How Productivity and Compositionality May Emerge from a Neural Dynamics of Perceptual Grounding

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Summary

The productivity and compositionality of language and thought have often been taken as evidence that higher cognition is a form of computation on systems of amodal symbols with combinatorial syntax and semantics [1]. Productivity refers to the ability to form an unbounded number of concepts or linguistic expressions by finite means. Compositionality is the principle that the meaning of a complex concept or linguistic expression is determined by the meanings of its parts and the way the parts are put together.

In respone to the lack of neural plausibility of amodal symbol systems, views of grounded cognition [2] propose that higher cognitive processes rely on representations and processes in the brain's modal systems. The current work is part of a research program to provide a neural processing account for grounded cognition [3,4,5]. Here, we present a neural dynamic architecture that can ground combinatorial concepts in perception, i.e., establish a link between a combinatorial concept and an object in the perceptual array.

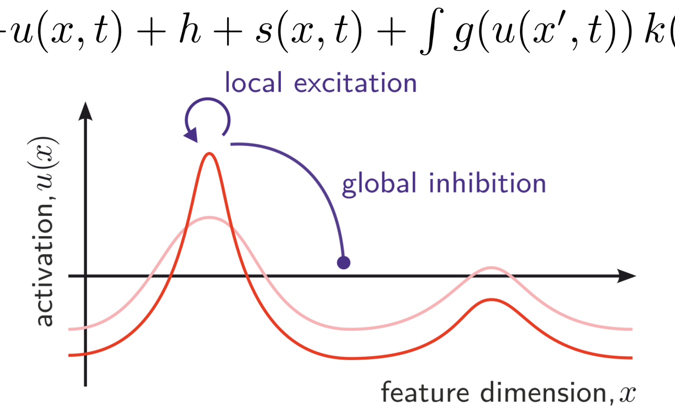
The components of a combinatorial concept tree are sequentially grounded from the leaves to the root, while the output of each grounding step is passed on to the next grounding step by means of a mental map. This way, productivity and compositionality are emergent properties of the neural dynamics and do not require any form of symbolic information processing.

We are currently working to extend the architecture to allow for the grounding of arbitrary feature conjunctions in multiple perceptual spaces (e.g., color, orientation, size). Ultimately, we seek to introduce negation and universal quantification to arrive at an architecture that can resolve arbitrary denotational phrases expressible in first-order logic. These are all necessary prerequisite steps towards neurally plausible models of higher cognitive functions like reasoning, belief and natural language understanding.

