Spatiosemantic Lateral Connectivity of Primary Visual Cortex in Convolutional Neural Networks

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Introduction

Continually deepening CNNs obtains state-of-the-art results but sacrifices computational feasibility, and plausibility in goal-driven neuroscientific research. In contrast, the search for brain-inspired structural improvements adds no network parameters and naturally increases biological plausibility.

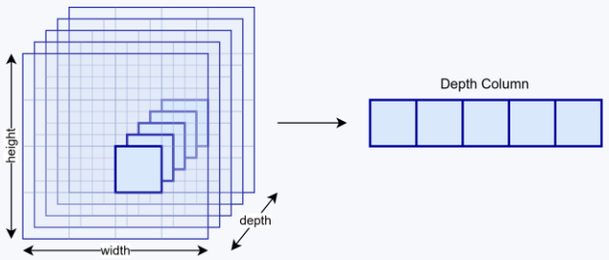
Our work emulates **three types of lateral connections** (LC) as found in primary visual cortex:

- **Spatial** connections to integrate and segment contours [1]
- **Semantic** connections facilitating orientation selectivity [2]
- **Complex** cells carrying phase-invariant representations [3]

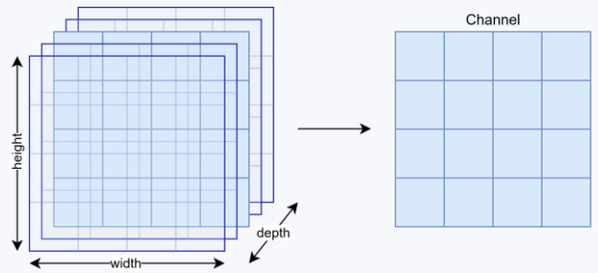
Model

We extend the first convolutional layer by biologically inspired wavelet transforms along both the spatial domain and the channel domains to simulate the former two. To avoid explicit recurrent connectivity, the linear dynamical system of neural activity is solved for its steady state.

Semantic connections are realized by 1D convolutions along the channel domain. The connectivity profile is a biologically inspired Mexican hat function.

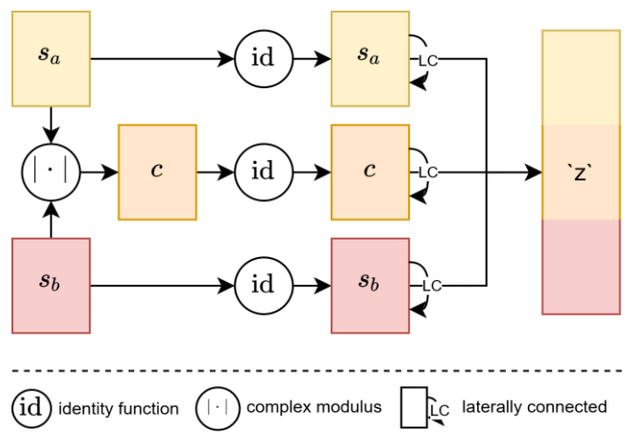


Spatial connections are 2D convolutions along the spatial domains, independent over channels. The channel-dependent connectivity profile is a biologically inspired composition of Gaussians balancing short-range suppression and long-range facilitation along a channel-specific axis of rotation.

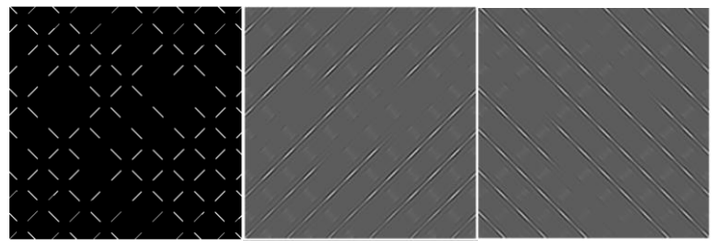


Complex cells are simulated by merging two independent cell populations through a pairwise complex modulus non-linearity.

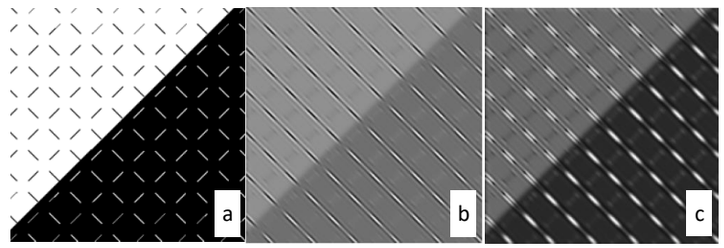
Full Layer Architecture



Results



Spatial lateral connections *give rise to the integration and segmentation of contours in a disconnected grating.*



Without **phase invariant complex cells** (b)*, spatial lateral connections cannot integrate contours with differently phased segments. Adding the former (c) however enables the latter to link them.*

	Objects	Textures
Vanilla	82.37	86.37
Vanilla + Spatial LC	85.23	89.49
Vanilla + Spatiosemantic LC	84.37	89.59
Complex	87.29	89.78
Complex + Spatial LC	87.05	91.00
Complex + Spatiosemantic LC	86.87	90.49

Classification accuracy of a shallow convolutional neural network can be increased by spatial and spatiosemantic lateral connectivity and complex cell convolution.

Conclusion

The proposed model of lateral connectivity
- is a single non-parametric feedforward operation
- significantly improves small-scale networks
- fosters the biological plausibility of CNNs

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References

[1] Kang, K., Shelley, M., Sompolinsky, H.: Mexican hats and pinwheels in visual cortex. PNAS 100(5), 2848 - 2853 (2003)
[2] Lorenceau, J., Giersch, A., Series, P.: Dynamic competition between contour integration and contour segmentation probed with moving stimuli. Vision Research 45(1), 103 - 116 (2005)
[3] Hubel, D.H., Wiesel, T.N.: Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. The Journal of Physiology 160(1), 106 - 154 (1962)