow speaking rate:

no increase in articulatory effort per speech action

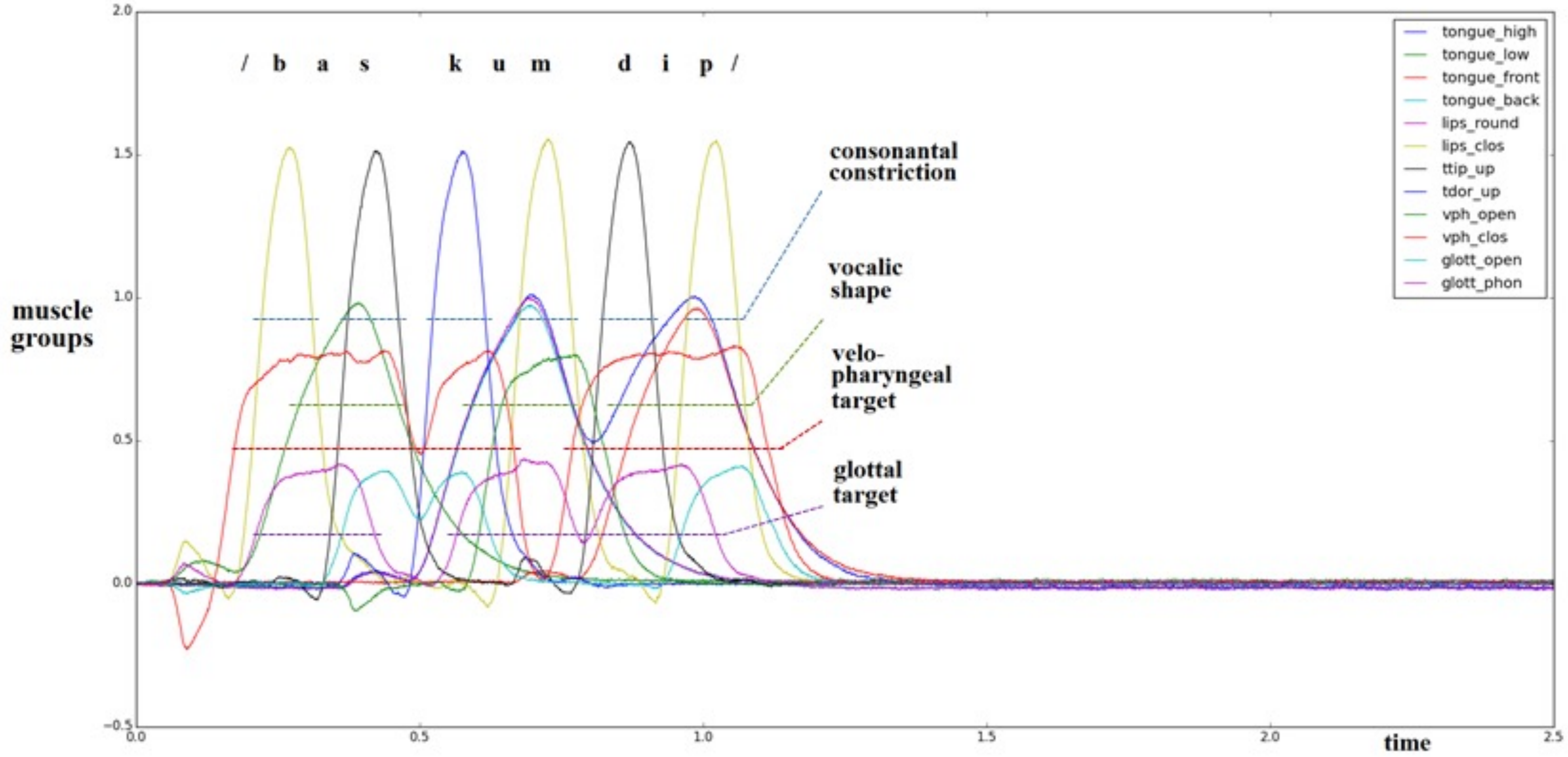


Results

- constant phasing of actions leads to correct production of speech sounds at each speaking rate:
- normal speaking rate:

