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The multidimensional perceptual space of local orientation signals

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Motivation and Overview

The orientation cues present in natural scenes are much richer than the orientation cues that are present in the simple grating and line stimuli typically used to study how orientation is processed. One aspect of this richness is that multiple orientations can occur at a single location. Another is that orientation cues can arise not only from positive correlations, but also from negative ones. A third is that the correlations that carry orientation information need not be limited to pairwise correlations: third- (and higher) order correlations can also be oriented.

To determine whether the human visual system makes use of this rich set of cues, and if so, how they interact, we constructed a set of visual stimuli (binary textures) in which each of these different kinds of cues can be introduced independently and in combinations. The results show that human observers make use of multiple kinds of orientation cues, and that they interact in a relatively simple fashion.

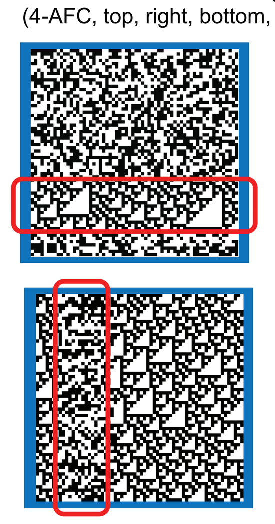
Methods

SUBJECTS
7 subjects
VA: 20/20, with correction if needed
Practice: approx 1600 trials

CONDITIONS
8 repeats of 20 on-axis points
16 repeats of 8 off-axis points
288 trials per block, random order
15 blocks = 4320 trials per plane
Feedback during practice only

STIMULI
Pixel Size: 14 min
Display Size: 14.8 deg^2
Binocular viewing at 1m
Contrast: 1.0
Duration: 120 ms (followed by mask)
Target: 16 x 64 pixels on a 64 x 64 array
Trials either have a structured target on a random background, or random target on structured background

TASK
Find the location of the target stripe
(4-AFC, top, right, bottom, left)

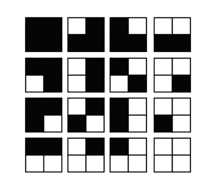


In this sample stimulus, the target stripe (defined by $\theta_{\lrcorner}$) is on the bottom on a random background.

Here, the target stripe (on the left) is random on a structured ($\theta_{\lrcorner}$) background.

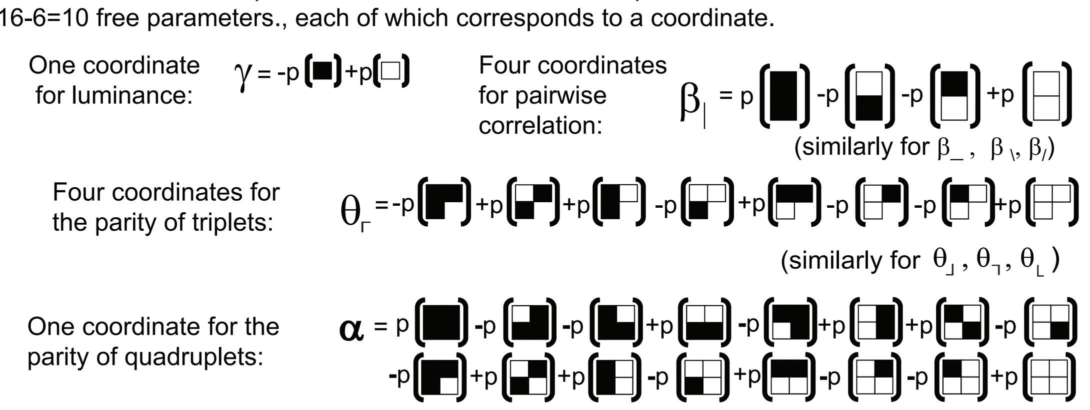
Thresholds were not significantly different for these two conditions and did not depend on target location.

