Hierarchical processing of simple shapes and natural movies in rat visual cortex

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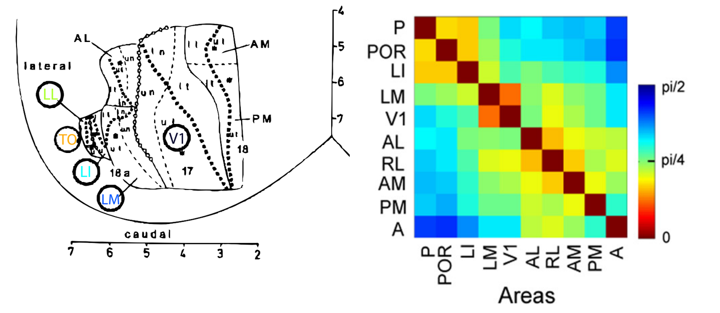
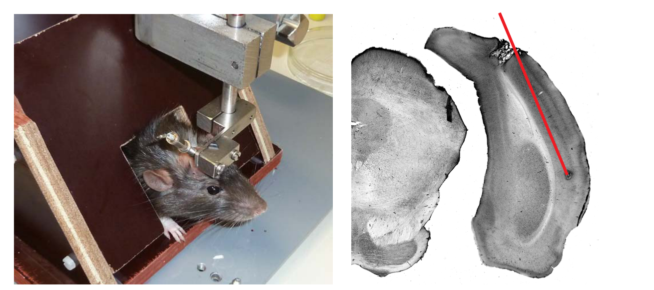
Introduction

- Earlier studies have established the hierarchical organization of multiple areas surrounding V1 in rats and mice [1].
- Recently, a functional connectivity between these regions has been described in mice in terms of vertral and dorsal streams [2].
- Possibly, this hierarchical organization is capable of extracting increasingly complex visual information, reminiscent of the ventral visual stream in primates.

