Space-Variant Time-Asynchronous Visual Sampling

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Contents

- What is space-variant sampling?
- What is time-asynchronous sampling?
- Why would we want either?
- Some simulations and results

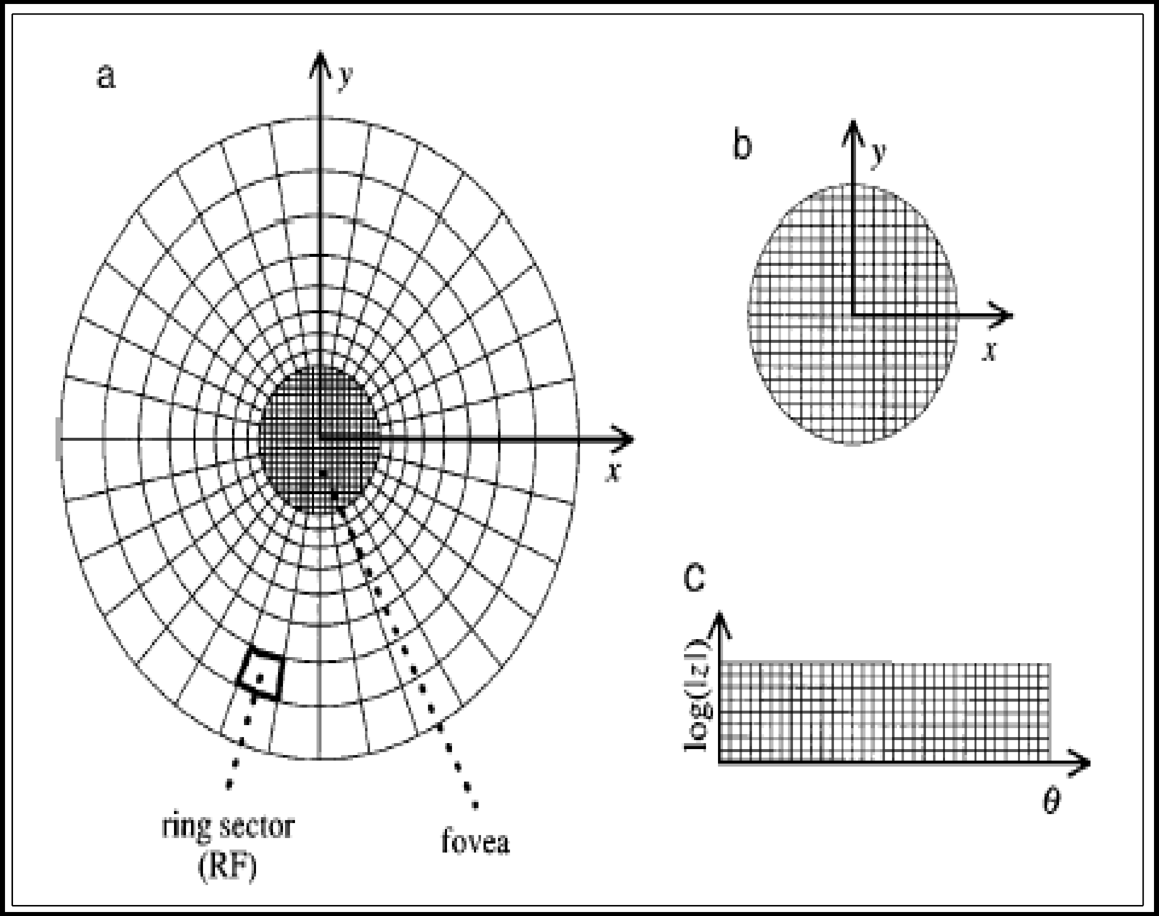
Space-variant sampling

- Uniform resolution
  - Visual sensor with individual receptors of equal size and separation
  - Can be thought of as the number of pixels needed to capture an image on a computer screen.
- Non-uniform resolution
  - Any photosensor utilizing a variable density of photoreceptors across the surface of the sensor
  - Biological retinae
  - Biological systems employ a high resolution fovea and increasingly low resolution periphery
  - Density of receptors in fovea differs across species

Non-uniform resolution sensors

- Two main classes of models:
- Conformal mapping:
  - Log-polar, monopole, dipole
- Overlapping receptive fields
  - Pseudo-triangluar tesselation, pseudo-rectangular tesselation

