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Dual representations of a visual perceptual space

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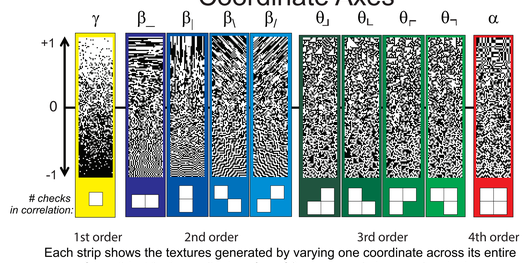
Motivation and Overview

A perceptual space is a representation of a sensory domain (e.g., color, faces, or image statistics) that serves as a substrate for discrimination, classification, and working memory. It is unclear how perceptual spaces are represented within biological constraints. The main challenge is that most perceptual spaces have high dimension. Consequently, representing each region of the perceptual space independently leads to a dimensional explosion: the resources required to represent a space grow exponentially with the number of dimensions. Two broad classes of strategies can surmount the dimensional explosion: representations via projections onto coordinates, and distributed representations. **Here, using the perceptual space of local image statistics as a model, we present psychophysical studies that imply that both of these strategies are used in parallel.**

Coordinate Axes



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.

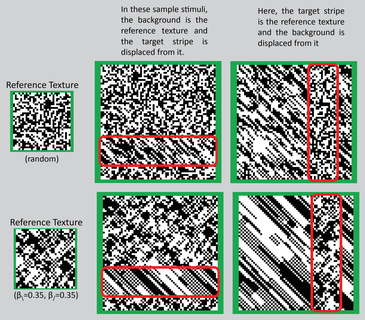
Methods - Threshold Segmentation Expt.

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

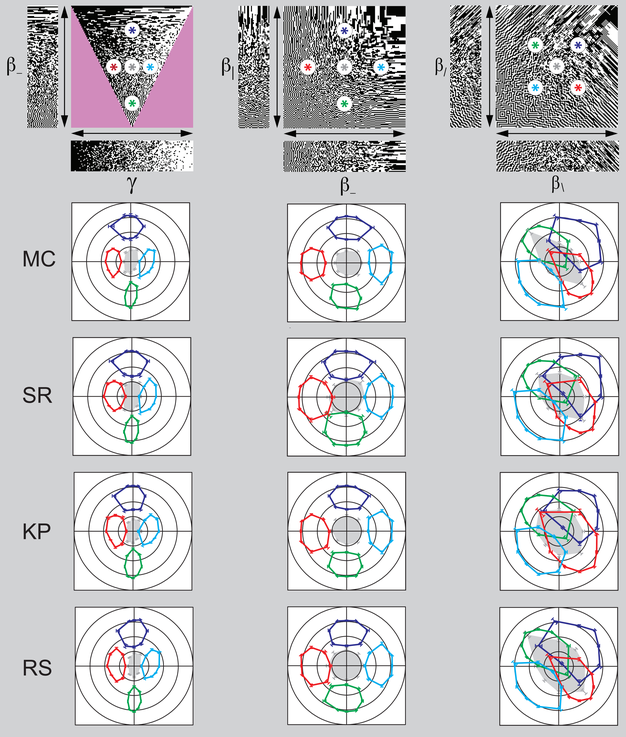
CONDITIONS
8 repeats of 20 on-axis points
16 repeats of 8 off-axis points
288 trials per block, random order
15 blocks = 4320 trials per plane
Feedback during practice only

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

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



Results - Isodiscrimination Contours



We used *isodiscrimination contours* to summarize threshold judgments. Gray contours, centered at the origin of the space, show thresholds for discriminating a structured texture from a random one. Colored contours, in the periphery of the space, show thresholds for discriminating one structured texture from a reference texture, as indicated by the markers in the stimulus planes above each column. **Thresholds in the periphery of the space are only slightly higher than thresholds at the origin, and the isodiscrimination contours have a similar orientation throughout the space.** Contours correspond to 62.5% correct, halfway between chance and perfect. Error bars indicate 95% confidence limits.

