Toward higher cognition:

A case study in the grounding of nested phrases

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Motivation

- Towards understanding the biological neural processes that give rise to the higher cognitive competences
  - Reasoning
    - Deductive
    - Analogical
  - Language understanding
  - Planning
  - …

Theoretical starting point

- Higher cognitive competences are “grounded” in perceptual-motor representations and processes
  - Makes use of them
  - Evolved “on top of” them
  - Same neural principles
  - Reviews: Barsalou (1999, 2008)

Contrast:
Classical computational theory of mind

- Higher cognitive competences (language, reasoning, planning, problem solving, …) best explained as algorithmic processing of amodal symbols

Research program

- Demonstrate how higher cognitive competences may emerge from neural dynamics postulated in DFT
  - Neural fields with their instabilities (detection, selection, working memory)
  - Binding
  - Sequence generation
  - Coordinate transformations
  - Concepts

Example

- Ragni & Knauff (2013)

The Porsche is parked to the left of the Dodge
The Ferrari is parked to the right of the Dodge

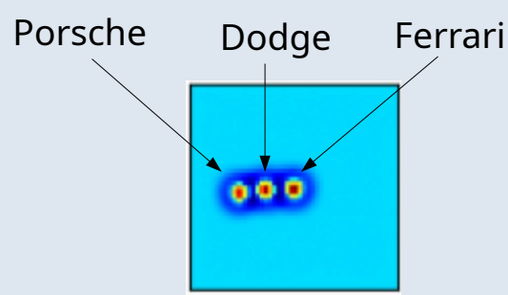
_____

Therefore, the Dodge is parked to the left of the Ferrari

Algorithmic proof systems

$$\exists x \exists y \exists z \left(Porsche(x) \wedge Porsche(x) \wedge Dodge(y) \wedge Ferrari(z) \right.$$
$$\left. LeftOf(x, y) \wedge RightOf(z, y) \right) \rightarrow LeftOf(y, z)$$

Spatial layout models



Ragni & Knauff (2013), Kounatidou, Richter, & Schöner (2018)

Example

- Ragni & Knauff (2013)

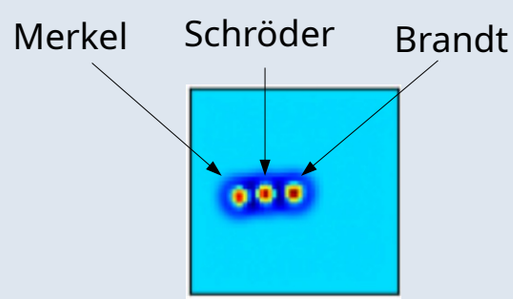
Willy Brandt was more popular than Gerhard Schröder
Gerhard Schröder was more popular than Angela Merkel

Therefore, Willy Brandt was more popular than Angela Merkel

Algorithmic proof systems

$$\exists x \exists y \exists z \left(Porsche(x) \wedge Porsche(x) \wedge Dodge(y) \wedge Ferrari(z) \right.$$
$$\left. LeftOf(x, y) \wedge RightOf(z, y) \right) \rightarrow LeftOf(y, z)$$

Spatial layout models



Ragni & Knauff (2013), Kounatidou, Richter, & Schöner (2018)

The hallmarks of higher cognition

- Combinatorial structure of language and thought
- Compositionality

- Often argued to lend support to classical computational theory of mind (Fodor & Pylyshyn, 1988)

