Evolutionary convergence in computation of local motion signals in monkey and dragonfly

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Motivation & Background

Many species extract motion from visual signals to perform complicated and critical tasks such as navigation, obstacle avoidance, and prey capture. The visual systems of macaques and dragonflies provide an interesting contrast because both species are expert at these tasks, but clearly lack anatomical/ancestral homology. Thus, comparing them may yield insights into successful computational strategies for motion analysis.

Analysis of visual motion is generally thought to occur in two stages: extraction of local motion signals, followed by their integration. Local motion signals include those that drive the classical Reichardt detector (pairwise spatiotemporal correlation, also known as Fourier (F) motion), as well as signals that the Reichardt detector cannot extract. The latter includes spatiotemporal correlations of higher order: non-Fourier motion (NF), which can arise from motion transparency or occlusion, and Glider (G) motion, typically associated with objects that are looming (G expansion) and receding (G contraction).

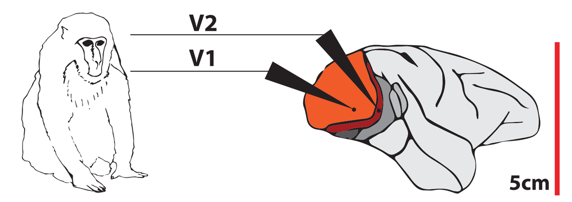
Macaques and dragonflies are visual specialists with evolutionary lineages that diverged nearly 300 million years ago and with profoundly different brain structures.

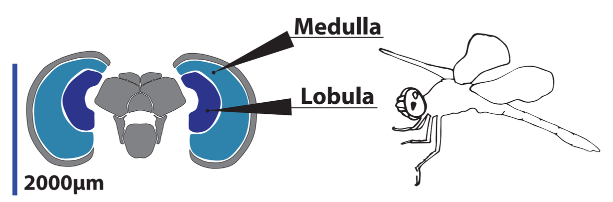
Do their brains process motion cues similarly?

- Can neurons extract directional signals from all three kinds of motion?
- At the level of neuronal populations, are there differences in the responses between species and specific brain areas?
- How do individual neurons process different motion signals?
- How does motion processing unfold across brain regions?

Methods

Physiology:





Single-unit recordings using multi-tetrode arrays were made in V1 and V2 of 13 macaques, anesthetized with propofol and sufentanil, and paralyzed with vecuronium or rocuronium. In most cases, recording sites were determined from histological identification of lesions and tracks.

Single-unit recordings using single electrodes were made in the medulla and lobula of 26 dragonflies. Recording sites were determined from visual inspection of the recording area.

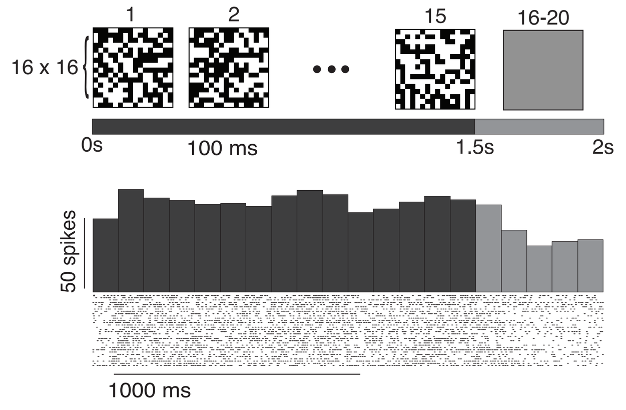
Data Analysis:

Spike sorting: After bandpass filtering (300 to 9000 Hz) and thresholding, waveforms were clustered using custom versions of KlusterKwik and Klusters (Hazan et al, 2006). Features consisted of peak amplitudes and principal components.