Coordinates for a Local Binary Texture Space



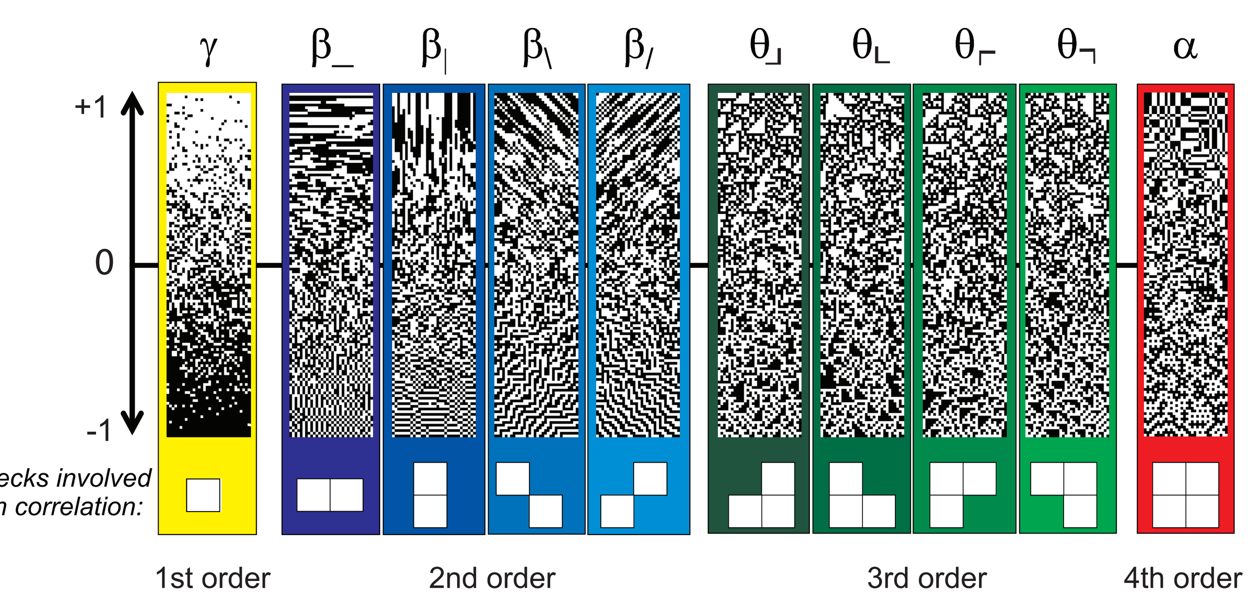
Textures are defined by the distribution of colorings of 2x2 blocks. There are 16 ($=2^{2x2}$) possible colorings (right). However, there are constraints among these probabilities because the probabilities of smaller blocks cannot depend on *where* they occur within the 2x2 block.

Since there are 6 independent linear constraints on 16 probabilities, there are 16-6=10 free parameters., each of which corresponds to a coordinate.