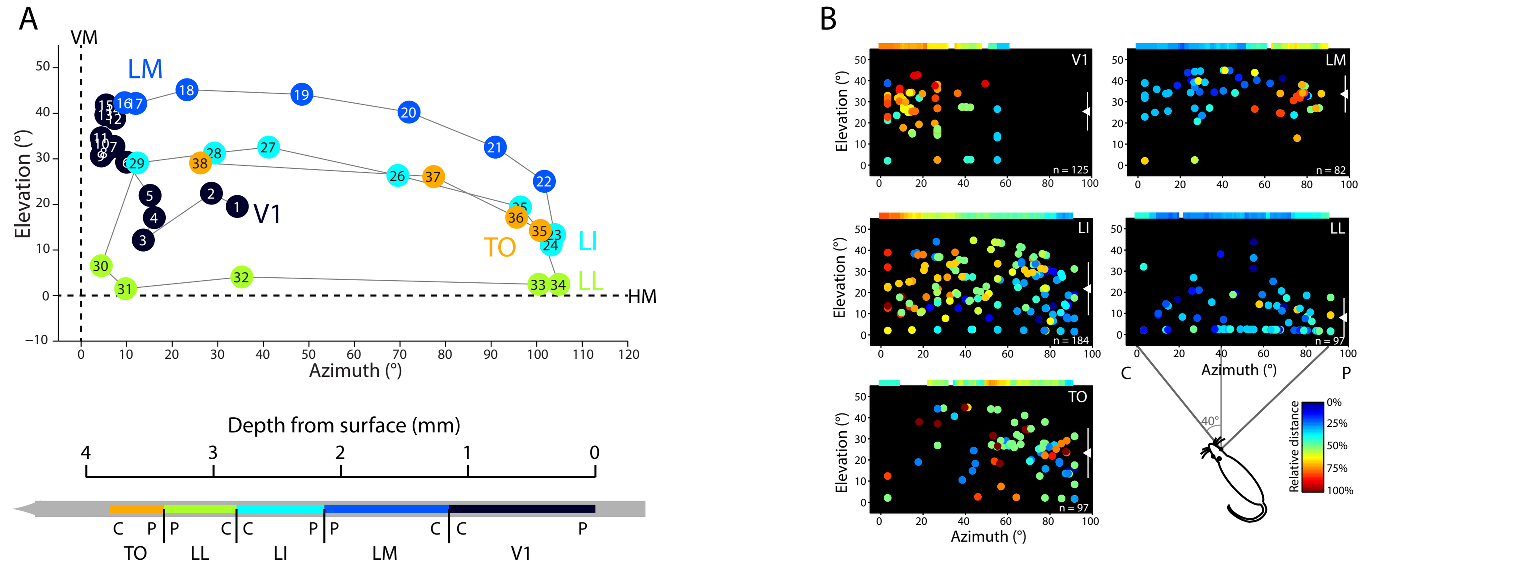




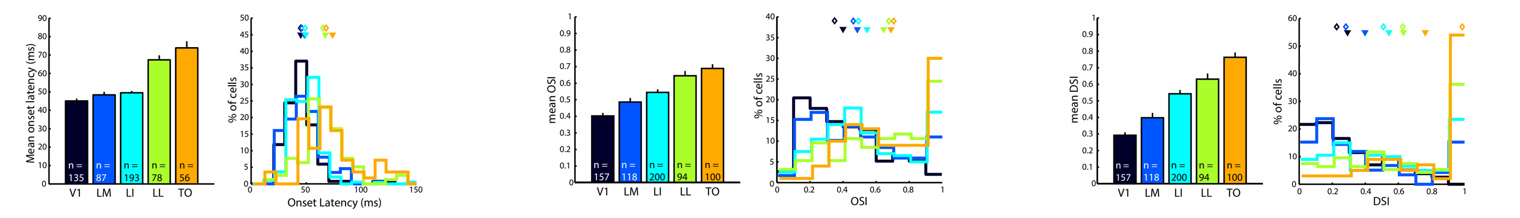
Methods

- We designed a study in rats that targets two hallmarks of the hierarchical object vision pathway in primates: higher tolerance for image transformations and selectivity for behaviorally relevant dimensions.
- We investigated a progression of five visual areas from primary visual cortex (V1) over areas LM, LI, LL, up to newly-found lateral occipito-temporal cortex (TO).
- By advancing the electrode under an angle relative to cortex, we were able to successively record from five areas in single animals.
- Based on traditional properties of the neurons, we defined area membership of each neuron.
- We carried out further analysis on the populations responses to a series simple geometric shapes using pattern classifiers.

Retinotopy

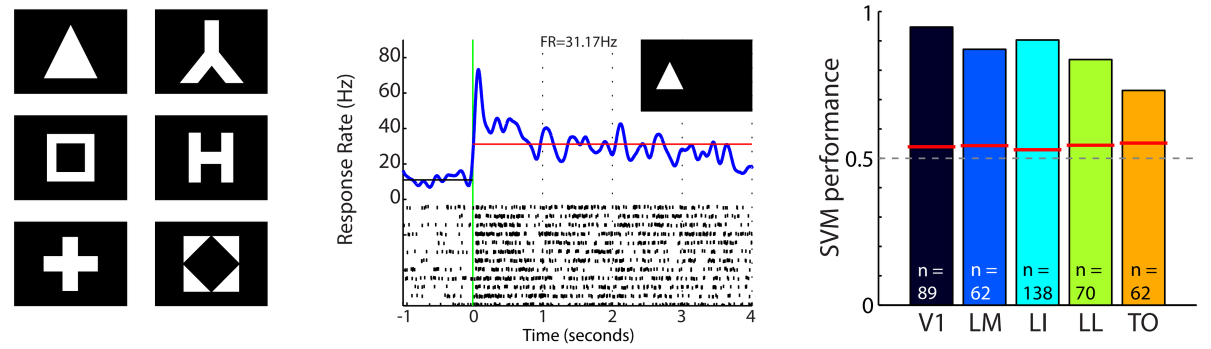


Response Latency / Orientation Selectivity (OSI) / Direction Selectivity (DSI)