Conformal Mapping models

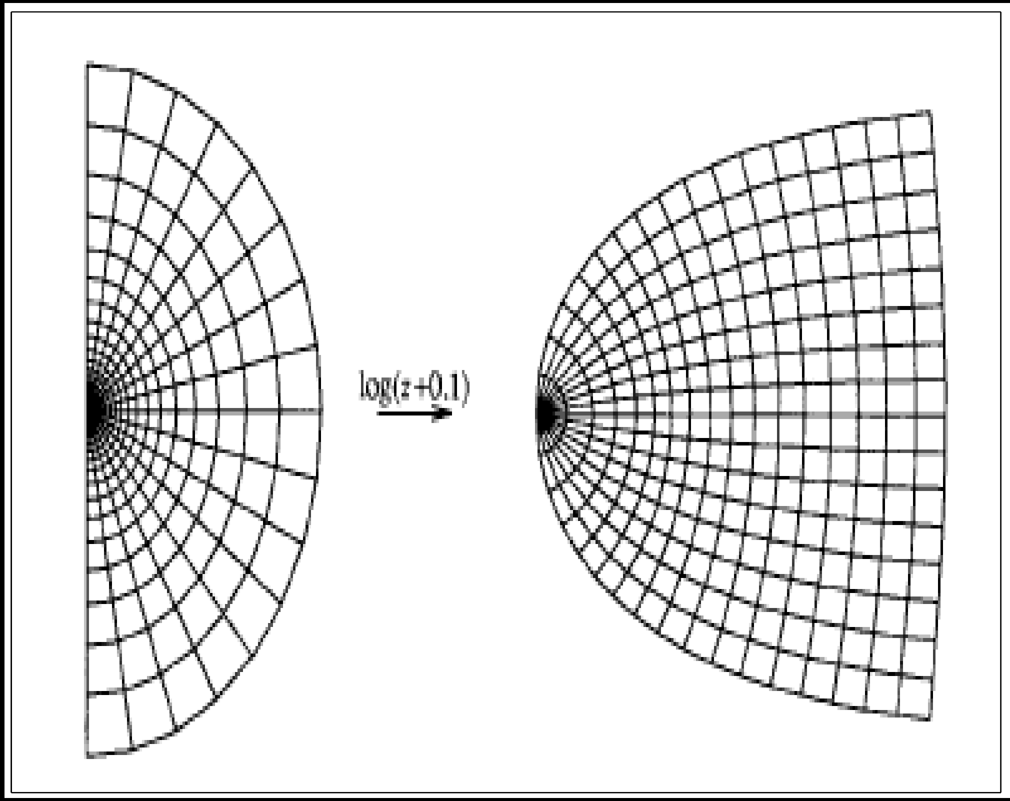


- Log-polar:
  - Characterized by conformal mapping: $w = \log z$
  - Contains a singularity at $z = 0$
  - Not a real issue because entire foveal region is assumed to be linear (uniform)

Log-polar model

- Uniform foveal region overcomes two problems:
  - Singularity at $z = 0$
  - Fractional pixel sizes at deep fovea
- Maintains scale and rotation invariance, good for image processing later on
- Uniform fovea patch is discontinuous from patch to rest of mapping
- Peripheral pixels uniformly average input intensities