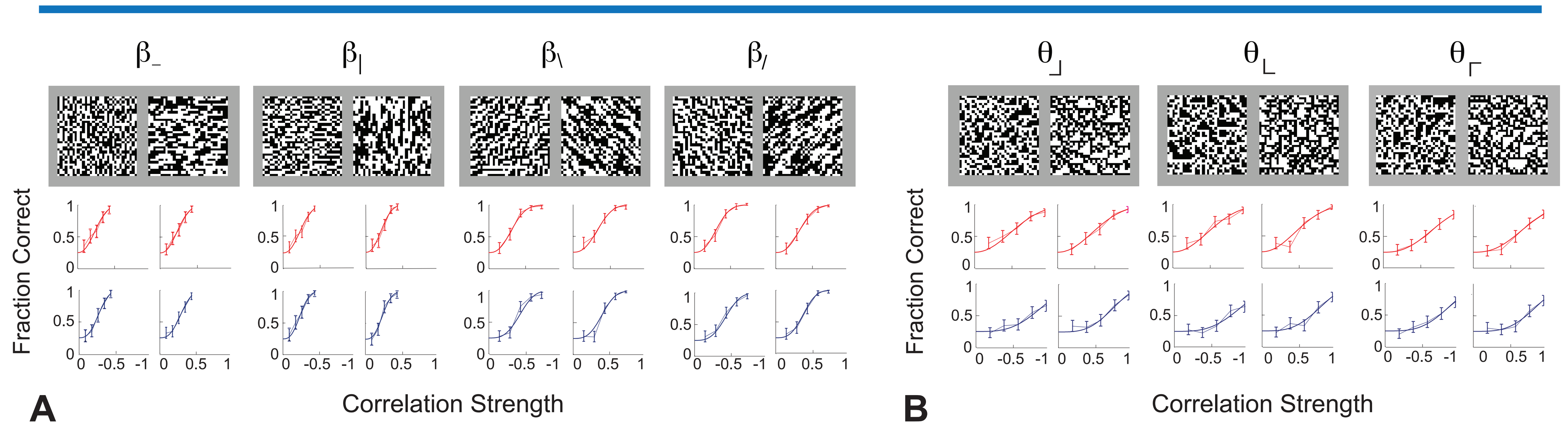


Coordinate Axes

The diagram on the right shows all 10 coordinates of the texture space. Of these, the four second-order coordinates (the betas) and the four third-order coordinates (the thetas) are potential carriers of orientation information. We focus on these.



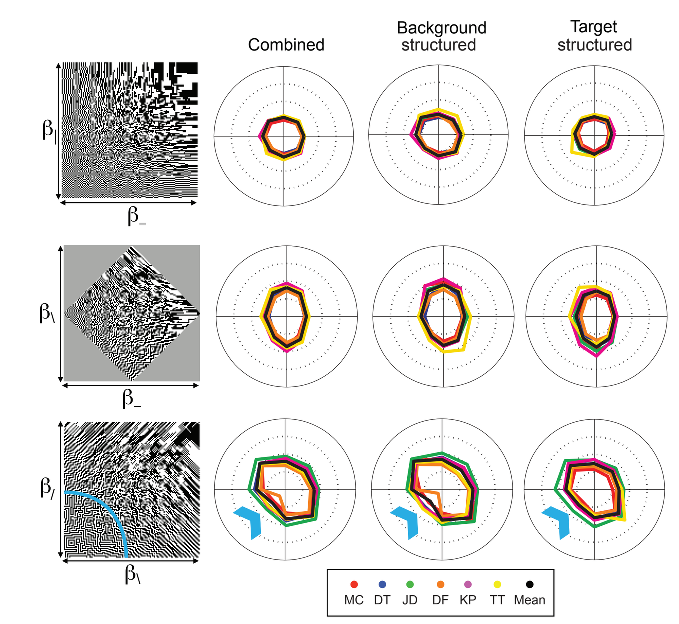
Each strip shows the textures generated by varying one coordinate across its entire range from -1 to +1. A coordinate value of 0 corresponds to a random texture.



Psychometric functions for individual image statistics that carry orientation information. A: Second-order statistics, B: Third-order statistics. For each statistic, psychometric functions are shown for negative values (left element of each pair) and positive values (right element of each pair). Chance performance is 0.25. Data from two representative subjects, MC (red) and DT (blue). N=6.

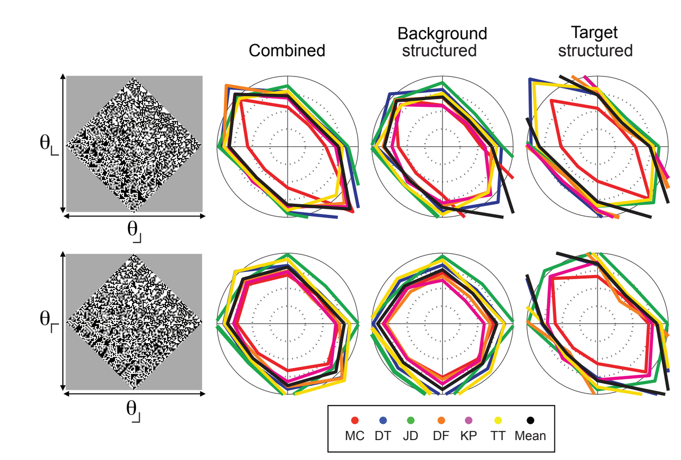
How pairs of orientation statistics interact