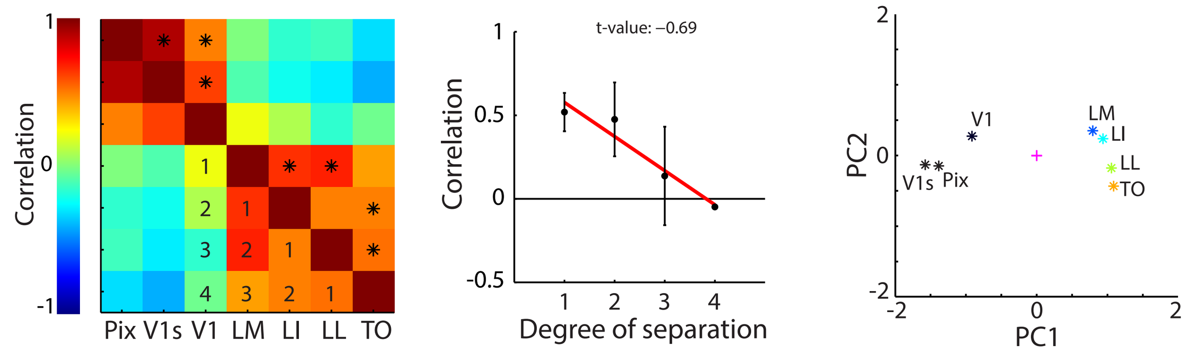


Shape Selectivity

Responses for 6 translating geometric shapes were recorded and used for population analysis. We trained pattern classifiers (SVM) to distinguish between response vectors belonging to 1 of 2 shapes. The average SVM performance over 15 shape pairs for 5 areas is show in the right panel.