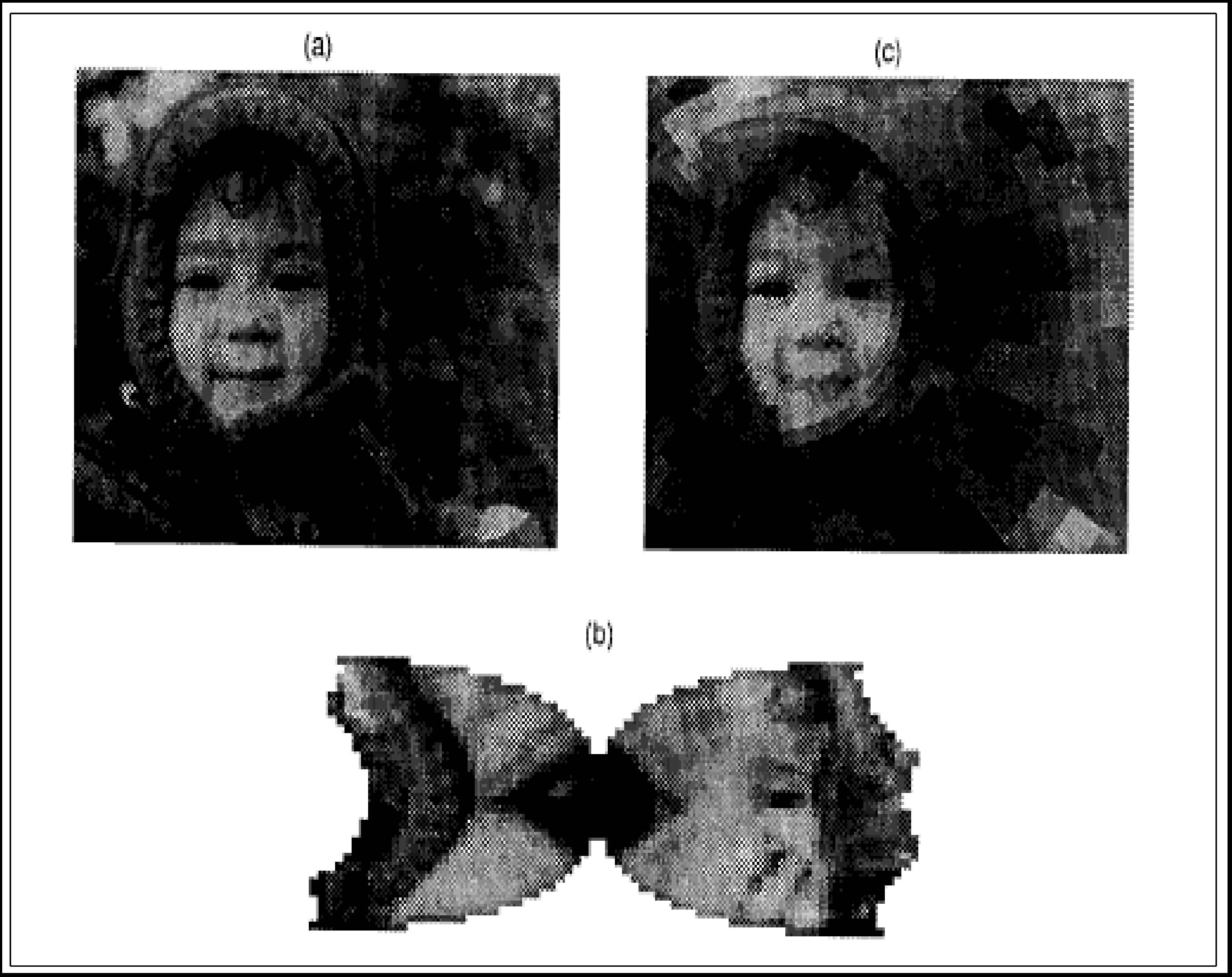
Monopole model



- Proposed by Schwartz
- Charaterized by: $w = \log z + a$
- a parameter shifts log singularity to $z - a$ allowing compression and magnification in the fovea mapping.
- No need for unform resolution patch