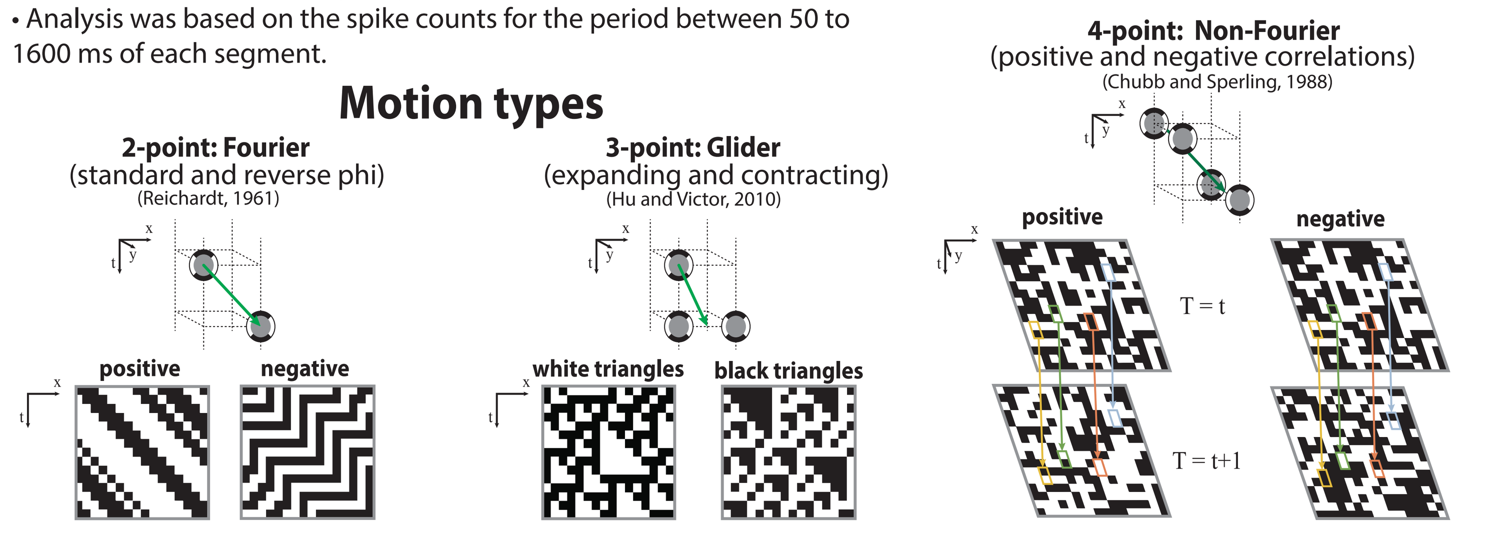
Spike sorting: After lowpass filtering (10,000 Hz) and thresholding, waveforms were clustered using custom versions of WaveClus (Quiroga et al, 2004). Features consisted of peak amplitudes and wavelet components.

Visual stimuli:

- 32 pseudo-randomized repeats of 25 blocks (~26 minutes total).
- Each motion block contains a specific kind of motion (see below) for 1500ms, followed by 500ms of grey (see right).
- Segments containing motion in opposite directions were presented sequentially.
- Check size and orientation:
  - Macaques: optimized response of an easily-isolated neuron in the recorded cluster. Single check typically = 0.1 - 0.5 degrees.
  - Dragonfly: Check size typically = 2.5 degrees.
- Repeats: macaque x4; dragonfly x1
- Analysis was based on the spike counts for the period between 50 to 1600 ms of each segment.