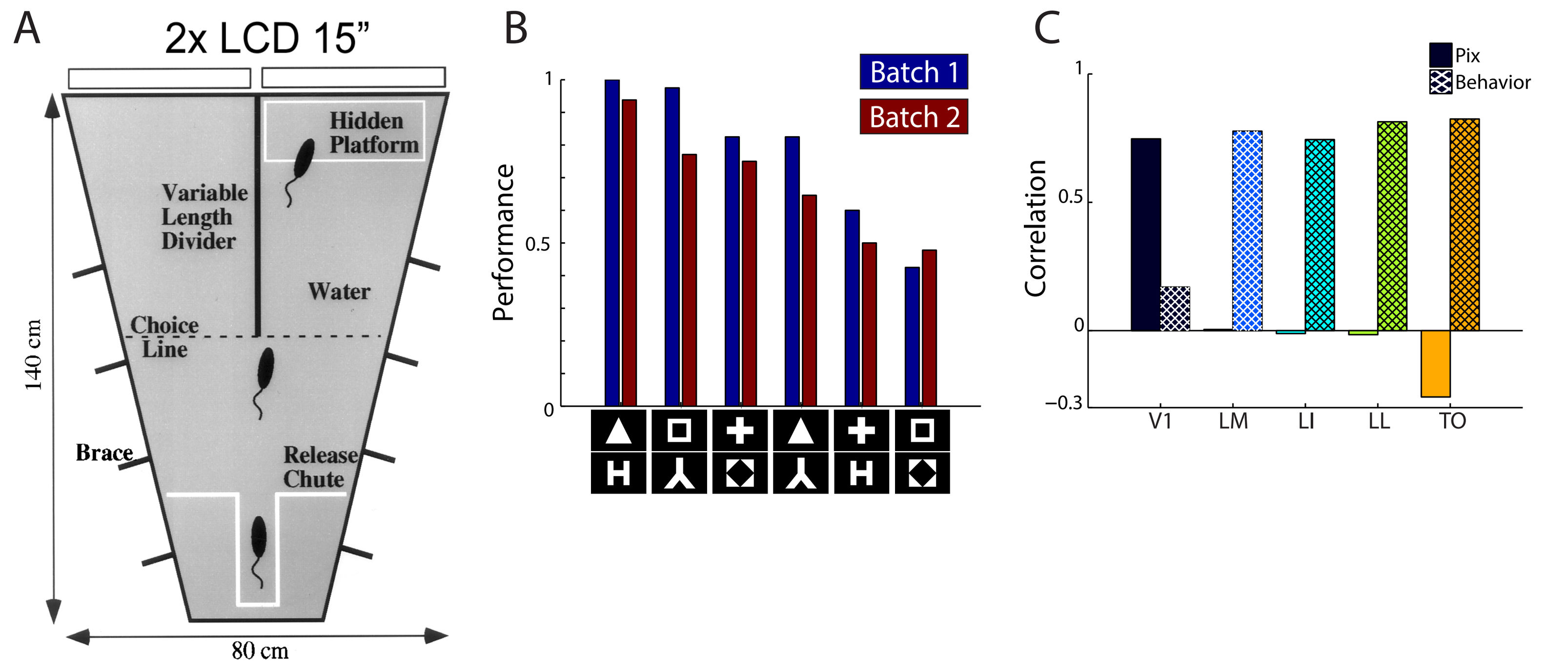


The correlation between performances on these 15 pairs is shown in the left panel and indicates that the representation of shapes changes gradually over areas. The middle panel below shows that areas that are spatially closer, correlate better. In the right panel, we show the first 2 principle components of the correlation matrix shown above. Both analyses are indicative of a gradual transformation of the information as it is passed on through the hierarchy.



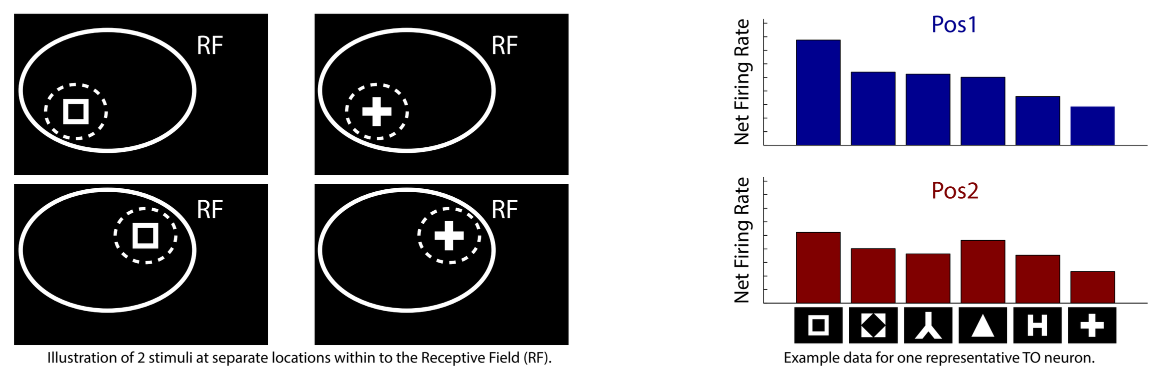
Selectivity correlates with behavior

We used a visual water maze [3] (see panel A). By trial-and-error the rat learned stimuli that predict platform location. Two batches of 6 rats performed 2 sessions of 12 trials each day. Each animal was trained to discriminate 1 of 6 shape pairs (out of possible 15). We hypothesized and confirmed (see panel B) that these pairs differed enough in difficulty to pick up correlations. Higher areas correlated best with behavioral performance, while V1 correlated most with pixel-based similarity measures (euclidean distance and simulated V1 response; see panel C).