Monopole processing

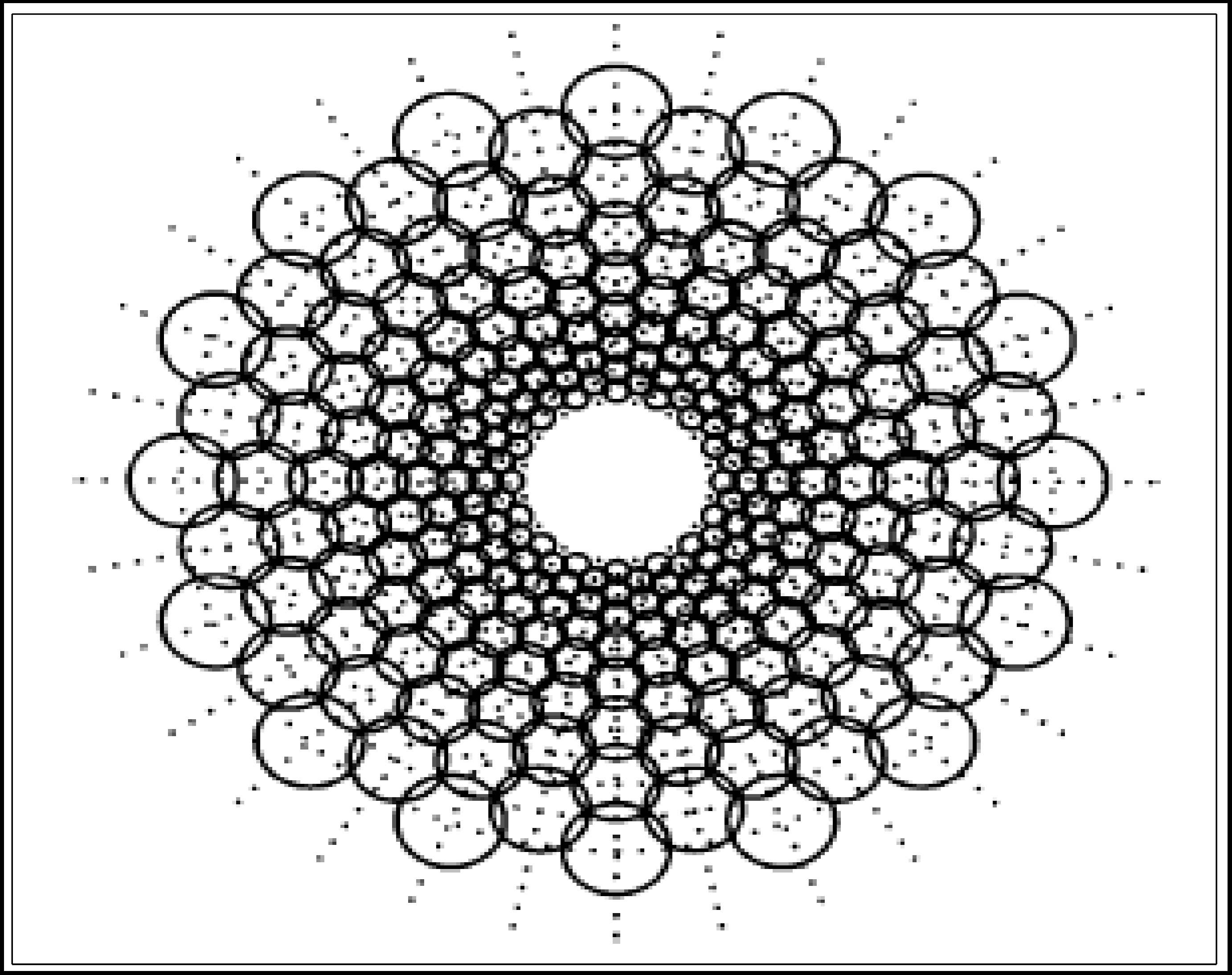
Below is a monopole mapping and inverse mapping



Pseudo-triangular tesselation model

- Areas of overlap are minimized under the constraint that there are no gaps
- Adjacent receptive fields (RF) are not at the same eccentricity
- RF radius is a function of eccentricity and the total number of RF's of the same size at a given eccentricity
- Specifically: $r = \frac{2\pi}{3N} e$
- RF's are centered logarithmically from the fovea
- Fovea treated separately as a uniform patch
- Such a model is proposed by Sandini *et al.*