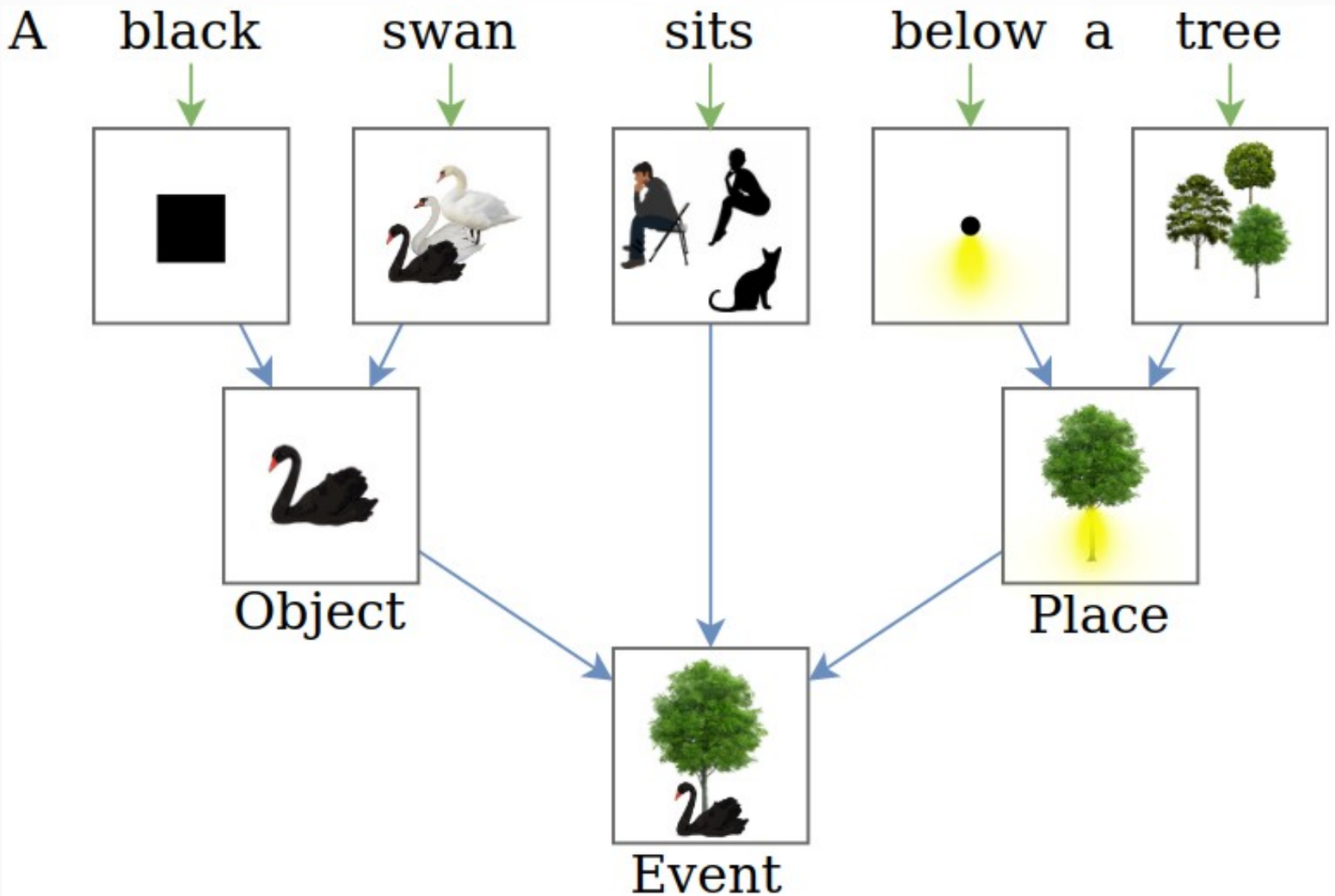
Combinatorial structure of language

- Ability to produce and understand an indefinite range of expressions by finite means (von Humboldt, 1836)
  - the house
  - the lake
  - the house at the lake
  - the tree to the right of the house at the lake
  - the red ball moves towards the big tree to the right of the house at the lake

Compositionality

- “This would be impossible, were we not able to distinguish parts in the thoughts corresponding to the parts of a sentence, so that the structure of the sentence serves as the image of the structure of the thought” (Frege, 1923)

Compositionality:
Combining concepts in accordance with structural arrangement



Conceptual structure

- Theory: We combine concepts in accordance with structural arrangement by explicitly representing the **conceptual structure** of a natural language expression
- Hypothesized level of cognitive representation that captures the logical meaning of an expression as a combination of concepts (Jackendoff, 2002)

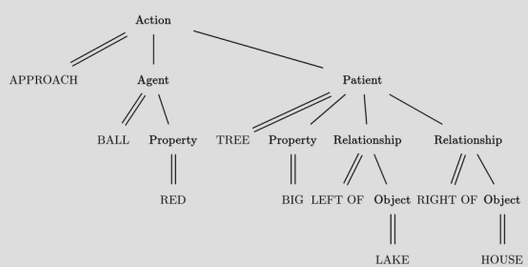
Conceptual structure

Language

"The ball approaches the tree which is to the right of the house and to the left of the lake."

language processing

Neural representation of conceptual structure



grounding

Scene

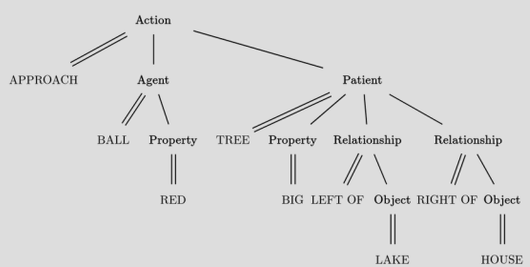
Conceptual structure

Language

"The ball approaches the tree which is to the right of the house and to the left of the lake."

language processing

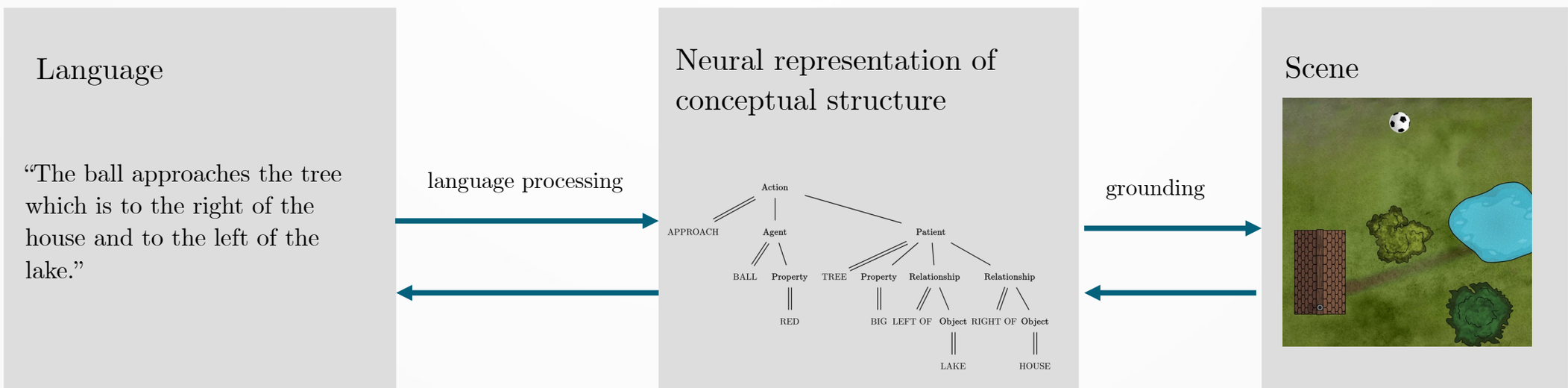
Neural representation of conceptual structure