Pairs of second-order statistics



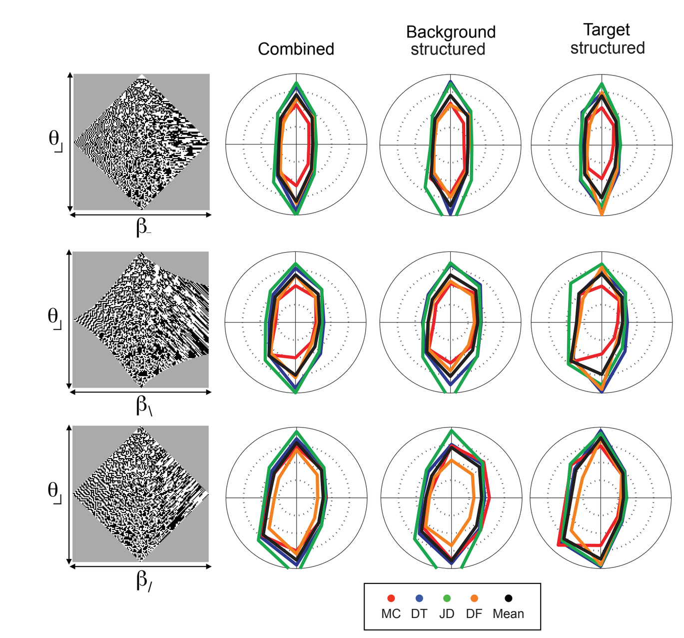
For pairs of second-order statistics, isodiscrimination contours are generally circular or elliptical, and there is little dependence on whether the background or the target was structured. Note the flattening for the $\beta_{\backslash}\,\beta_{/}$ -pair when both statistics are negative (blue arrow, lower row). This corresponds to the region of the gamut in which corners are present (light blue). N=6.

Pairs of third-order statistics



For pairs of third-order statistics, isodiscrimination contours are elliptical, but they are tilted with respect to the coordinate axes. This indicates partial cancellation between orientation signals in different directions, when they occur with opposite sign. Global organization matters: there is a dependence on whether the background was structured (second column) or the target was structured (third column). N=6.

Mixtures of second- and third-order statistics

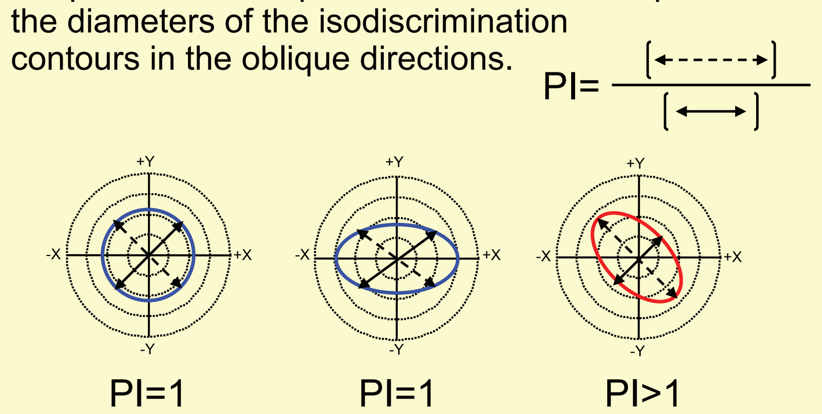


For mixtures of second- and third-order statistics, isodiscrimination contours are approximately elliptical, with the short axis along the β -axis and the long axis along the θ -axis. The axis ratio corresponds to the lower thresholds for β than for θ, and the near-vertical orientation of the ellipse indicates that there is little interaction between the statistics. There is also little dependence on whether the background or the target was structured. N=4.