no increase in articulatory effort per speech action

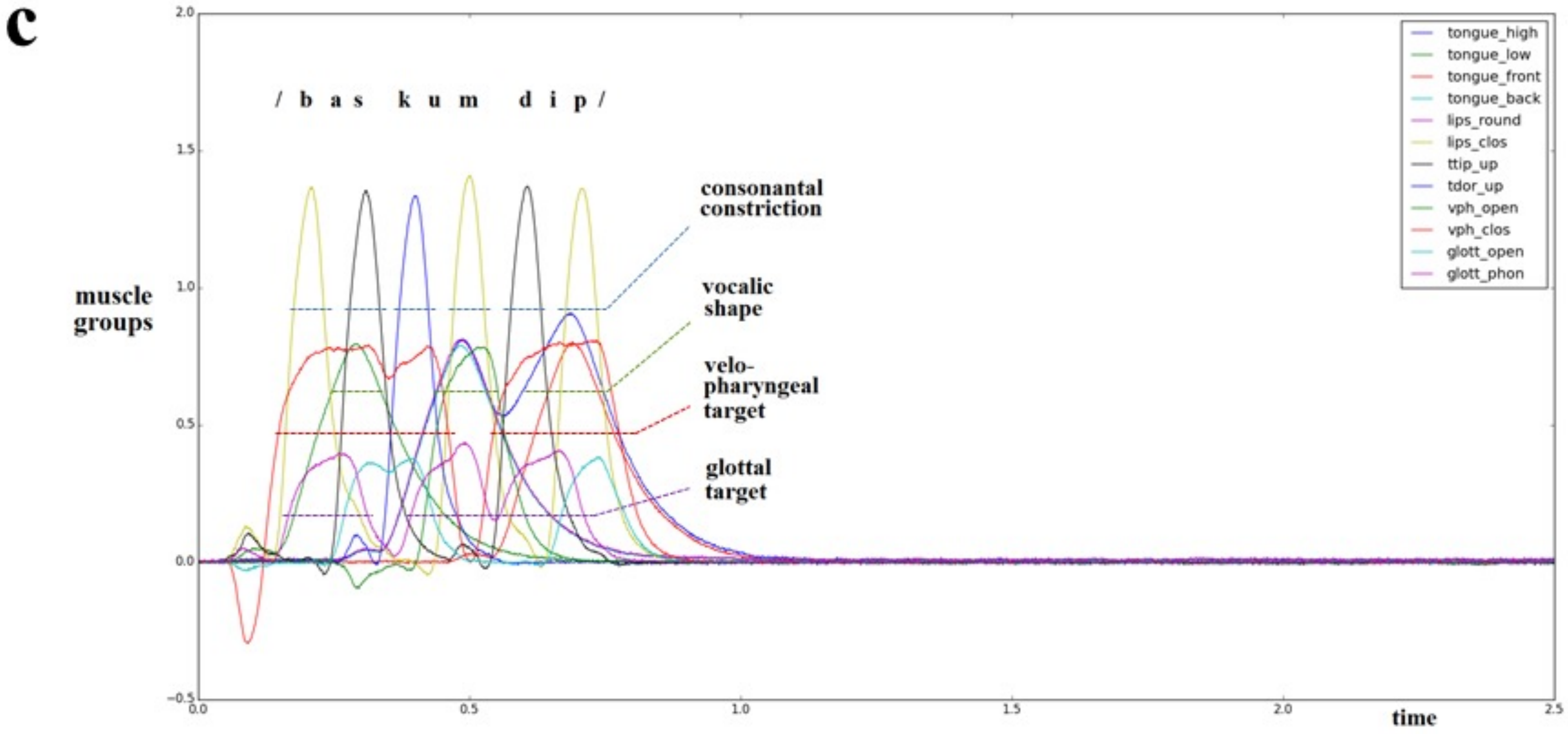
b



Results

- constant phasing of actions leads to correct production of speech sounds at each speaking rate:
- fast speaking rate:

no increase in articulatory effort per speech action



Overall conclusions

- the large-scale model approximates human behavior surprisingly well in many cases: e.g.,
  - Modeling different types of aphasia -> decrease of performance for production or perception or repetition tasks, depending on the type of dysfunction
  - cues are helpful in case of “tip of the tongue”-situations: -> increase of correct word naming from 20-45% (no cues) to 55-70% -> cues are helpful in specific situations of overburdening (borderline situations)
- a basic concept for sensorimotor part of the model exists

Benefits for medical research from modeling:

Medical / speech therapy research:

- creation of specific “model patients” suffering from specific neural dysfunctions with specific degrees of severity
- multiple simulations can be performed: with each specific model patient
- that allows to optimize medical screenings (evaluate its sensitivity for a specific disorder)

THANK YOU VERY MUCH

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