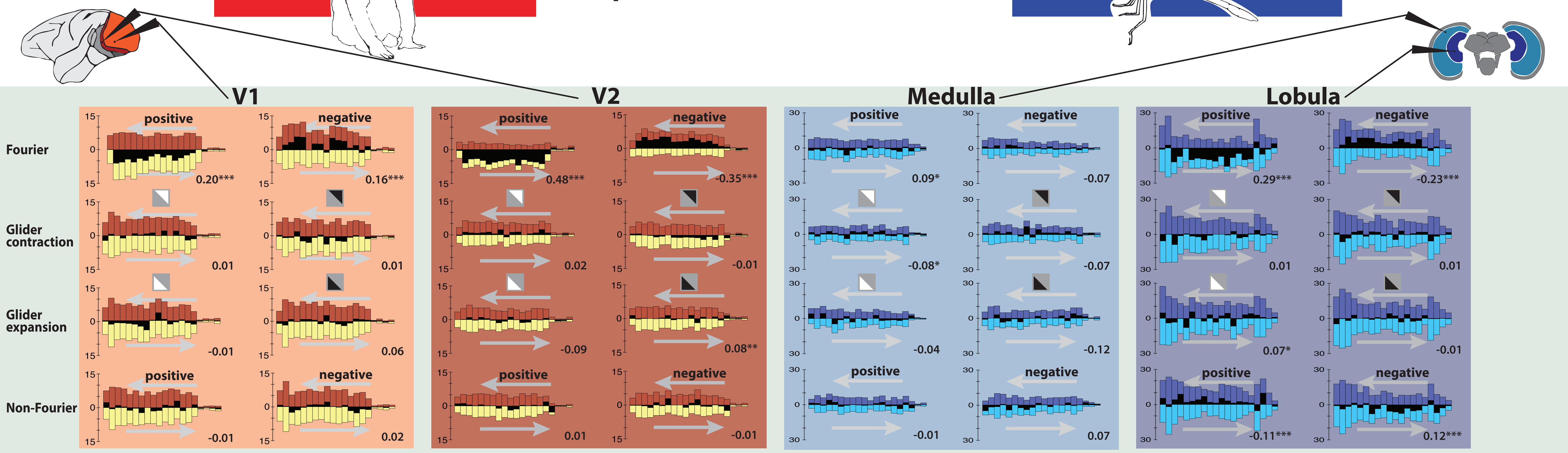


Motion types



Results

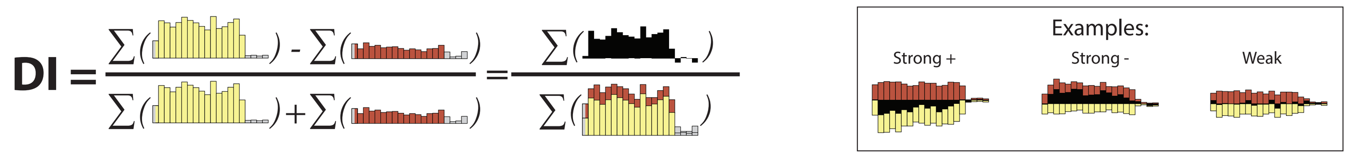
Responses of individual neurons



Example neurons from macaque (V1, V2) and dragonfly (Medulla, Lobula). Plots show responses to opposing directions; differences are represented by black bars. The directional index (DI) and its significance (* for p<0.05, ** for p<0.01, *** for p<0.001) is shown for each response pair.