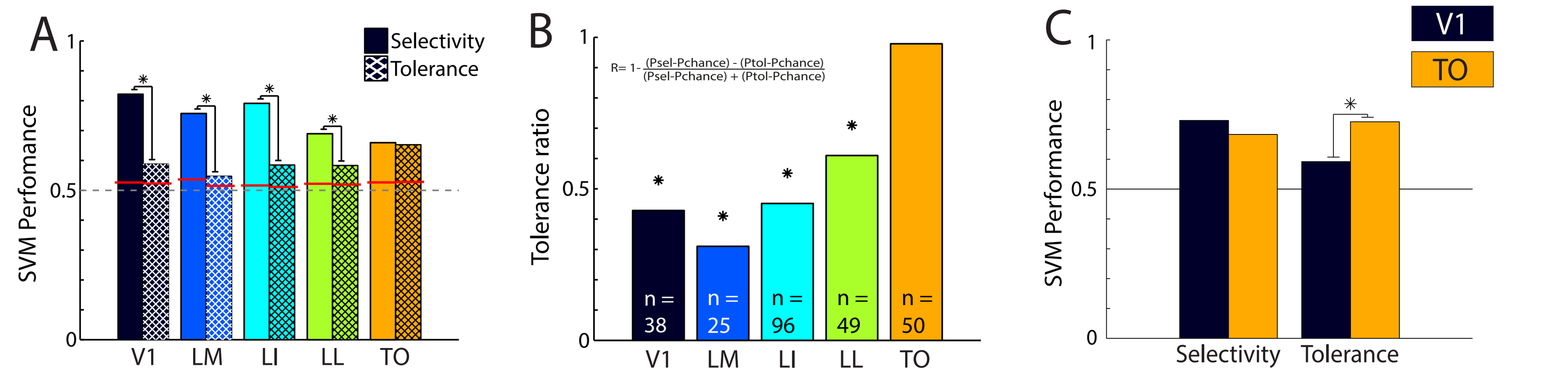


Position Tolerance

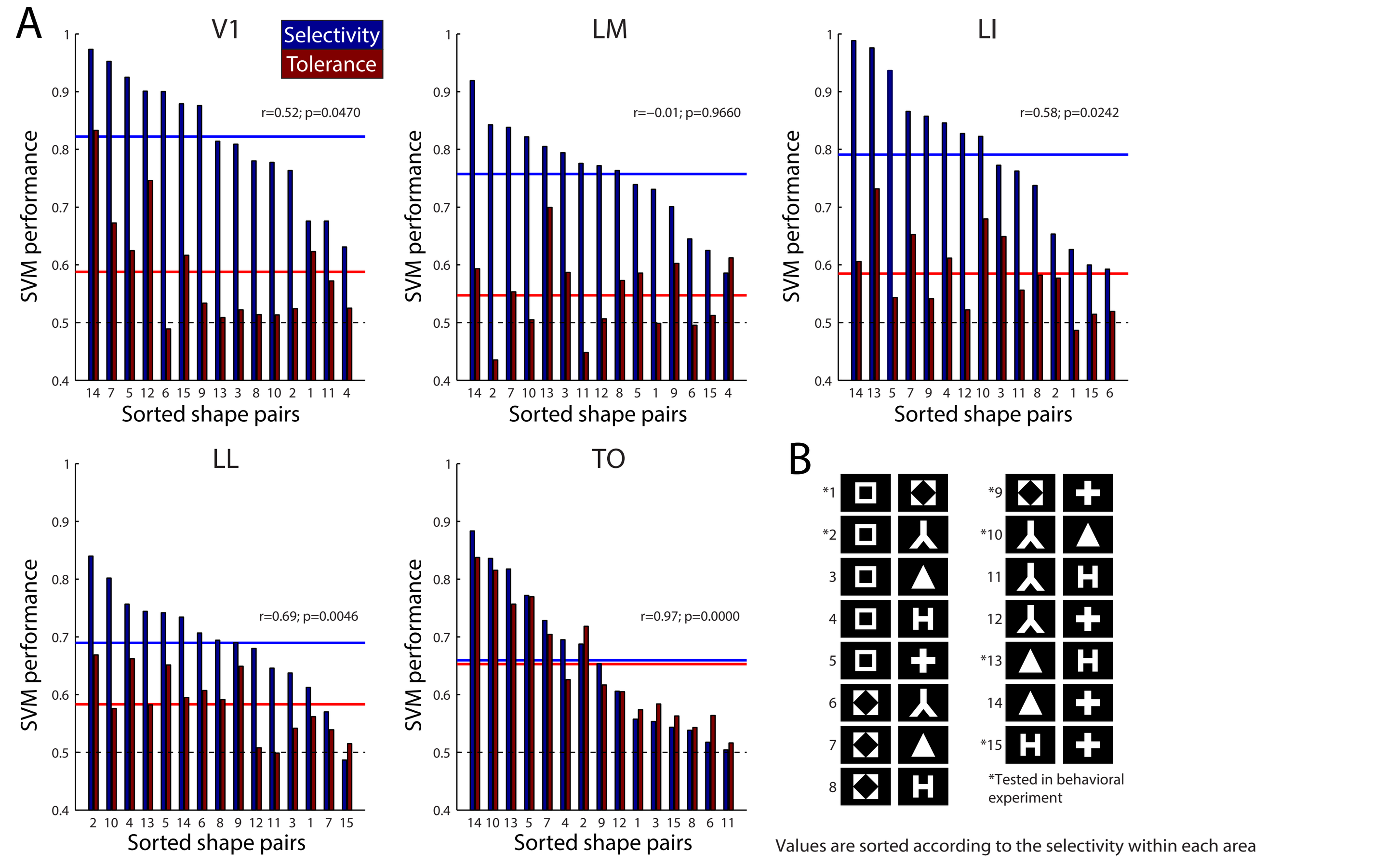
We sequentially presented 6 shapes at two non-overlapping positions within the receptive field of single neurons.