Pseudo-triangular tesselation example

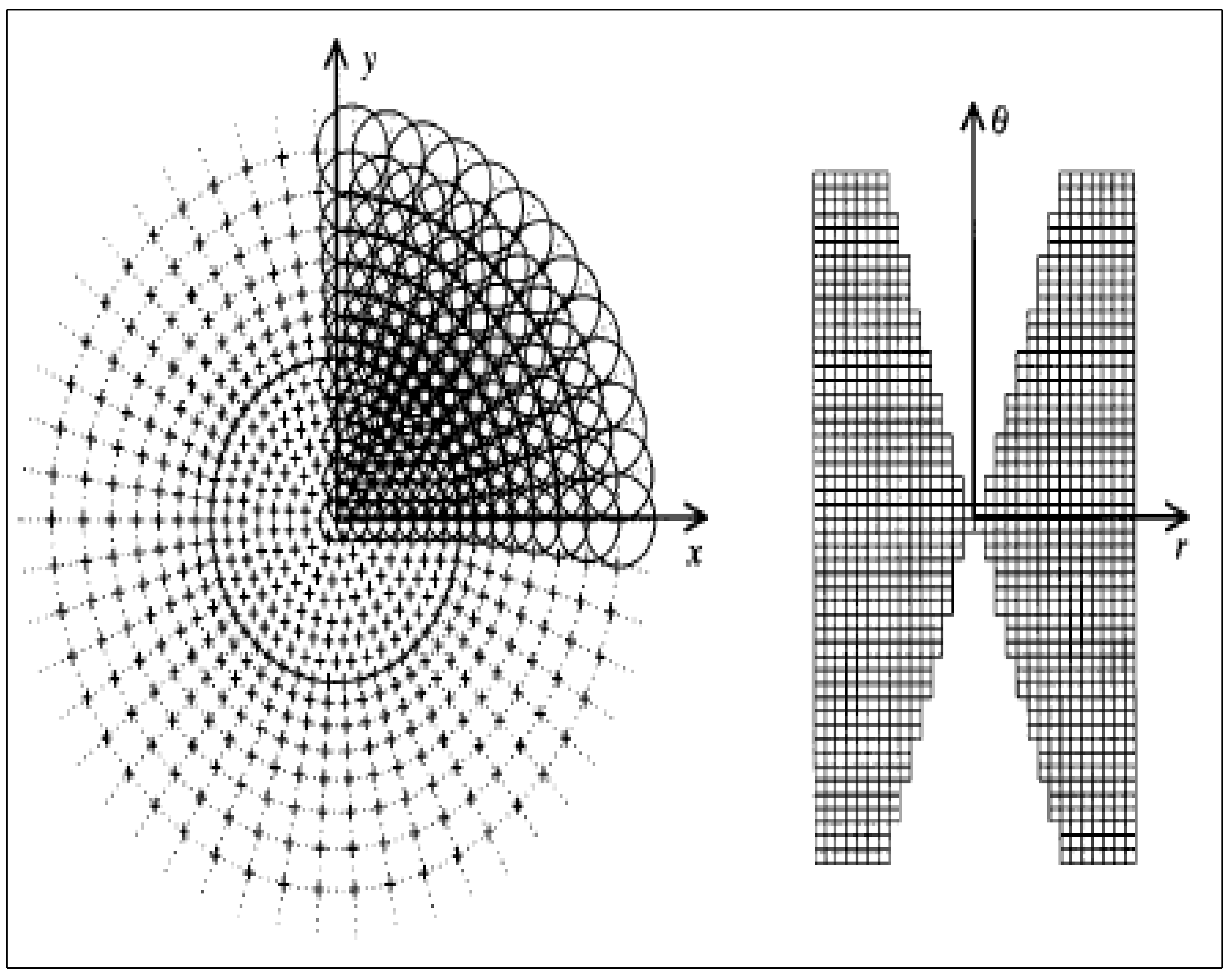


Pseudo-rectangular tesselation model

- Wilson's model uses a constant 50% RF overlap
- RF's are logarithmically spaced
- Uses overlapping RF in fovea
- Foveal RF size == smallest peripheral RF size
- Number of foveal RF's per concentric ring in fovea decreases towards the center

Wilson’s example

The output is similar to the output of the monopole model



Where are we?

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No Clock?

- A fundemental property of digital processing→clock cycles
- Conventional sensors sample images at a given rate
- All pixels in the photosensor array report their value at each instance at the sampling interval
- Once again, not the way biological systems work
- There is no clock in the brain, or retina
- Neurons fire when they are capable of doing so

Asynchronous sampling

- Very similar to event timing (AER: Mahowald) and interrupt based programming
- With no polling, an asynchronous sensor can inform its controller of its name and value as soon as its “firing” condition has been met
- In biological systems, this is occurs when Ganglion cells are sufficiently activated by photoreceptors (among others)
- The photoreceptors themselves increase in activity logarithmically
- Sandini et al. (2000) use the FUGA pixel which has a logarithmic response to illumination

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Space-complexity

- Rojer and Schwartz (1990) illustrates that the number of pixels needed in a non-uniform resolution sensor can be many orders of magnitude smaller than a uniform resolution
- The reduction in information using space-variant sensors can enable image processing at frame rate (30Hz)