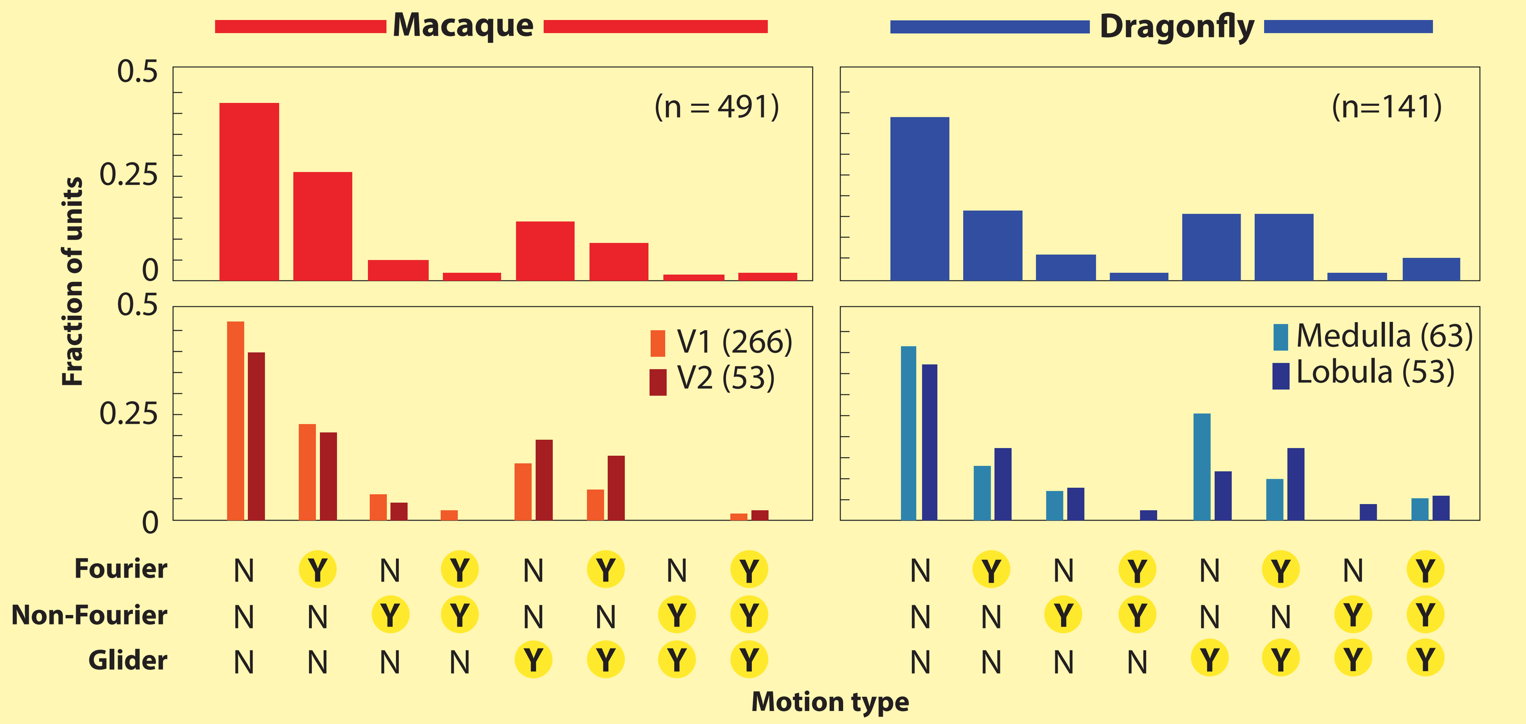
Neurons in both areas were sensitive to three kinds of motion.
Many neurons were sensitive to more than one kind.

Directional Index (DI)



Significance was determined by a t-test (paired, two-tailed) across 25 trials containing the given motion type.

Sensitivity to multiple kinds of motion across populations



In both species the pattern of responses to motion is similar.

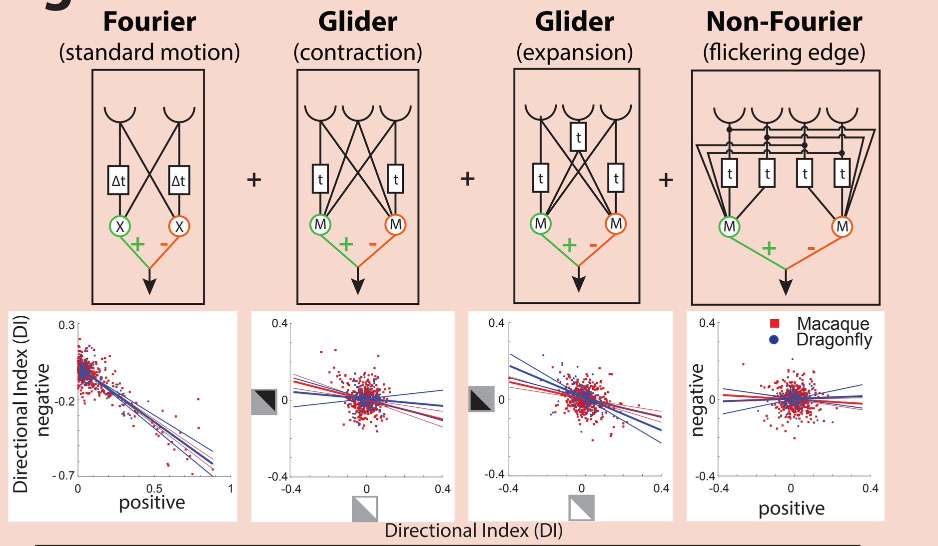
Motion Processing Across Brain Areas

Each kind of local motion signal can be extracted by the classical Hassenstein-Reichardt (HR) model or an elaboration of it (see right).