Methods

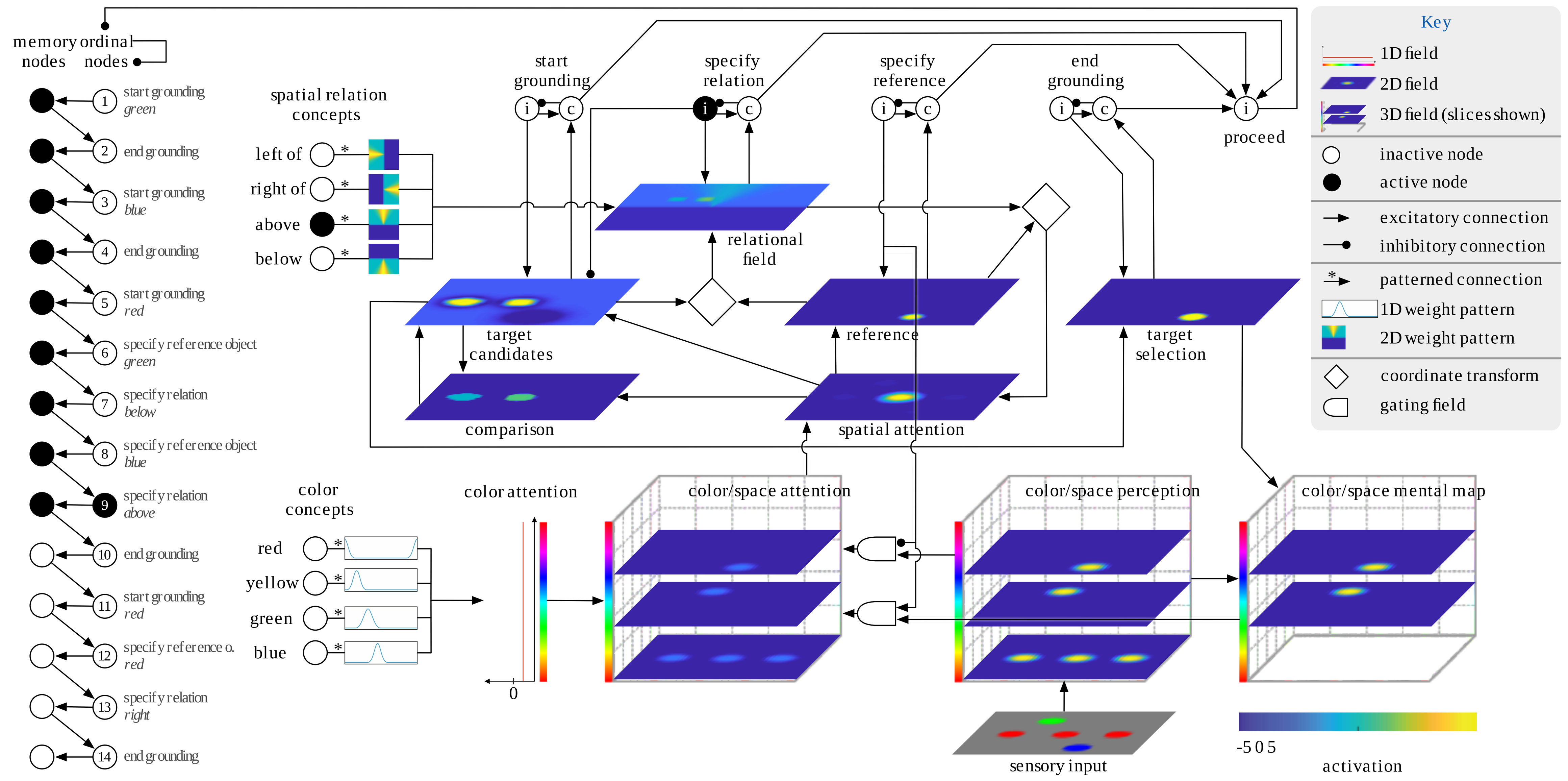
Our account is based on neural principles formalized in dynamic field theory [6]. Multi-dimensional dynamic activation fields represent metric feature dimensions and are driven by input from the sensory surfaces and by strong recurrent interaction:

$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t) + \int g(u(x',t))\, k(x-x')\, dx'$$