grounding

Scene

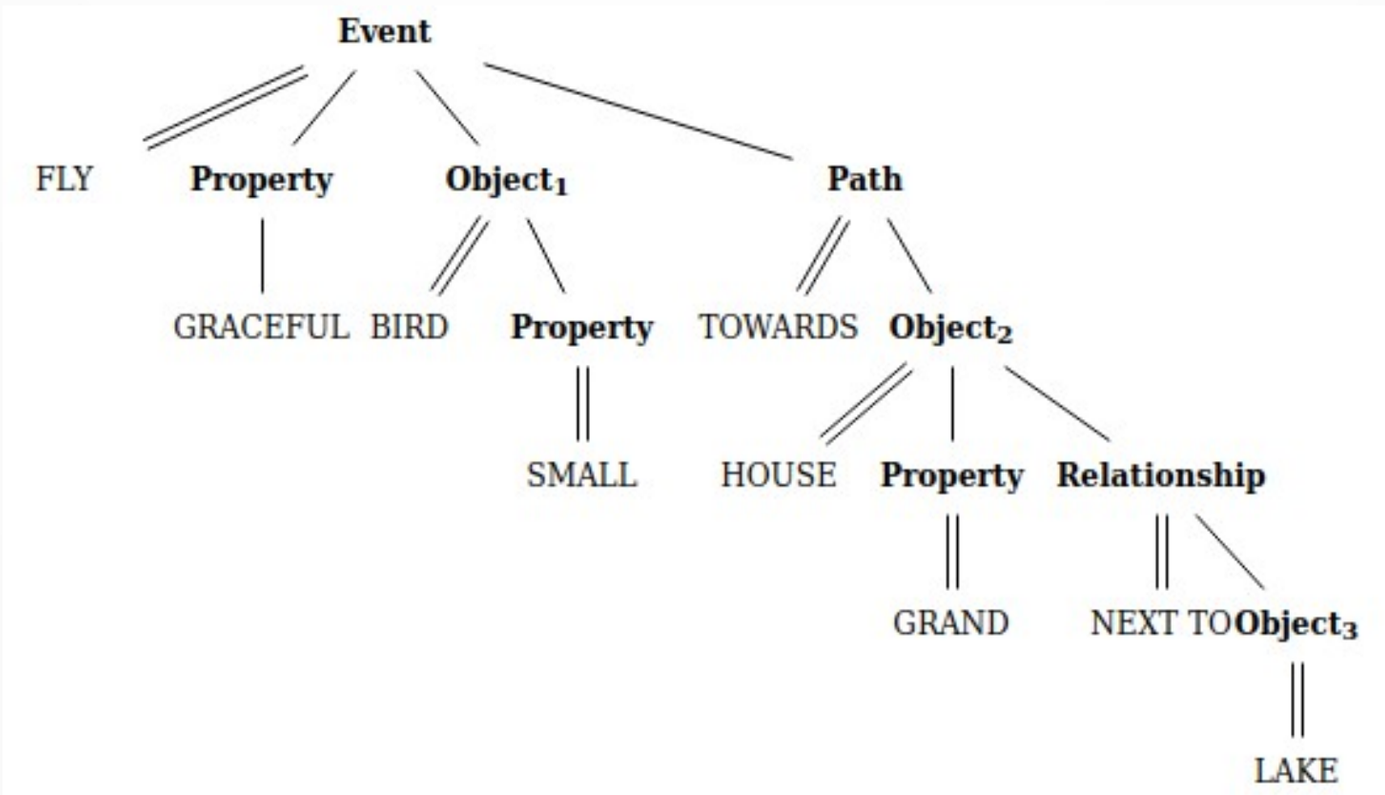
Conceptual structure



Hypothesis (Jackendoff):
higher cognitive competences like reasoning and planning are underwritten by conceptual structure

Conceptual structure

- “The small bird flies gracefully towards the grand house next to the lake.”

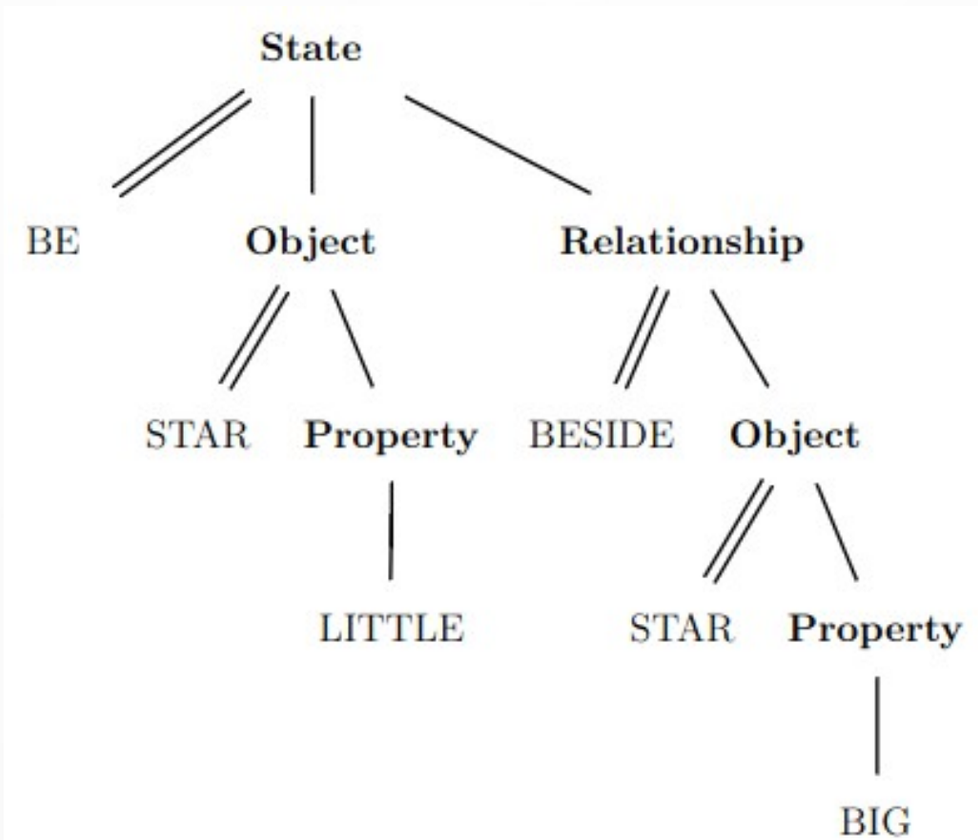


Jackendoff’s challenges

- Neural activation patterns need to encode structural dependencies among entities
- Examples
  - The little star's beside a big star.
  - The big star's beside a little star.
  - Beside a the big little star star's. (Jackendoff, 2002, p. 58)
- Binding problem

