Neural Computations of Polar Angle Asymmetries

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Abstract

Visual performance varies around polar angle and this variation has been related to *quantitative* factors (e.g., cone density, retinal ganglion cell density and cortical surface area). However, retinal or cortical factors only explains a small portion of polar angle asymmetries, indicating that *qualitatively* distinct neural computations may also contribute to asymmetries. Here, we investigated whether two computations –featural representation and internal noise– vary around polar angle and underlie polar angle asymmetries. Using a detection task and the psychophysical reverse correlation, we derived the representation of orientations and spatial frequencies, which differed around polar angle in distinct ways. Critically, the extent of asymmetries of orientation sensitivity correlated with the corresponding performance differences, indicating that the sensitivity to orientation (but not spatial frequency) underlie polar angle asymmetries. Concurrently, we estimated internal noise using double-pass method and a noisy observer model, revealing a similar level of internal noise around polar angle and no correlation between the extent of asymmetries. Thus, polar angle asymmetries stem from differential featural representation, but not internal noise.

Keywords: polar angle asymmetries; reverse correlation; featural representation; internal noise

Human visual performance varies across isoeccentric locations as a function of polar angle (Fig 1A): performance is better along the horizontal meridian (HM) than the vertical meridian (VM), termed horizontal-vertical anisotropy (HVA), and better along the lower- than the upper-VM, termed the vertical-meridian asymmetry (VMA) (see Himmelberg et al., 2023 for a review). These asymmetries are evident across fundamental visual dimensions such as contrast sensitivity (e.g., Himmelberg et al. 2020, 2021; Baldwin et al., 2012) and acuity (e.g., Barbot et al., 2021; Kwak et al., 2023). Polar angle asymmetries have been associated with *quantitative* factors: locations with better performance have higher density of cones (Polyak, 1941) and midget retinal ganglion cells (Curcio

& Allen, 1990) and larger V1 surface area dedicated to processing stimuli (Himmelberg et al., 2021, 2022). However, an encoding model shows that optical and retinal factors only explain a small portion of polar angle asymmetries (Kupers et al., 2019, 2022); And equating V1 surface area only eliminates the eccentricity effect in contrast sensitivity, but not polar angle asymmetries (Jigo et al., 2023). These findings indicate that in addition to the quantitative factors, *qualitative* factors such as neural computations may also contribute to performance differences around polar angle. Here, we investigated whether two neural computations –featural representation and internal noise– differ around polar angle and underlie polar angle asymmetries.
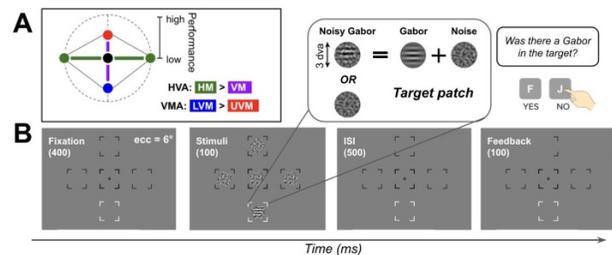
Fig 1. (A) Polar angle asymmetries (HVA and VMA). (B) Observers (n=15) detected a Gabor embedded in filtered noise around polar angle.

Featural Representation Underlie Polar Angle Asymmetries

First, we derived the representation of two fundamental visual features –orientation and spatial frequency– which are jointly encoded by V1 neurons (Blakemore and Campbell, 1969). We used a psychophysical detection task (Fig 1B) and the psychophysical reverse correlation to estimate the sensitivity to and selectivity for orientation and SF (Ahumada, 2002; Fernández et al., 2019, 2022; Xue et al., 2024). On each trial, observers reported whether a

2 cpd horizontal Gabor appeared at one of four isoeccentric at 6 deg eccentricity while fixating at the center. A Gabor was embedded in filtered noise (SF=1-4 cpd, contrast=20%) in half of the trials. Contrast sensitivity (Fig 2A) –the reciprocal of signal contrast necessary to attain 70% accuracy– was higher at HM than VM and higher at the lower- than upper-VM, indicating HVA and VMA, respectively.
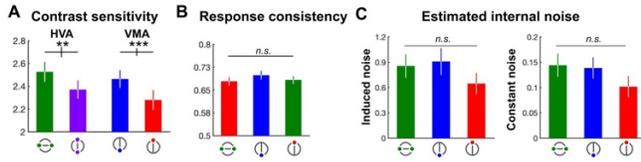
Fig 2. (A) Contrast sensitivity (B) response consistency, (C) estimated induced and constant internal noise around polar angle.

