The virtual rat: Building a computational model of the rodent whisker trigeminal system

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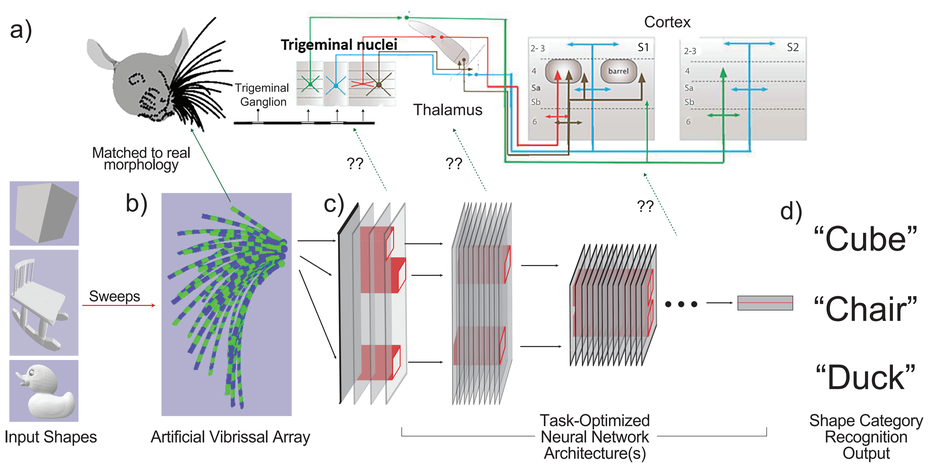
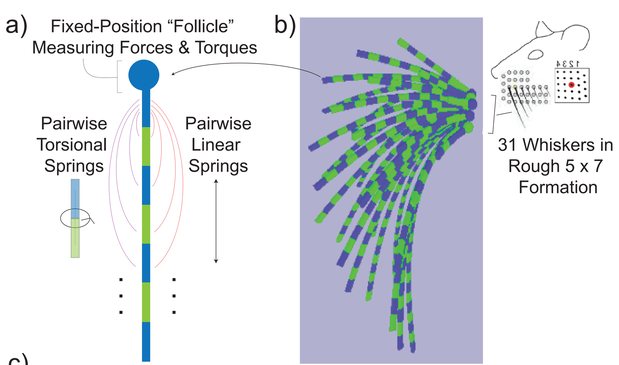
Introduction

In large part, rodents "see" the world through their whiskers, a powerful tactile sense enabled by a series of brain areas that form the whisker-trigeminal system. Despite extensive experimental investigations, the computational operations of this system remain largely unknown. In the present work, we take a goal-driven deep neural network (DNN) approach to modeling these computations. After constructing a biophysically-realistic whisker array model and then generating a dataset of whisker sweeps across 3D objects, we train DNNs from several distinct architectural families for shape recognition, where each architectural family represents different hypothesis for information processing. With most networks performing poorly, we find that specific architectures from several families can achieve reasonable performance levels. Finally, we show that Representational Dissimilarity Matrices (RDMs) can separate these higherperforming networks.

Goal-Driven DNN Modeling Approach



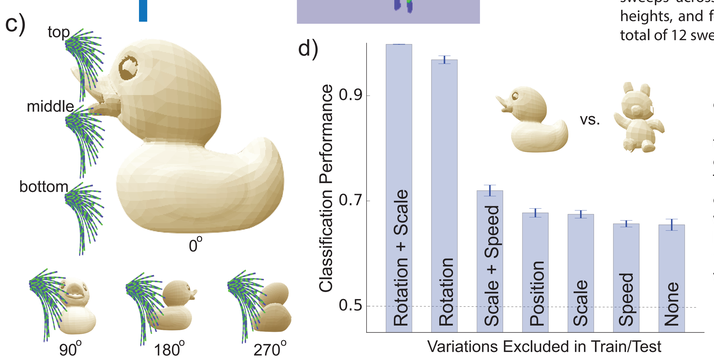
3D Kinematic Whisker Model & Dataset



a) Each whisker element is composed of a set of cuboid links. The number of cuboid links and spring equilibrium displacements are chosen to match known whisker length and curvature [1], while damping and spring stiffness parameters are chosen to ensure mechanically plausible whisker motion trajectories.