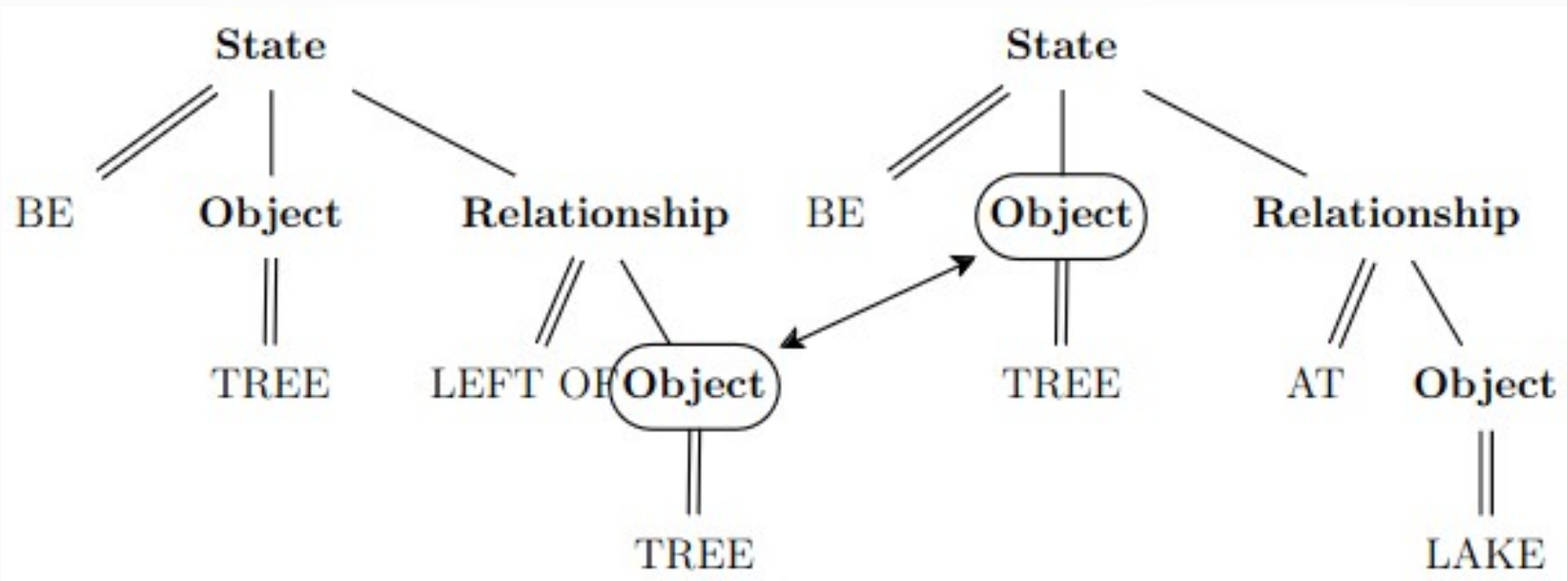
Jackendoff's challenges

- "The little star's beside a big star."



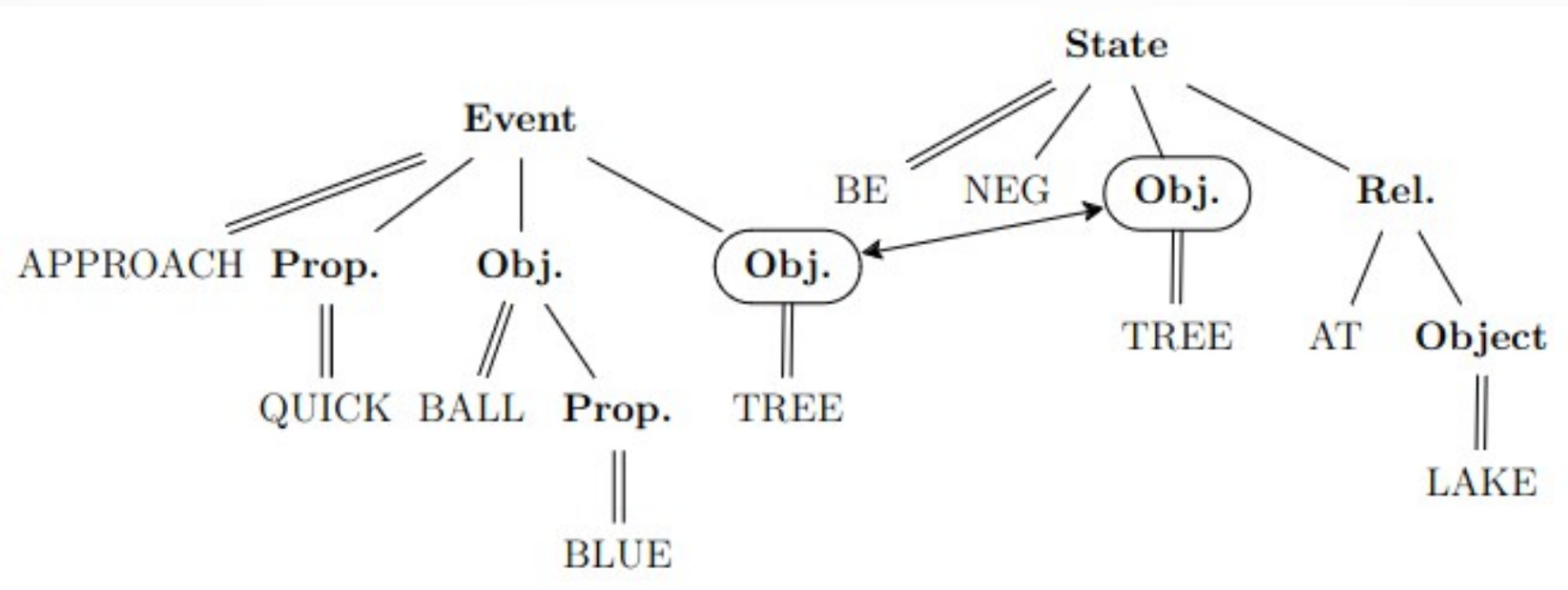
Jackendoff's challenges

- "The tree is to the left of the tree which is at the lake."