The response to the same stimulus at two different positions was compared, revealing higher tolerance (train Pos1, test generalization at Pos2) relative to selectivity (train/test at same position) (see panels A&B) in higher areas. For sub-populations with matching selectivity, tolerance was significantly higher in area TO (panel C).

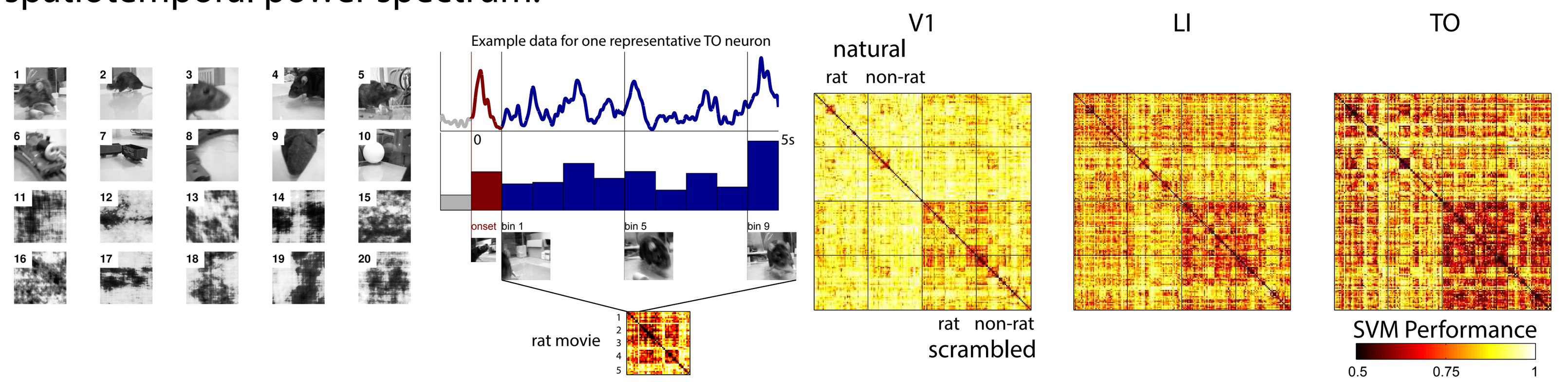


We looked at the correlation in SVM performance between selectivity (panel A, blue bars) and tolerance (red bars) per shape pair (all pairs are shown in panel B). These correlations increase with area. In TO, neural responses at both positions are indistinguishable, reflecting the maximal generalization performance. These properties might underly earlier behavioral work [4] showing position-tolerant object recognition capabilities in rats.

