Cortical representations that support color-shape associations in macaque monkeys

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Humans use color and shape features to acquire different kinds of knowledge. Color might indicate object state while shape reveals object identity. Neurological cases together with functional imaging suggest that cortical representations of color and shape are somewhat separate, reflected as distinct color-biased regions (CBRs) and shape-biased regions in inferior temporal cortex. But the brain must connect color and shape because the meaning of color is shape dependent. To understand the neural basis of color-shape associations, quantitative data on stimuli likelihood, priors, and reward probabilities throughout life are needed, data largely unavailable in humans.

To address this, we deployed a learning paradigm in two juvenile macaques over four years. Monkeys learned about the colors and shapes of 14 colored objects using in-cage touchscreens. In each trial, a colored shape was presented, and liquid reward was provided for touching the matching color or shape. Subsequently, association trials were introduced: monkeys were cued with a shape or color and rewarded for touching the associated color or shape—this is analogous to tests of color-shape agnosia in humans. The monkeys achieved >90% accuracy on all trial types.

Three fMRI experiments were then conducted. A localizer identified CBRs and other category-selective regions of interest (ROIs). Second, a block-design experiment measured responses to blobs of shape-associated color, achromatic color-associated shapes, and other uncolored shapes. Third, a version of the association task assessed task-related activity and was used as input for decoding models. A whole-brain convolutional decoder achieved shape-identity decoding with 66% accuracy and cross-decoding of associated colors with 52% accuracy (chance 20%). Linear Support Vector Classifiers trained on color-associated-shape responses in each ROI showed greater cross-decodability of color in more anterior temporal regions (max. accuracy 39 +/- 3%, CI via bootstrapping), including perirhinal cortex and the temporal pole. Univariate analyses showed that the anterior CBRs responded to color-associated shapes and color-blobs over unassociated shapes, while V4 and posterior IT CBRs did not.

Overall, the results uncover a cortical network which engages category-selective regions, memory systems, and prefrontal cortex to represent learned color-shape-reward contingencies. The approach provides a data-driven method to understand the neural mechanisms supporting the behavioral objectives of vision.