Jackendoff's challenges

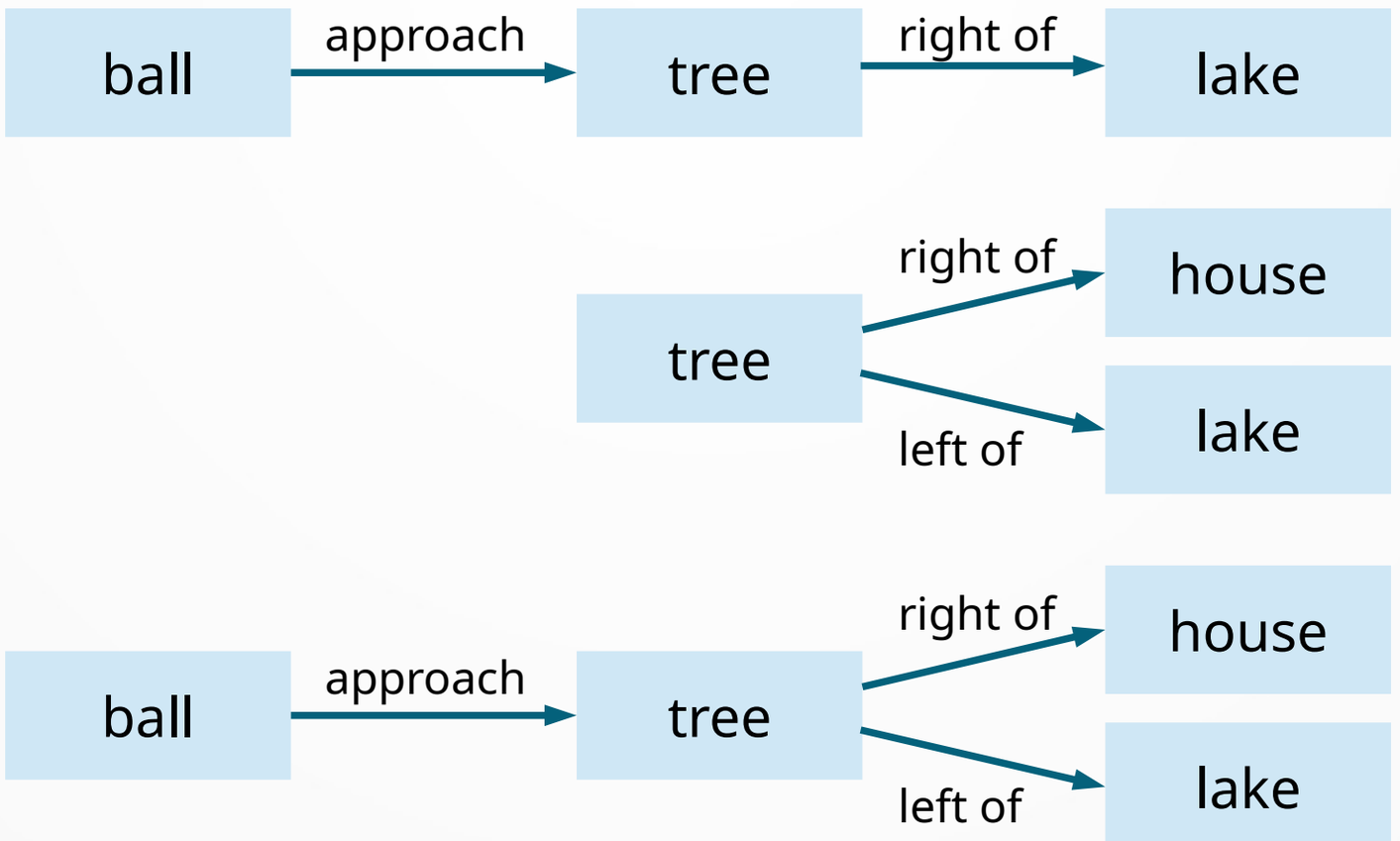
- "The blue ball quickly approaches the tree which is not at the lake."



Case study: Grounding nested phrases

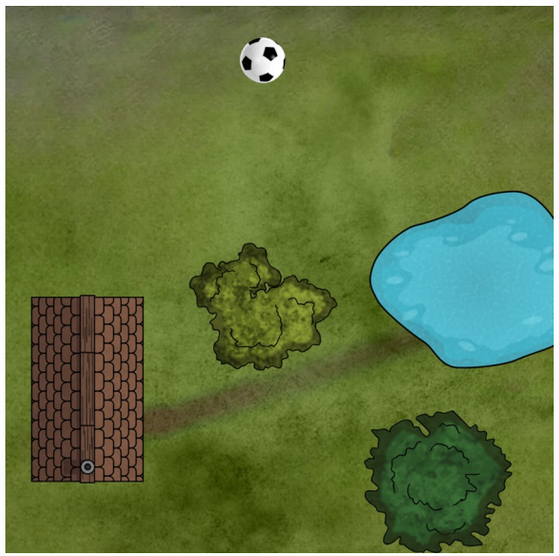
- **Nested phrase:** Phrase that describes the flexible interrelationships among objects
  - The ball approaches the tree which is at the lake
  - The ball approaches the tree which is to the right of the house and to the left of the lake
  - The man kicks the ball that approaches the tree which is at the lake
  - The tree to the left of the house is bigger than the tree to the right of the lake.

Structural dependencies



- How may a neural dynamics encode such structural dependencies?