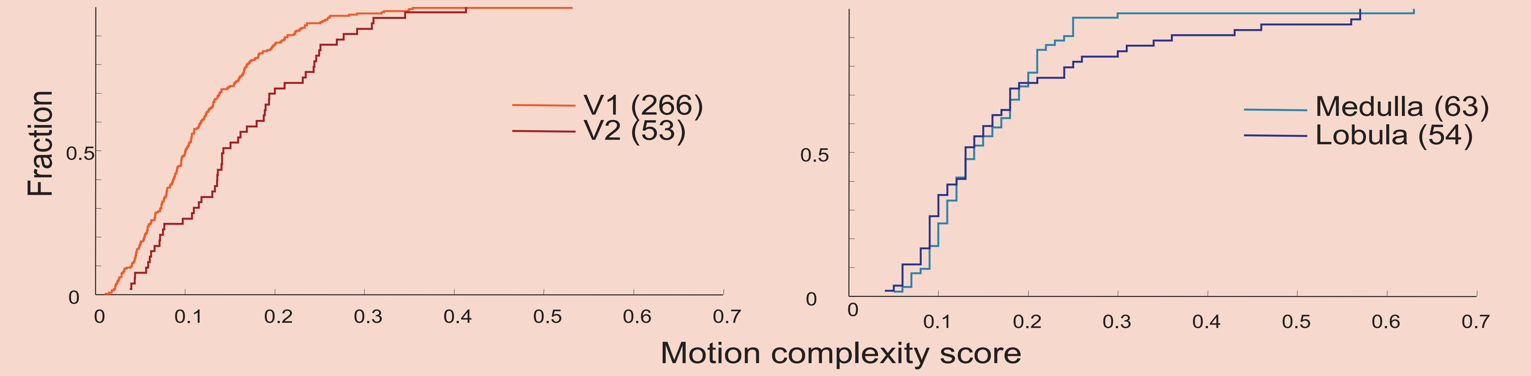
Since these models all have an opponent stage they predict that a neuron that responds to a positive motion singnal in one direction will respond to a negative motion signal in the opposite direction. Here we test this.

To a first approximation, this holds.

To identify systematic deviations from this prediction, we introduced a “motion complexity” (MC) score. MC = 0 when this prediction holds and MC > 0 when it fails.



$$MC = \sum \left| DI(m,+) + DI(m,-) \right|, \; m \in \{F, G\text{-cont}, G\text{-exp}, NF\}$$