Asynchronous time sampling

- Biologically similar non-uniform space sampling features:
  - large peripheral RFs
  - highest spatial frequency response in fovea, lowest in periphery
  - meaning high density of photoreceptors in fovea
- Biologically similar asynchronous time sampling features:
  - fast activation and decay in peripheral RFs
  - slow temporal response in fovea
- Other properties exist, concentrating on the above

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Simulation outline

Non-uniform spatial structure

- Pseudo-rectangular tesselation model
- Monopole already modeled by Polimeni and Schwartz (2001)
- Uses nice geometric shapes (circles) for receptive fields
- Overlap helps form boundaries in output image
- Overlapping receptive fields found in anatomy
- No separate foveal patch

Simulation Outline: temporal sampling scheme

- Two layers of leaky integrators
- First layer serves as photoreceptor input to ganglion cells
- Second layer: ganglion cell activation

Space-Variant Implementation

- RF centered on logarithmic scale from fovea, scaled for actual eccentricity
- RF size linearly related to distance from fovea
- Smallest RF (foveal) size == 1 image pixel, arbitrary arc length of visual field
- Image pixels are averaged underneath each RF to form RF pixels
- Center-surround not implemented

Asynchronous Implementation

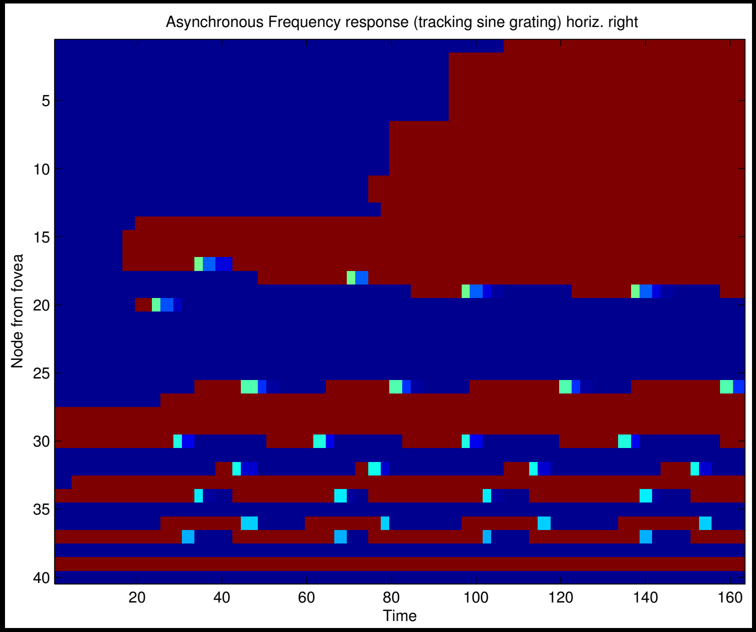
- Two layers of processing
- First, logarithmic accumulation of input over time in photoreceptors
- Second, “firing” of Ganglion cell analogs to sufficient photoreceptor input
- Both layers characterized by leaky integrator: $dx/dt = -\alpha x + I$
- For photoreceptors α is linearly related to receptor size in such a way to increase slope of excitation and decay for larger RF, I falls along the range 0.0 to 1.0
- For ganglions α is fixed and I linearly related to its RF size; a representation of information sent during a firing event