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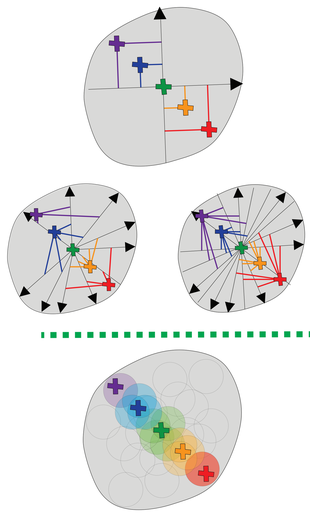
Summary and Conclusions

- We studied perceptual distances in a 10-dimensional space of local image statistics – a space large enough to make a brute-force representation implausible.
- One experiment determined perceptual distances between nearby points. Thresholds were close to uniform throughout the space; this is readily explained by a coordinate-based representation.
- A second experiment determined perceptual distances between distant points. Along some axes, distant points that were on opposite sides of the origin were perceived as similar. This is readily explained by a distributed representation whose resources are concentrated near the origin of the space.
- **Neither representation, alone, can account for both sets of findings. Thus, the experiments suggest two coexisting representations: a coordinate-based strategy that supports near-threshold judgments and a distributed one that supports suprathreshold judgments.**

References

Victor, J. D. & Conte, M. M. (2012). Local image statistics: maximum-entropy constructions and perceptual salience. J Opt Soc Am A 29, 1313-1345.
Victor, J. D., Thengone, D. J. & Conte, M. M. (2013). Perception of second- and third-order orientation signals and their interactions. J Vis 13, 1-21.

Models for the representation of perceptual space



Representation of a perceptual space via projection onto coordinate axes. Here, the perceptual distance between two points is determined by the difference in their coordinate values. This model cannot account for perceptual similarity between points that are at opposite ends of the space, since their coordinate values will be very different.

Alternative coordinate-based representations. Left: a representation via projections onto multiple coordinate axes, rather than just a minimal set of orthogonal axes. Right: A representation via projections onto rays, rather than axes that run in both directions from the origin. As with a standard coordinate representation (top), these models cannot account for perceptual similarity between points that are at opposite ends of the space.

A distributed representation, in which points in the space are represented by the pattern of activity across broadly-tuned coding units. The perceptual distance between two points is determined by the number of units that respond differently to them. If units are concentrated near the origin of the space, then perceptual distances between points in the periphery will be small.

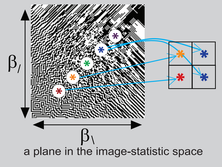
Methods - Border Salience Expt.

SUBJECTS
4 subjects
VA: 20/20, with correction if needed
Practice: approx. 50 trials

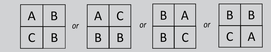
STIMULI
Pixel Size: 7 min
Display Size: 14.8 deg^2
Binocular viewing at 1 m
Contrast: 1.0
Duration: 120 ms (followed by mask)

CONDITIONS
5 points total along each direction
Stimuli constructed from three points, with one point repeated in each map
240 trials per block, random order
10 or 20 blocks = 2400 or 4800 trials per direction
6 directions tested

TASK
Find the most salient border.
(4-AFC, top, right, bottom, left)



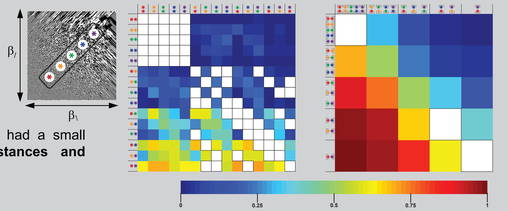
Construction of stimuli to determine perceptual distances in the ($\beta_\backslash$, $\beta_/$)-plane. Points along a line in image-statistic space (far left) specify the four quadrants of a stimulus (near left).