Grounding nested phrases



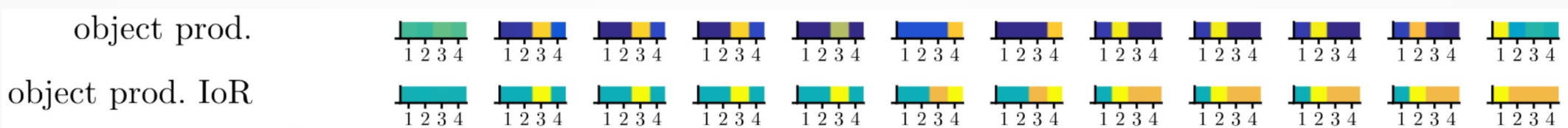
The ball approaches
the tree which is
to the right of the house
and to the left of the lake.

- How may a neural dynamics organize cognitive operations (visual search, processing relationships) in accord with these structural dependencies?

Discrete neural fields

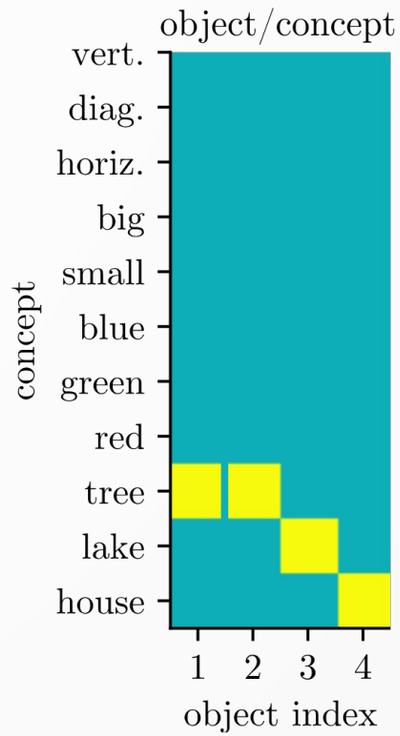
$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t) + c_{\text{exc}} \cdot \sigma(u(x,t)) - \sum_{x' \neq x} c_{\text{inh}} \cdot \sigma(u(x',t))$$

- Analogous instabilities as continuous neural fields



Binding through index

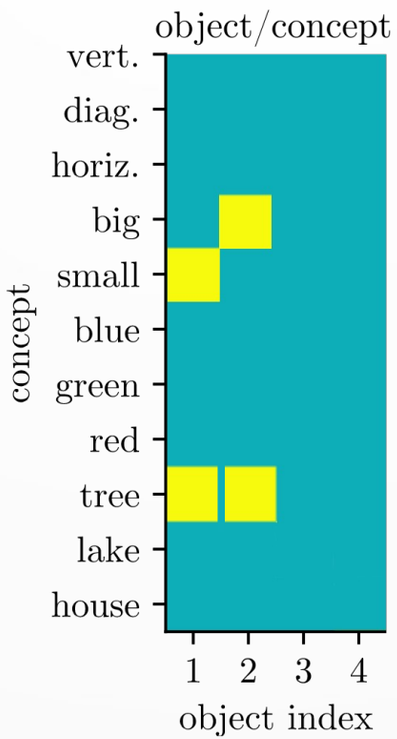
- Embed each mentioned object into a discrete index dimension
  - "the tree [O1] is to the right of the tree [O2] which is below the lake [O3] and above the house [O4]"
- The index may serve as a binding agent (just as space in binding through space)



Discrete neural field

$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t) + c_{\text{exc}} \cdot \sigma(u(x,t)) - \sum_{x' \neq x} c_{\text{inh}} \cdot \sigma(u(x',t))$$

Binding through index

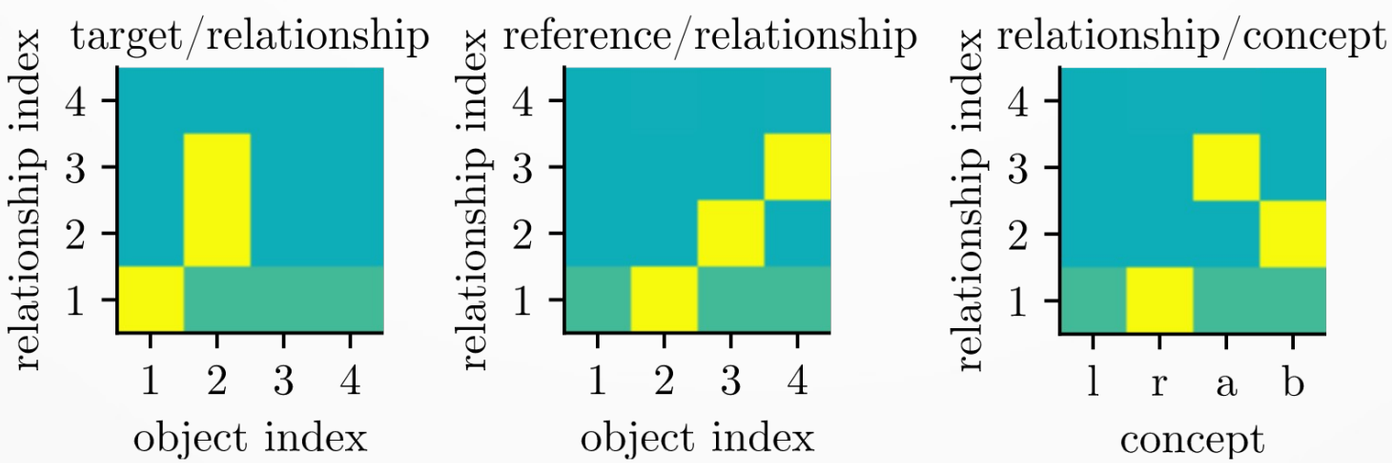


Binding through index

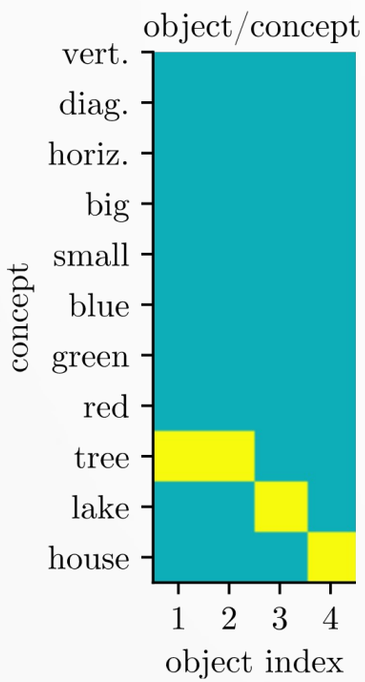
- Embed each mentioned relationship into a discrete index dimension
  - “the tree is to the right of [R1] the tree which is below [R2] the lake and above [R3] the house”
- Enable binding objects to relationships in particular roles

