While color categorization shows some stability across human languages, there is inter-language and inter-individual variability, pointing to a mixture of linguistic and innate drivers of color categorization behavior. (For example, many languages share a common set of ‘basic color terms’ English speakers and Berinmo speakers group colors into categories differently.) Color categorization behavior has been primarily assessed in humans using language-based tasks, so disentangling the contributions of language and innate color mechanisms to color categorization behavior is difficult.

Using a non-verbal task in assess color categories in macaques, we can assess the extent to which macaques and humans show similarities in their color categorization behavior. While humans and macaques have near-identical retinal and early cortical mechanisms to support color vision, macques don’t use language for color, suggesting that any differences in color categorization behavior between humans and monkeys must be the result of differences in color use between the two species.

Additionally, we use macaques as a model organism for understanding general concepts in neuroscience. We have a good understanding of their low level visual system (similar to human) but a poor understanding of their high level visual system (categories, associations, memory etc) and understanding the extent to which they use color categories will better enable us to use them as models for further work.

Obviously we can’t employ the standard language-based tests for color categories.To assess color categorization behavior, we used a non-verbal 4-Alternative Forced Choice task. We had four primates perform this task over the course of roughly 6 months. They initiated each trial by fixating on a small spot on a monitor. A colored disk (the cue) was presented at a parafoveal location. After a short pause, animals were shown 4 colored disks, and were rewarded for fixating on the one which matched the cue for that trial. Colors were 64 equally spaced hues, of equal saturation and luminance (CIELUV). We also ran an analogous experiment on Amazon Mechanical Turk with 72 participants, where they had to click the matching color.

Working memory research has shown that memories of colors are biased toward color category centers and away from color category boundaries. For example, we might remember a blue-ish green color as more blue than it really was. In continuous spaces where categorization occurs, we can think of category centers as attractor points and category boundaries as repellor points. This means that, in our task, when the participant selects an incorrect match, we expect their choice to be biased toward a category center and away from a category boundary. For each cue color, we can compute the average incorrect response and get a measure of the color’s “bias”.

When we plot bias as a function of cue color, attractor points, or category centers, are represented as points where the bias goes from positive to negative i.e. the average incorrect response is pulled toward this point, and repeller points, or category boundaries, are points where the bias goes from negative to positive, i.e. the average incorrect response is pushed away from this point.

We had a few hypotheses for how monkeys might categorize colors.

* First, they might not display any color categories. This would result in zero bias across all cues and no attractor or repellor points.
* Secondly, the monkeys might display human-like color categories -4
* Category centers might also align with the four unique hues or the DKL axes.

When pooled together, our data for our four monkeys showed two strong color categories.Our human data displayed four color categories, two of which were shared with the monkeys. We verified that our task is able to non-verbally pull out color categories by comparing our human data with data from two other papers in the working memory literature - you can see that the results here are comparable.

There is some individual variability in categorization across monkeys. Here we have the data from all of our individual monkeys, laid out in cartesian space so we can easily compare the locations of the categories. One of our monkeys had 4 categories, while the others all had two. You see that they all share a “warm” and “cool” category. The consistency of these two categories across monkeys and humans suggests that trichromatic primates innately categorize colors into these two categories, with additional categories reflecting differences in color use across species and cultures.

We designed our stimuli to have equal saturation, but depending on which colorspace you use, saturation can be defined in different ways. This concerned us, because we know that more saturated colors are more salient, at least to humans. Could it be that the biases we recover are just the results of inadvertent saturation differences between cues? If our monkeys were just selecting the most saturated colors, then on trials where there is a distractor of the same hue but different saturations, we would expect to see them reliably pick the higher saturation option. In our data we see a very minor bias for higher saturations, but it seems highly unlikely that this bias is strong enough to underlie the main results. This analysis is ongoing.

We also explored how learning rates varied for different colors in our paradigm by applying a reinforcement-learning framework that captures mechanisms of reward-based learning. Here we see the learning rates for each color plotted by in DKL color space. A fourier analysis of this data shows a harmonic aligned with the S-cone axis, suggesting that performance improved for colors along the S-cone axis faster than those along the L-M axis.