Color categories in macaque monkey and their sources

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Categorization and memory are hallmarks of cognition, often studied with color, a controllable, continuous variable of behavioral relevance. One question has been the extent to which categorization and memory are impacted by language. The question has been challenging to answer, not only because all cultures have language, but also because sets of colors used to assess categorization and memory are defined by color spaces assumed to be perceptually uniform, an assumption known to be only approximate. Macaques, who have the same cone types and a similar cortical organization as humans but obviously lack language, provide an opportunity not only to assess these behaviors in the absence of language, but also to evaluate assumptions about the perceptual uniformity of color spaces.

Four macaque monkeys were tested in multiple weekly sessions over several years (~220,000 trials) in an alternative forced-choice color-matching task adapted from a study of humans in which systematic errors in color matches provide a metric of color categories (Bae et al., J Exp Psychol Gen, 2015). The macaques learned to perform the task at above chance levels within ~5000 trials and plateaued at ~85% accuracy (chance = 25%) for the easiest color discriminations within ~30,000 trials.

The data were fit with a mixture model where errors are a mixture of guessing and noisy memory. The analysis shows a common pattern of errors across the four animals, consistent with two color categories. These line up with human designations of warm (hue angle = 13° in CIELUV, SD = 17°) and cool (hue angle = 210° in CIELUV, SD = 13°). Some of the monkeys also showed additional idiosyncratic pattern of errors, stable over time, providing evidence of individual differences in color categorization.

We next asked about the underlying causes of the errors. One possibility is that they have a cognitive origin; another possibility is that they reflect unrecognized non-uniformities in the presumed uniform color space. These possibilities cannot be distinguished by a mixture model but we show they can be distinguished with a modification of the "target confusability competition model" (Schurgin et al., Nat Hum Behav, 2020). The analysis shows that the pattern of errors common to all four animals are best explained by a previously unrecognized non-uniformity in color space (delta-Akaike Information Criterion = 2x103), while the individual differences appear to have a cognitive origin. Finally, we used the monkeys’ behavioral results to estimate the non-uniformities, to reconstruct a color space that is perceptually uniform and uncontaminated by language.