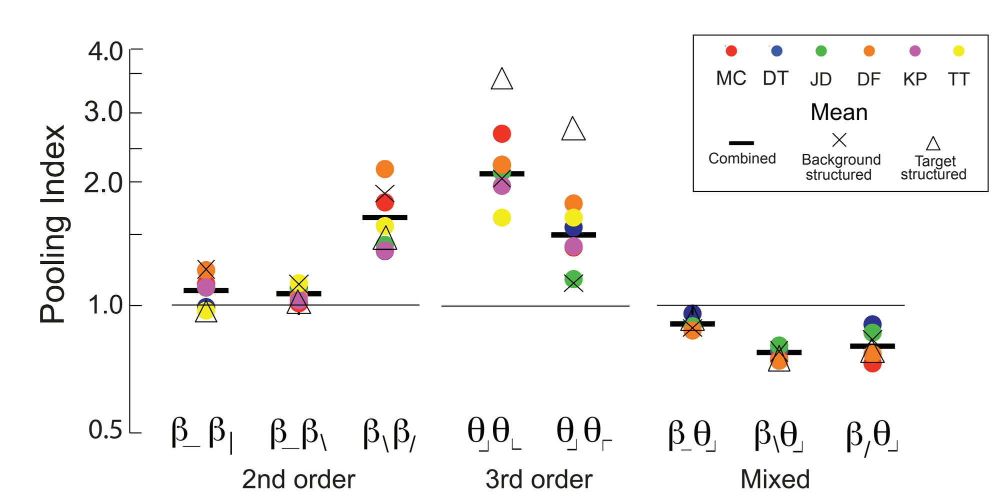
Isodiscrimination contours for pairs of orientation statistics. The image at the left of each row shows the gamut of images corresponding to each pair of statistics. The center of each gamut is the random texture (image statistics=0); ends of the axes correspond to maximal structure (image statistics of ± 1). Polar plots show the location in the gamut for criterion performance (fraction correct = 0.625). Colored traces correspond to individual subjects; the black trace is the harmonic mean across subjects.

Pooling Index

To quantify the extent to which two image statistics are processed in a pooled fashion, we compare the diameters of the isodiscrimination contours in the oblique directions.

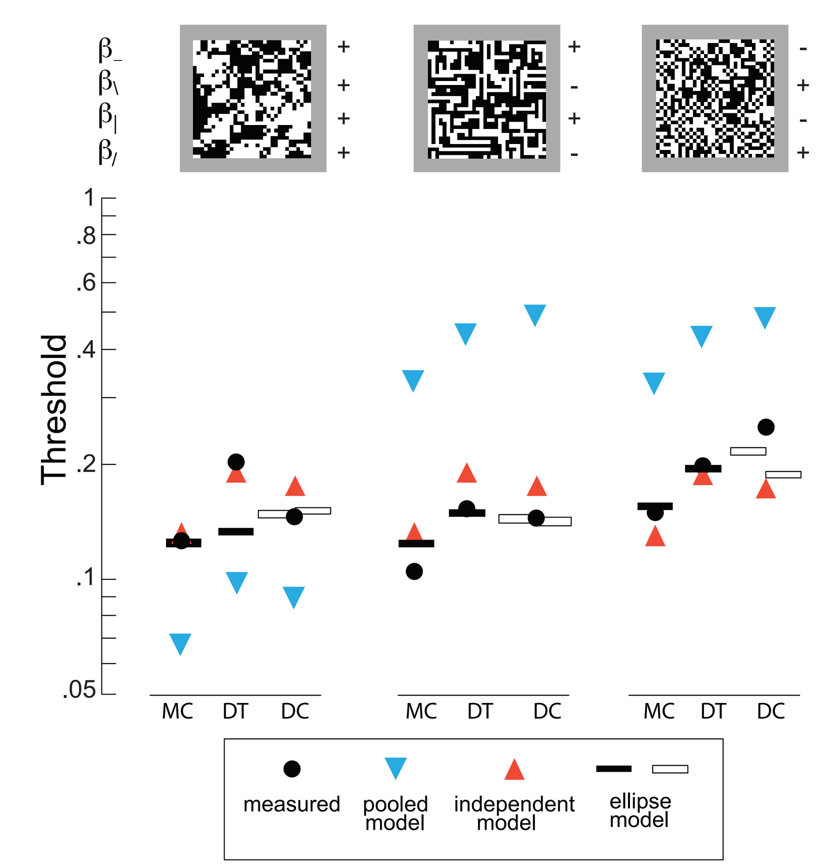


This ratio, the "pooling index", is 1 if image statistics are processed independently, and >1 if they are pooled.