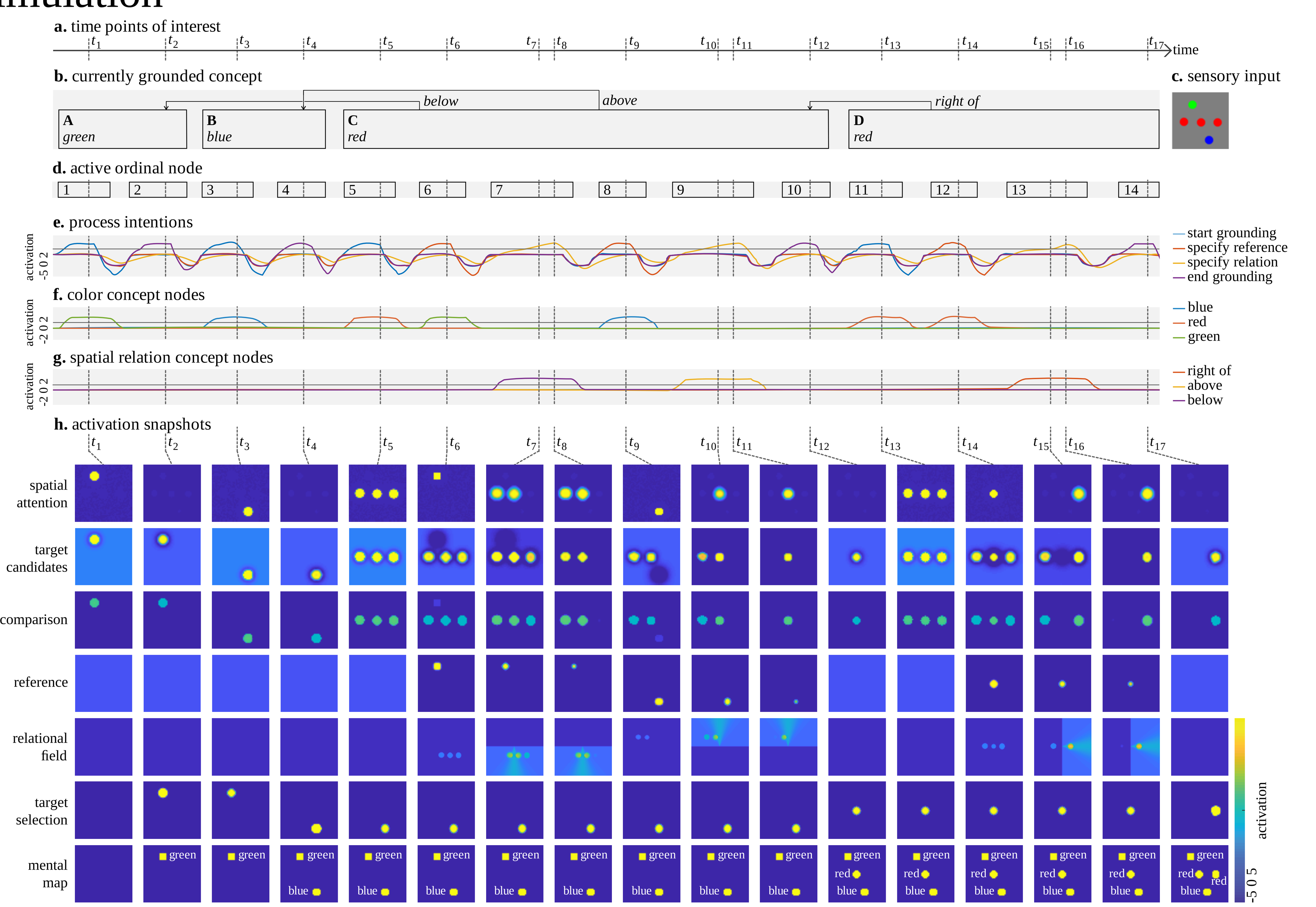


Dynamic activation nodes represent atomic concepts. Their coupling to feature fields enables perceptual grounding of atomic concepts through activation patterns that effectively link an activated atomic concept to an object in the perceptual array [5].

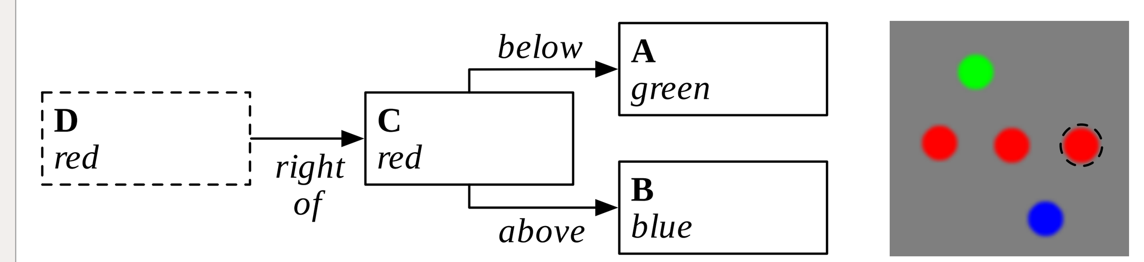
Architecture



Simulation



Combinatorial concept example



Left: Example for a combinatorial concept that can be described by the linguistic phrase "a red object, which is to the right of a red object that is below a green object and above a blue object". Each rectangle specifies an object, and the target object is surrounded by a dashed line. Right: Exemplary sensory input. The grounded target object is surrounded by a dashed line.

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