Using reverse correlation, we derived orientation (Fig 3A,B) and SF tuning functions (Fig 3C,D), indicating the perceptual weight assigned by the system to these features during the task. We then estimated orientation and SF peak amplitude (indicating *sensitivity*) and bandwidth (indicating *selectivity*) of the function. We found higher sensitivity to orientation at lower- than upper-VM (Fig 3B) and higher sensitivity to SF at HM than VM (Fig 3C), indicating sensitivity-related representations differ around polar angle.
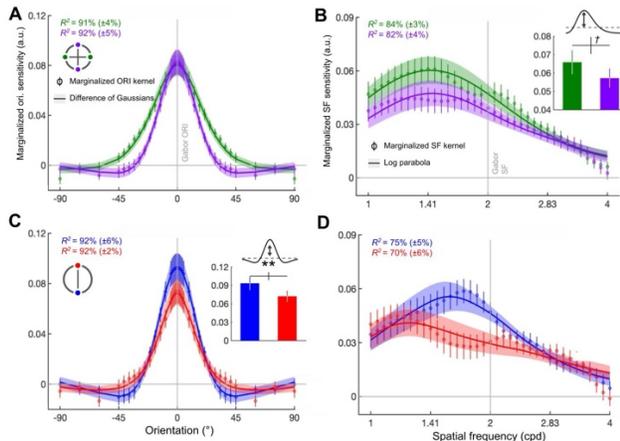
Fig 3. Orientation and SF tuning functions (curves) and feature sensitivity differs around polar angle.

To investigate whether featural representation underlies HVA and VMA, we assessed the correlation between the extent of HVA and VMA with the corresponding location difference in sensitivity and selectivity. Regarding HVA, higher contrast sensitivity at HM than VM was associated with higher sensitivity to orientation (Fig 4A) and SF (marginal, Fig 4B), but not the bandwidth. Regarding VMA, higher contrast sensitivity was associated with orientation sensitivity at

lower- than upper-VM (Fig 4C). Thus, sensitivity to orientation may underlie both HVA and VMA.
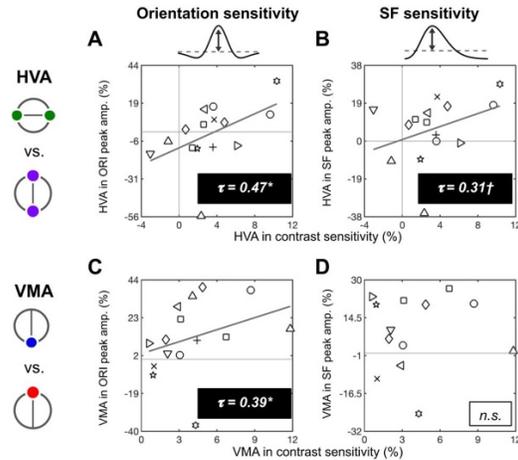
Fig 4. Correlations between the extent of HVA (A-B) and VMA (C-D) of sensitivity to orientation (A,C) and SF (B,D). Each symbol indicates one observer. The line indicates linear regression.

Internal Noise Does Not Underlie Polar Angle Asymmetries

Second, we estimated internal noise around polar angle, which has been shown to limits visual performance (e.g., Pelli, 1985; Lu and Dosher, 1999) and exists throughout the visual hierarchy (Faisal et al., 2008). Although internal noise increases with eccentricity (e.g., Xue et al., 2024; Wardle et al., 2012), whether it varies around polar angle remains unclear. First, we measured response consistency using the double-pass method by presenting a physically identical stimulus twice (Burgess & Colborne, 1988). Response consistency was similar around polar angle (Fig 3B), indicating a similar level of internal noise. Then, we quantified two types of internal noise around polar angle using a *noisy observer model*, which characterizes how feature representation underpins task performance (see Lu & Dosher (2008) for a review). Neither the *induced* (variance depends on the external noise) nor *constant* (independent variance) internal noise differed around polar angle (Fig 2C). Critically, the extent of HVA nor VMA correlated with the corresponding location difference in internal noise.

In summary, higher sensitivity to task-orientations, but not internal noise, underlie HVA and VMA of contrast sensitivity in the perifovea. These findings provide evidence for the *qualitative* hypothesis: polar angle asymmetries are also mediated by different neural computations at different visual field locations.

Acknowledgments

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