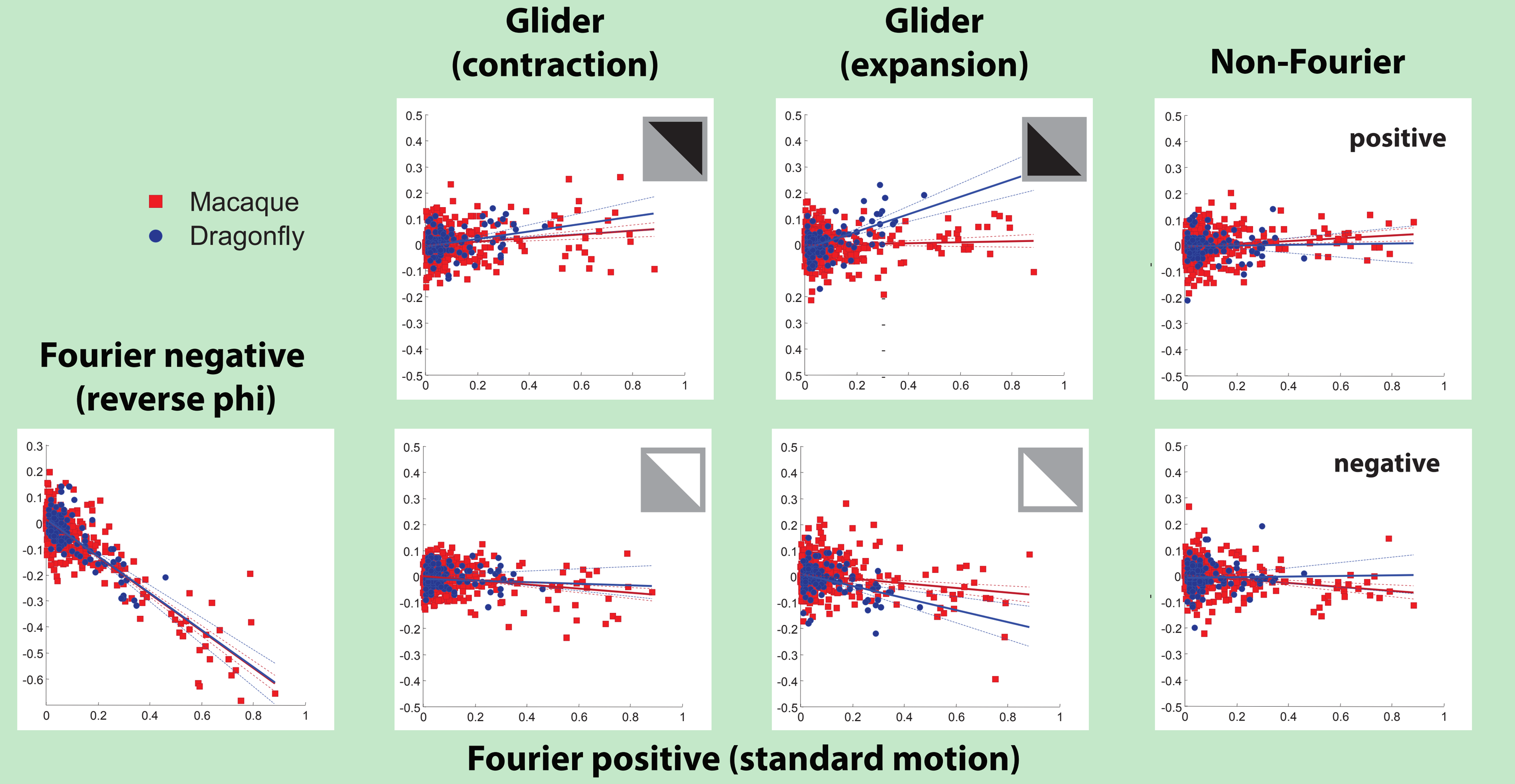


In both species, MC increases as processing unfolds.

In both species, all motion types contribute to the MC score, i.e. no motion type behaves in a strictly opponent fashion.

V1 and V2 differ primarily at low MC values while medulla and lobula differ primarily at high MC values.

Correlations between sensitivities of neurons to standard Fourier motion and other kinds of motion



Each scattergram compares the DI for standard Fourier motion (abscissa) with the DI for another motion type (ordinate). Thick and thin lines are regression lines and 95% CI.

Responses of individual neurons to different motion signals are correlated.
The pattern of correlation is generally similar across species.
However, dragonfly responses for glider expansion are stronger.

Summary and Conclusions

Despite extreme differences in evolutionary history and brain structure, macaques and dragonflies process motion cues similarly.

- Neurons extract directional signals from three kinds of local motion cues.
- At the level of neuronal populations, the pattern of responses to motion is similar.
- Responses of individual neuroons to different motion signals are correlated, and the pattern of correlation are generally similar across species--but dragonfly responses to glider are stronger.
- In both species, initial processing is consistent with opponent mechanisms but later processing is not.

These findings suggest that, despite their very different evolutionary lineages and anatomies, the visual systems of dragonflies and macaques use similar computations to detect local motion signals, but that later stages of processing emphasize the kinds of signals that are most important to their survival.

Funding & References

This research was supported by the National Institutes of Health: 5R01EY7977 and 5R01EY9314 to J.D.V., 5R01DC103 to R.R.H. E.I.N. is also supported by the Tri-Institutional Training Program in Computational Biology and Medicine. J.R.G was supported by a travel grant from Cornell Cognitive Science.

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