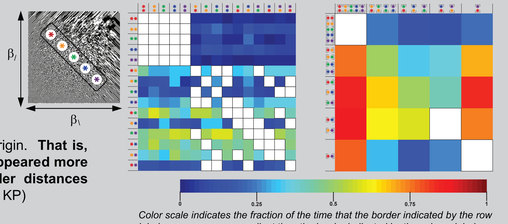
Each stimulus consists of four quadrants (left). The four quadrants contain samples of only three different points in the space, so every stimulus contains one "null" border, and three real borders.

The subject's task is to determine which of the four potential borders is the most salient. Because every stimulus contains one null border, we can use the extent to which the subject chooses the null border as the most salient as an internal control that the subject understands the task.

Border salience data on one diagonal (five points sampled) in the ($\beta_\backslash$, $\beta_/$)-plane. Near right, frequency that each kind of border is judged the most salient. Far right, border salience judgments grouped by veridical distances. Borders defined by pairs of points that had a large veridical distance were more salient than borders defined by a pair of points that had a small veridical distance. **That is, veridical distances and perceptual distances covaried. (**Subject: KP)

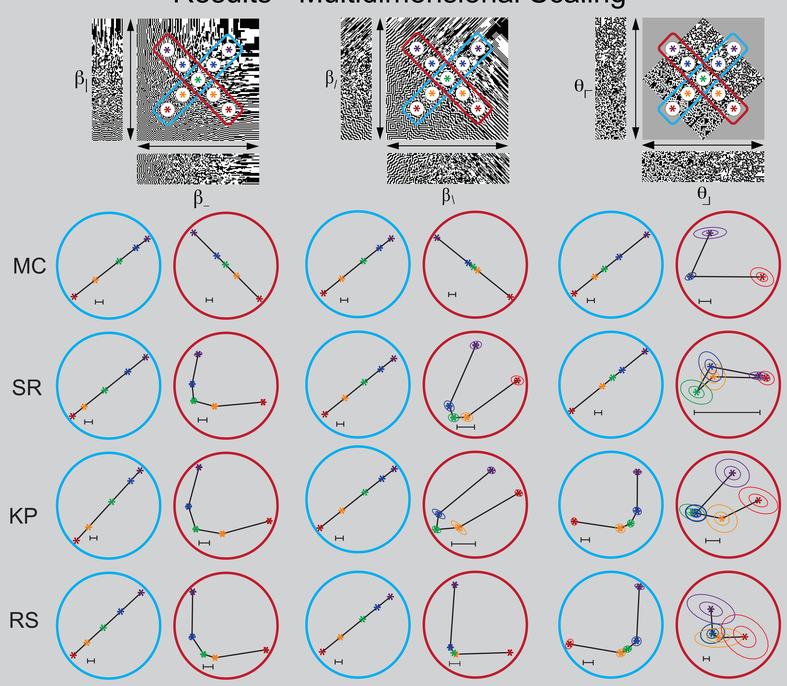


Border salience data on a second diagonal (five points) in the ($\beta_\backslash$, $\beta_/$)-plane. Near right, frequency that each kind of border is judged the most salient. Far right, border salience judgments grouped by veridical distances. Borders defined by pairs of points that had the largest veridical borders defined by pairs of distances were less salient than points that had a small veridical distance, and were near the origin. **That is, some points at opposite ends of the space appeared more similar to each other than points at smaller distances from each other, but near the origin. (**Subject: KP)



Color scale indicates the fraction of the time that the border indicated by the row label was seen as more salient than the border indicated by the column label.

Results - Multidimensional Scaling



We used *multidimensional scaling* to summarize suprathreshold judgments. Points corresponding to the five stimuli were positioned in the plane so that their pairwise distances best account for the border salience comparisons. In some directions, a straight line locus indicates a correspondence of the veridical and perceptual distances. **In other directions, consistent across subjects, the locus of points was strongly curved, corresponding to the perceptual similarity of points at opposite ends of the space.** Contour lines, when visible = 95% confidence limits. Scale bar = 0.1.