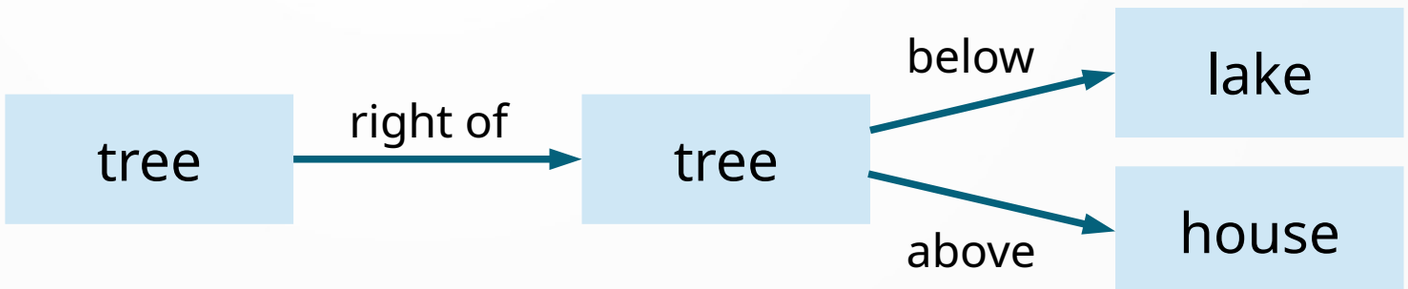
Binding through index

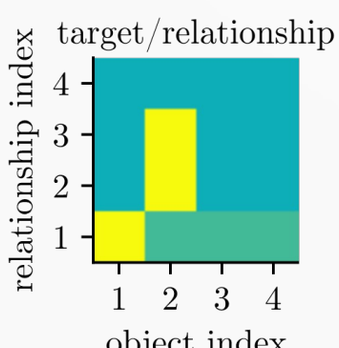
"the tree [O1] is to the right of [R1] the tree [O2] which is below [R2] the lake [O3] and above [R3] the house [O4]"