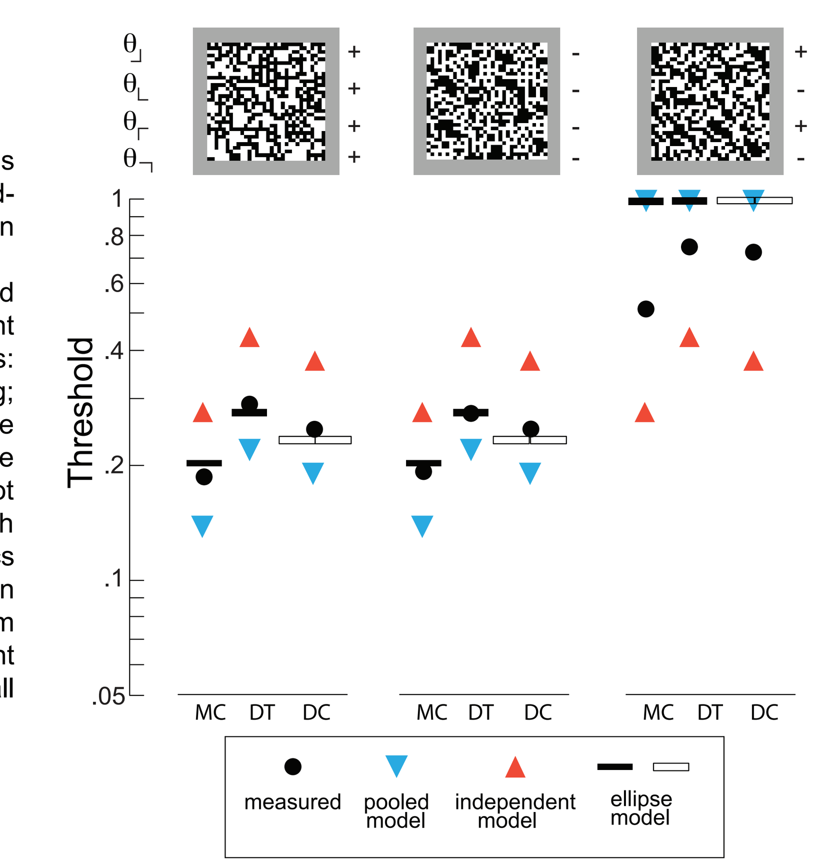


The pooling index describes how two image statistics interact. For the group means, the pooling index is calculated from all trials (solid bar), and for the subsets of trials separated according to whether the background was structured or the target was structured (X and △). Pooling indices are large for the third-order statistics, indicating that sensitivity to a positive correlation in one direction is reduced by the presence of a negative correlation in another direction. N=6 for pairings within order (second- or third-order), N=4 for pairings between orders.

Combinations of four image statistics



Thresholds for four-component mixtures of second-order statistics (left) and third-order statistics (right), and comparison with simple model predictions.
Circles: measured thresholds; upward triangle: prediction based on independent processing; downward triangles: prediction based on complete pooling; bars: predictions based on quadratic cue summation and the measured pairwise interactions. Since subject DC did not participate in experiments in which thresholds for pairs of image statistics were measured, the interaction parameters were determined either from subject MC (left open bar) or DT (right open bar). Example patches have all image statistics set to $\pm$ 0.225.



Summary and Conclusions

In addition to the standard orientation cues present in gratings (cues carried by pairwise correlations), third-order correlations also provide salient orientation cues. Both kinds of cues can occur at the same location, and with positive and negative signs.

Second- and third-order orientation cues are processed largely independently of each other, and the way that they are processed differs in two ways:

a. Pooling across orientations is more extensive for third-order cues than for second-order cues.

b. Dependence on global organization (i.e., whether signals arise in the foreground vs. the background) is characteristic of third-order but not second-order cues.

Superimposed on this picture, corners played a special role: when combinations of second-order orientation cues produced corners, these combinations provided a stronger signal for texture segregation than expected from their components.

Reference: Victor, J.D., and Conte, M.M. (2012) Local image statistics: maximum-entropy constructions and perceptual salience. *Journal of the Optical Society of America* A 29, 1313-1345.

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