

SUPPLEMENTARY INFORMATION

doi:10.1038/nature14103

Supplemental discussion

Fisheye distortion arises as stimuli presented on a tangent screen are projected onto the hemispherical retina. This can cause variation in the apparent angular widths of bars or spots that are of fixed pixel size on the screen. As neurons are likely to have width and speed preferences, in addition to orientation preferences, it introduces a potential confound. Here we consider whether these distortion effects could be at the root of the observed patterns of orientation tuning. We performed extensive analyses and experiments that exclude this interpretation of our results, because (1) the patterns of orientation tuning do not match those expected from the distortion hypothesis; and (2) experiments with stimuli that undo the distortions reveal the same patterns of orientation tuning. In detail:

1a) The patterns of orientation tuning are inconsistent with the distortion patterns. We analyzed the calcium imaging data presented in figure 5 and described in the results ($n=4$ animals, 63 cells). In these experiments we mapped receptive fields for orientation-tuned neurons in precise coordinates on our stimulus monitor. The foot point of the monitor is the point closest to the eye, at which a line from the eye is perpendicular to the screen. Therefore, fisheye distortion for any pixel on the screen will be along the radial axis from that pixel to the FP. With knowledge of the location of the foot point (FP) on the stimulus monitor, we could then determine the radial orientation, i.e. the orientation of a line from the FP to a cell's RF center. The distortion hypothesis predicts a close concordance between the measured preferred orientations and this radial orientation. That is clearly not the case (Extended Data Figure 2). In fact, the relationship between preferred orientations and the radial orientation varies considerably: in two volumes the preferred orientations are biased away from the radial orientation. In one instance many cells on one side of a field do have preferred orientations similar to the radial orientation, but cells on the other side of the field do not (see below).

1b) The orientation tuning pattern includes sharp fractures. The calcium imaging experiments with single-cell resolution show that the orientation bias can shift by 90 degrees in a few tens of microns (e.g. Fig 2c, Extended Data Figure 2), corresponding to just a few degrees change in radial orientation. The distortion hypothesis would predict a gradual change in bias across the display. Moreover, the handedness of the progression we observed can be either in phase with the radial progression or out of phase (Extended Data Figure 2).

1c) The orientation tuning of single cells is strongly biased towards horizontal and vertical bars (Extended Data Figure 6). The distortion hypothesis would predict equal numbers of cells biased to the oblique directions, particularly given the receptive field locations for most of our cells with respect to the FP.

1d) Our results are robust to errors in estimating the location of the FP. To determine how the position of the foot point might vary with imprecision in our measurements, we performed simulations in which we varied any or all of our distance parameters by ± 2.5 cm and our angle measurements by ± 3 degrees. The putative FP locations that emerge

from this simulation are a narrow cloud clustered near our original measurement, in the lower left quadrant of the screen. We next asked whether our data might fit the fisheye model if one of these locations were the actual FP. We repeated the analyses from Extended Data Figure 2 to compare preferred angle and radial angle for 4 potential FP locations at the extremes of this distribution. In each of these instances, the fisheye model does not explain the data. For this reason, our results are incompatible with the fisheye model regardless of the location of the FP on the stimulus monitor.

1e) We performed additional intrinsic imaging experiments to permit a similar analysis, placing a small grating patch at the foot point on the monitor or at locations that were horizontally, vertically, and diagonally displaced from the foot point to map these radial orientations. According to the fisheye distortion hypothesis, the pattern observed should be untuned (white in our color scheme) at the foot point, becoming more sharply tuned at eccentricity, with preferences always matching the radial axis. The data do not match any of these predictions (Extended Data Figure 7).

2) We performed intrinsic imaging experiments with a “pre-distorted” stimulus. While it is mathematically impossible to render straight bars of constant widths in a right-angle grid on a sphere, we applied the following transformation: “Bars” are drawn on the screen so that their edges are great circles centered on the eye. On a globe, they would correspond to thin segments between nearby lines of longitude, rotating about the polar axis. Furthermore we varied the bar width and velocity by $1/\cos(\theta)$, with θ the eccentricity from the foot point. The same transformation is applied to bars of all orientations. It ensures that at any point in the visual field, horizontal bars have the same width and velocity as vertical bars. The distortion hypothesis predicts that the orientation maps will disappear with this corrected stimulus, but instead our standard stimulus and this “pre-distorted” stimulus revealed similar orientation maps (Extended Data Figure 7).