b) We constructed a 31-whisker array, arranged in a rough 5x7 grid (with 4 missing elements) on an ellipsoid representing the rodent's mystacial pad. Whisker number and placement was matched to the known anatomy of the rat [1]

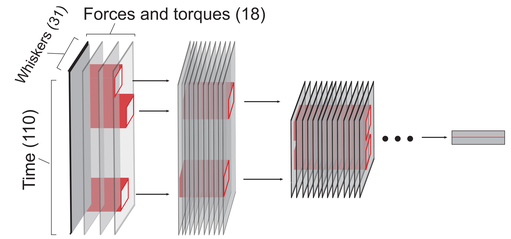
c) During dataset construction, the array sweeps across each object at three vertical heights, and four 90°-separated angles, for a total of 12 sweeps.



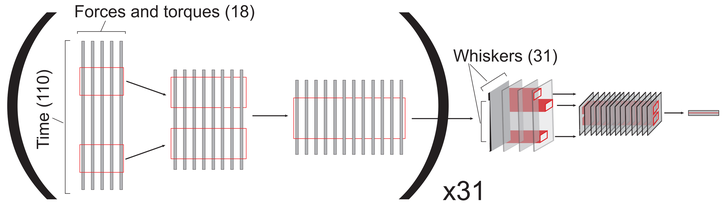
d) Basic validation of performance of binary linear classifier trained on raw sensor output to distinguish between two shapes. The classifier was trained/tested on several equal-sized datasets in which variation on one or more latent variable axes has been suppressed. "None" indicates that all variations are present.