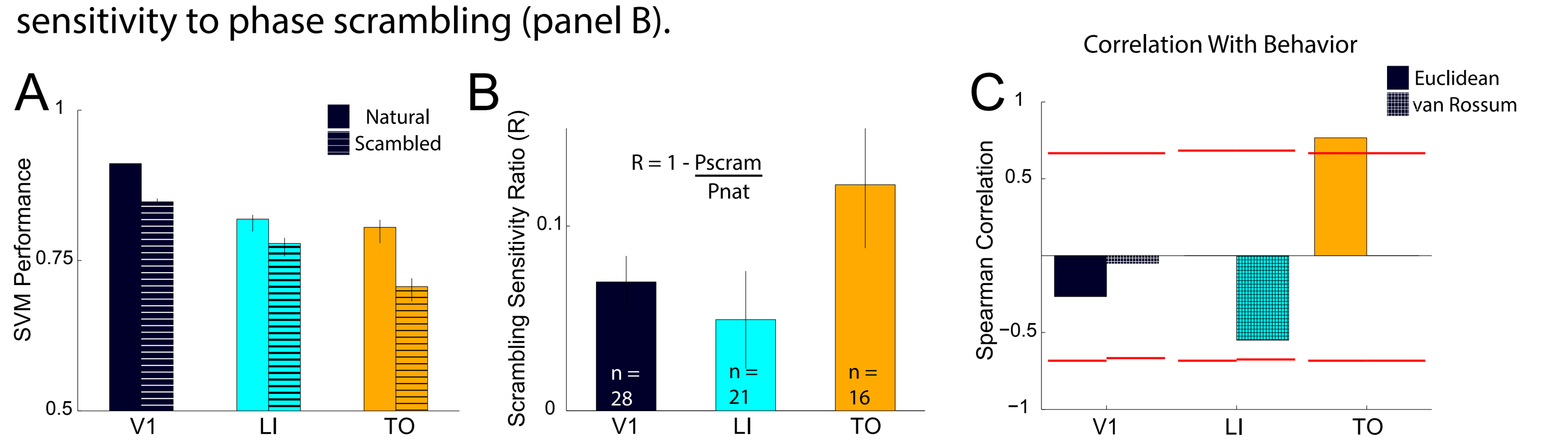


Natural Movies

We sequentially presented 10 natural movies and 10 scrambled movies derived from the intact stimuli by randomizing the spatial phase spectrum and preserving contrast, luminance and spatiotemporal power spectrum.



Responses of single units where recorded in areas V1, LI and TO and divided in 500 ms bins. Pair-wise population discriminability of response bins (excluding the first bin) was estimated by applying SVM. The resulting discriminability matrices for each area are depicted above. We assessed whether the difference in discriminability of natural versus that of scrambled stimuli changed over the areas under investigation. Specifically, we found that unlike with the shape stimuli or scrambled movies, selectivity for natural movies did not drop significantly going from LI to TO (panel A, hatched bars indicate scrambled stimuli), resulting in a significant increase in sensitivity to phase scrambling (panel B).



In addition, we trained 5 rats to discriminate 9 pairs of movies. Performance correlated significantly with Euclidean distance between spike-rate population vectors in TO (calculated over the full 5 sconds of the stimulus; panel C). No significant correlation was observed when a spike train metric incorporating information of spike timing (van Rossum distance) was used; red lines indicate 95% significance thresholds based on 10K permutations.

Conclusions

1) Functional characterization of a 'what' pathway in rat visual cortex
2) Gradual transformation of population shape selectivity over areas; related to behavioral discrimination performance
3) Increasing position tolerance of population response
4) Increased selectivity for a complex conjunction of natural features

References

[1] Espinoza, S. G., & Thomas, H. C. (1983). Retinotopic organization of striate and extrastriate visual cortex in the hooded rat. Brain Res, 272(1), 137-44
[2] Wang, Q., Sporns, O., & Burkhalter, A. (2012). Network analysis of corticocortical connections reveals ventral and dorsal processing streams in mouse visual cortex. J Neurosci, 32(13), 4386-99
[3] Prusky, G. T., West, P. W., & Douglas, R. M. (2000). Behavioral assessment of visual acuity in mice and rats. Vision Res, 40(16), 2201-9
[4] Vermaercke, B., & Op de Beeck, H. P. (2012). A multivariate approach reveals the behavioral templates underlying visual discrimination in rats. Curr Biol, 22(1), 50-5