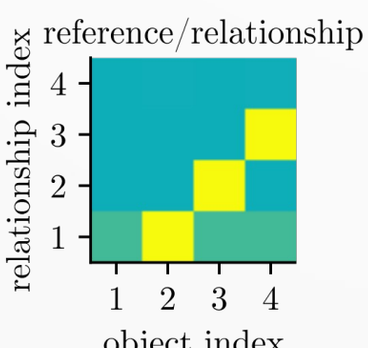


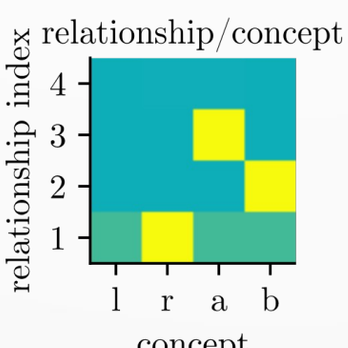
Conceptual structure







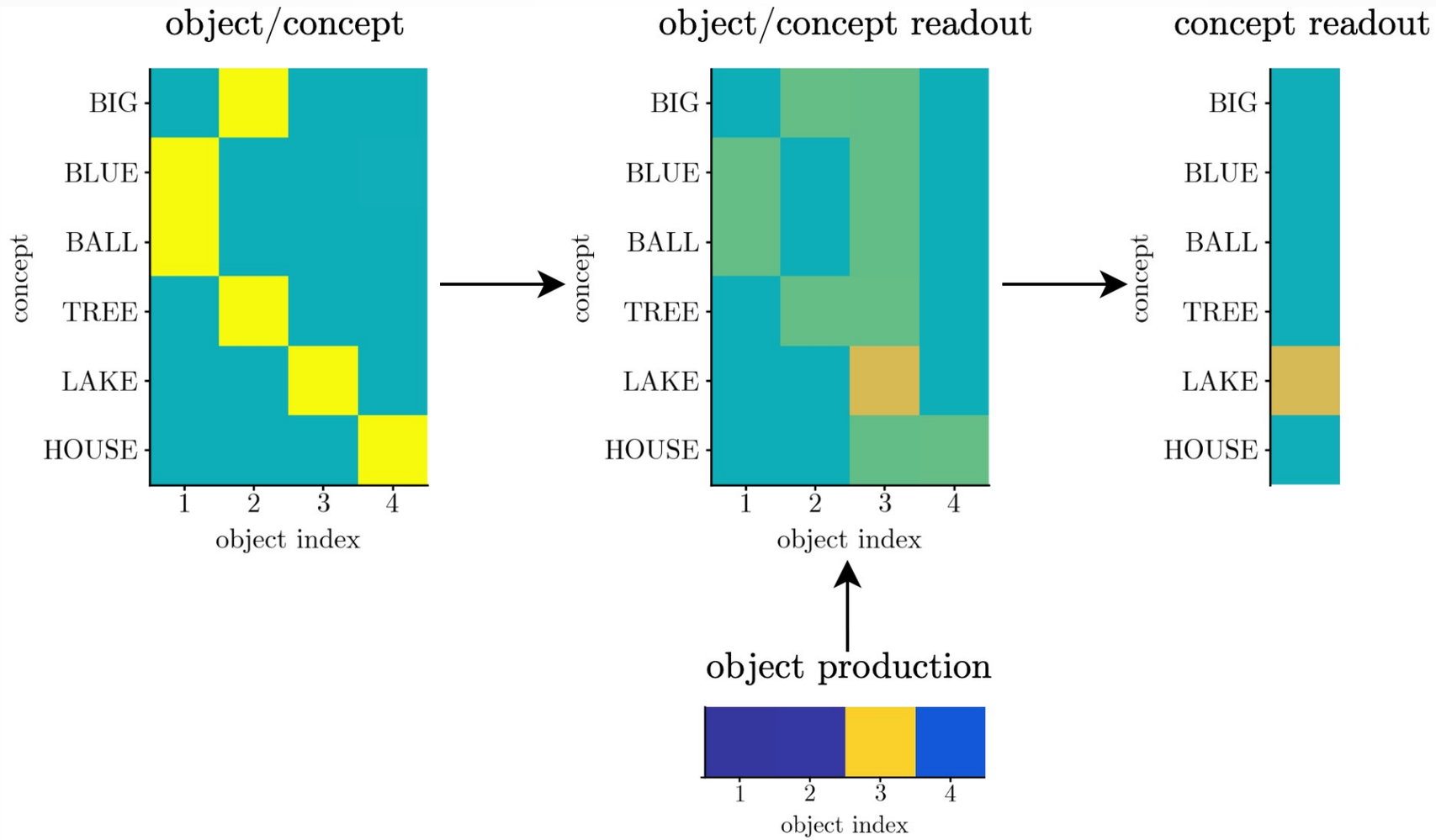




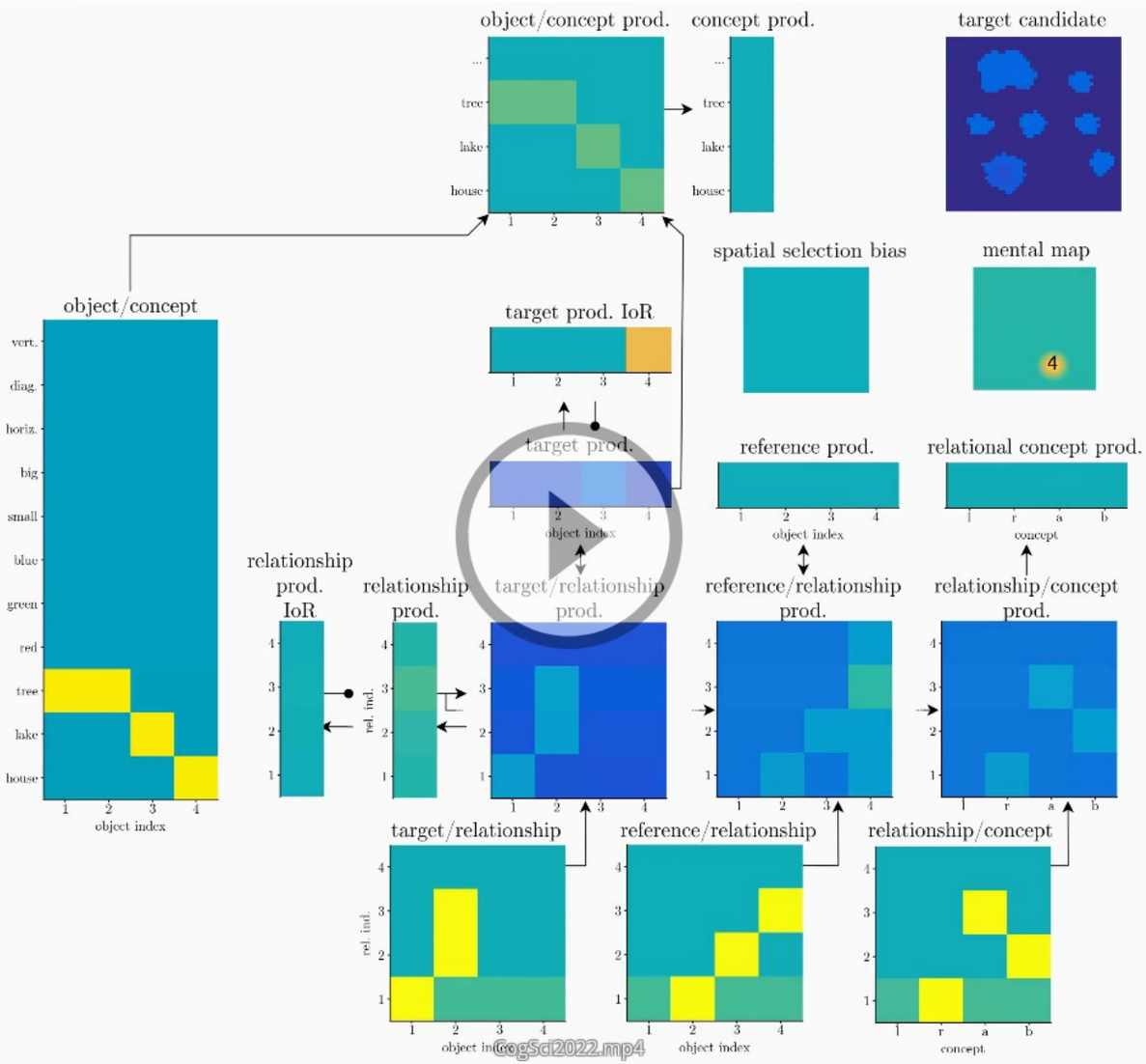
Grounding conceptual structure

- Not all of the object descriptions can simultaneously have an effect on grounding processes due to limited attentional capacities
- Only one relationship description can be verified at a time (Logan, 1994; Franconeri, 2012)

Grounding conceptual structure



Grounding nested phrases



Conclusion

- Demonstrated an autonomous DFT architecture that perceptually grounds arbitrary nested phrases
- … as a case study for grounding grammatically complex language more generally
- … as a case study for a higher cognitive competence

Paper

- Sabinasz, D., & Schöner, G. (2023).
  A neural dynamic model perceptually grounds nested noun phrases.
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