Network Architecture Families

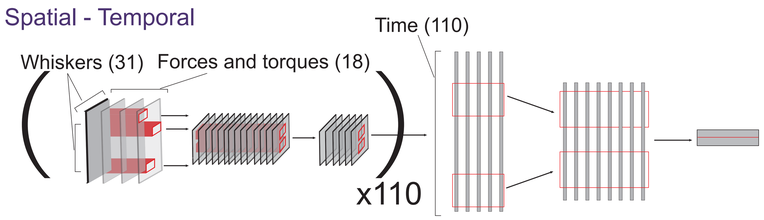
Spatiotemporal



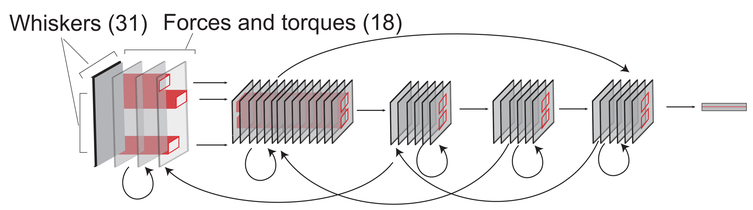
Temporal - Spatial

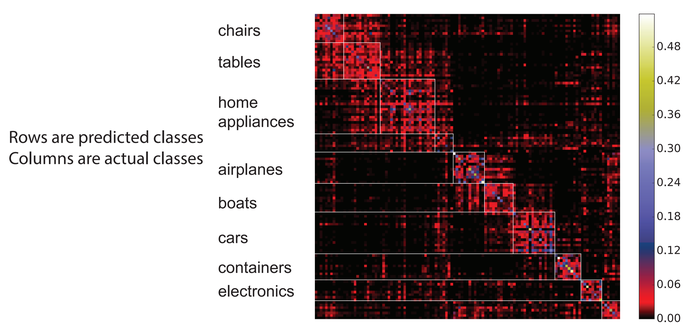


Spatial - Temporal



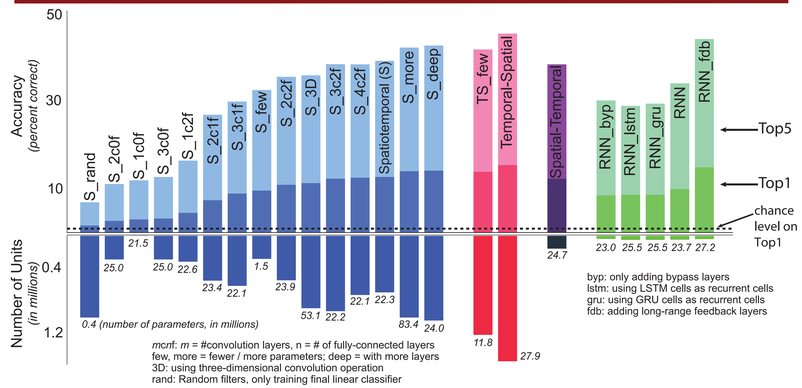
Recurrent Skip/Feedback





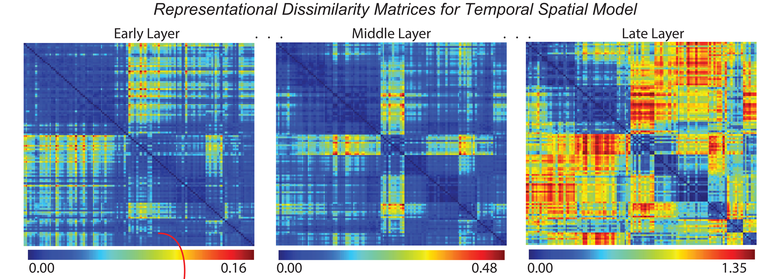
Confusion matrix of Temporal-Spatial model

Task Performance Results



Representational Similarity Analysis

Representational Dissimilarity Matrices for Temporal Spatial Model



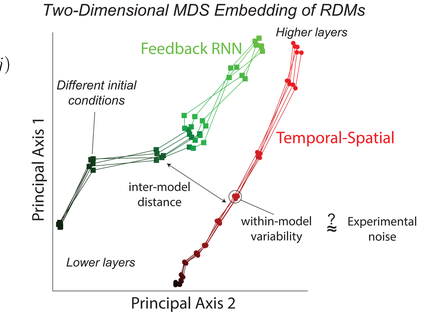
$$\mathbf{R}\text{epresentational}\mathbf{D}\text{issimilarity}\mathbf{M}\text{atrix}(i,j)$$

$$= 1 - corr(r_i, r_j)$$

$$= 1 - \frac{cov(r_i, r_j)}{\sqrt{var(r_i) \cdot var(r_j)}}$$

where r_i is the vector of resposes to stimulus i

Two-Dimensional MDS Embedding of RDMs



Conclusions

We have introduced a model of the rodent whisker array informed by biophysical data, and generated a large high-variability synthetic sweep dataset. We found that at higher variation levels deeper nonlinear neural networks are required to extract object identity. Furthermore, while many network architectures fail to solve the shape recognition task, reasonable performance levels can be obtained for specific architectures within network structural family tested. We then showed that a population-level measurement experimentally obtainable can distinguish between these higher-performing networks. Our results are a proof-of-concept that DNN models of the whisker-trigeminal system are potentially within reach.

Refs:
[1] R. Blythe Towal, Brian W. Quist, Venkatesh Gopal, Joseph H. Solomon, and Mitra J Z Hartmann. The morphology of the rat vibrissal array: A model for quantifying spatiotemporal patterns of whisker-object contact. PLoS Computational Biology, 7(4), 2011.
[2] Daniel L K Yamins, Ha Hong, Charles F Cadieu, Ethan a Solomon, Darren Seibert, and James J DiCarlo. Performance-optimized hierarchical models predict neural responses in higher visual cortex. Proceedings of the National Academy of Sciences of the United States of America, 111(23):8619–24, jun 2014.
[3] Nikolaus Kriegeskorte, Marieke Mur, and Peter a. Bandettini. Representational similarity analysis - connecting the branches of systems neuroscience. Frontiers in systems neuroscience, 2(November):4, 2008.

Acknowledgements

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