A mathematical framework for flexible and efficient neural cognitive computation

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Overview

Cognitive computation ought to be fast, efficient and flexible, reusing the same neural mechanisms to operate on many different forms of information. In order to develop neural models for cognitive computation we need to develop neurally-plausible implementations of fundamental operations. If the operations can be applied across sensory modalities, this requires a common form of neural coding. Weber-Fechner scaling is a general representational motif that may be exploited by the brain not only in vision and audition, but also for efficient representations of time, space and numerosity. That is, for these variables, the brain appears to support functions \( f(x) \) by placing receptors at locations \( x_i \) such that \( x_i - x_{i-1} \propto x_i \). The existence of a common form of neural representation suggests the possibility of a common form of cognitive computation across information domains. Efficient Weber-Fechner representations of time, space and number can be constructed using the Laplace transform, which can be inverted using a neurally-plausible matrix operation. Access to the Laplace domain allows for a range of efficient computations that can be performed on Weber-Fechner scaled representations. For instance, translation of a function \( f(x) \) by an amount \( \delta \) to give \( f(x + \delta) \) can be readily accomplished in the Laplace domain. We have worked out a neurally-plausible mapping hypothesis between translation and hippocampal theta oscillations. Other operations, such as convolution and cross-correlation are extremely efficient in the Laplace domain, enabling the computation of addition and subtraction of neural representations. Implementation of neural circuits for these elemental computations would allow hybrid neural-symbolic architectures that exhibit properties such as compositionality and productivity.

References