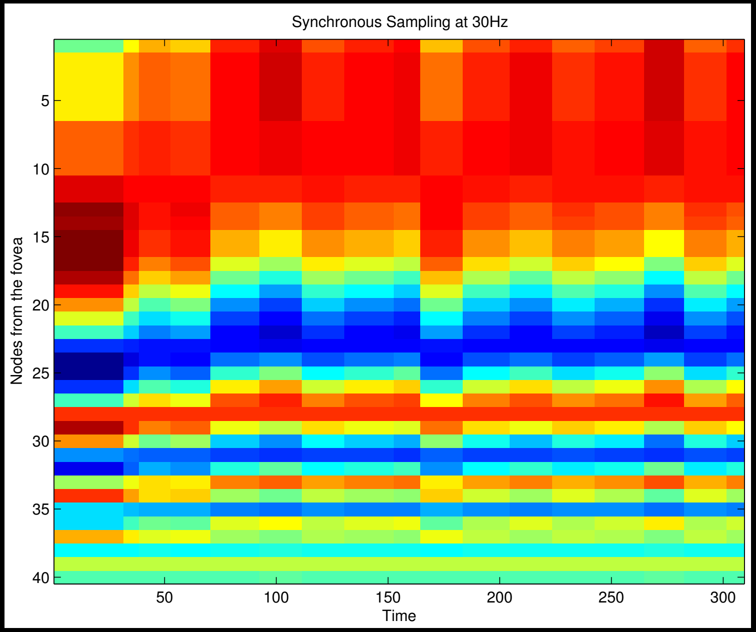
Experiment

- Main Experiment
  - A sine grating of frequency 3π was shifted in phase (to cosine) at 20Hz
  - The synchronous model set at sampling rate of 30Hz
  - By definition asynchronous has no sampling rate
- Other experiments (not reported)
  - Effects of sampling (both models) under shot, additive and multiplicative noise
  - Motion tracking

Hypothesis: Synchronous sampling will not be able to track 20Hz sine grating, but asynchronous will

Results





- Left: Plot of Asynchronous firing rate. Red is maximum, blue is minimum. Y-axis = Eccentricity from fovea, X-axis = time
- Right: Plot of synchronous sampling at 30Hz. (intensity values averaged). Same axes apply.
- All eccentricities are from the fovea outward to the right along the horizontal meridian

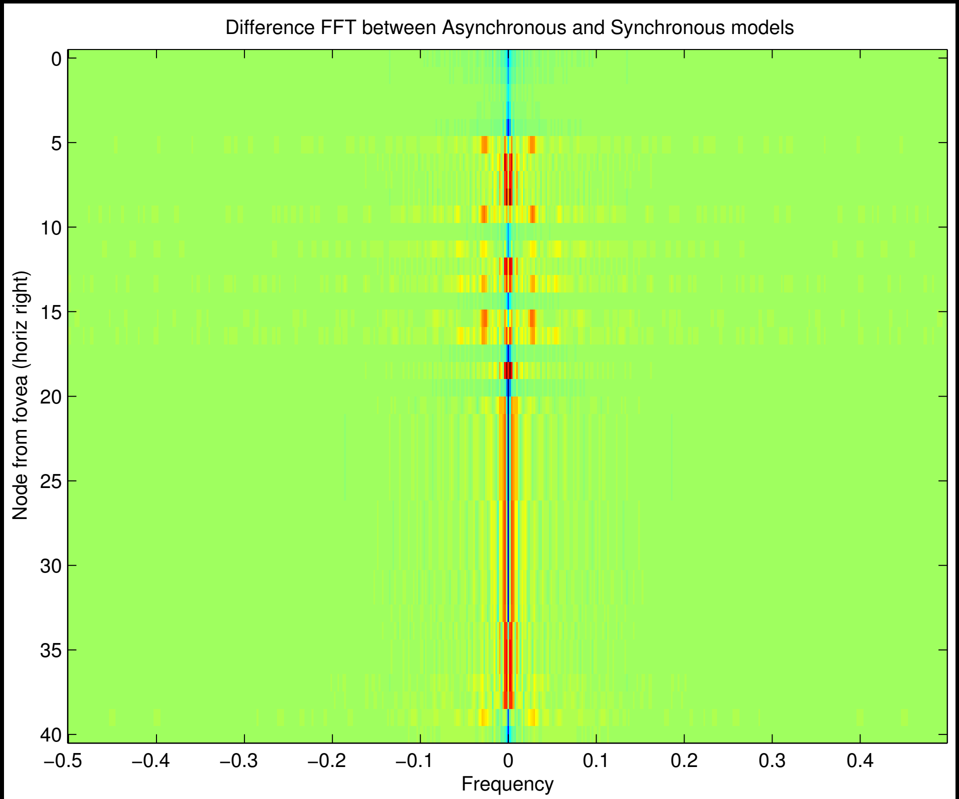
More Results

- Tracking is indicated by modulations of firing rate at approximately the stimulus flicker rate
- Asynchronous tracking begins between nodes 16 and 24 corresponding to 6.6^o and 17^o eccentricity respectively
- Variations due to RF location (Horizontal/Vertical Meridians)
- Synhcronous shows no image intensity modulation (at least not as sharp)

Frequency response

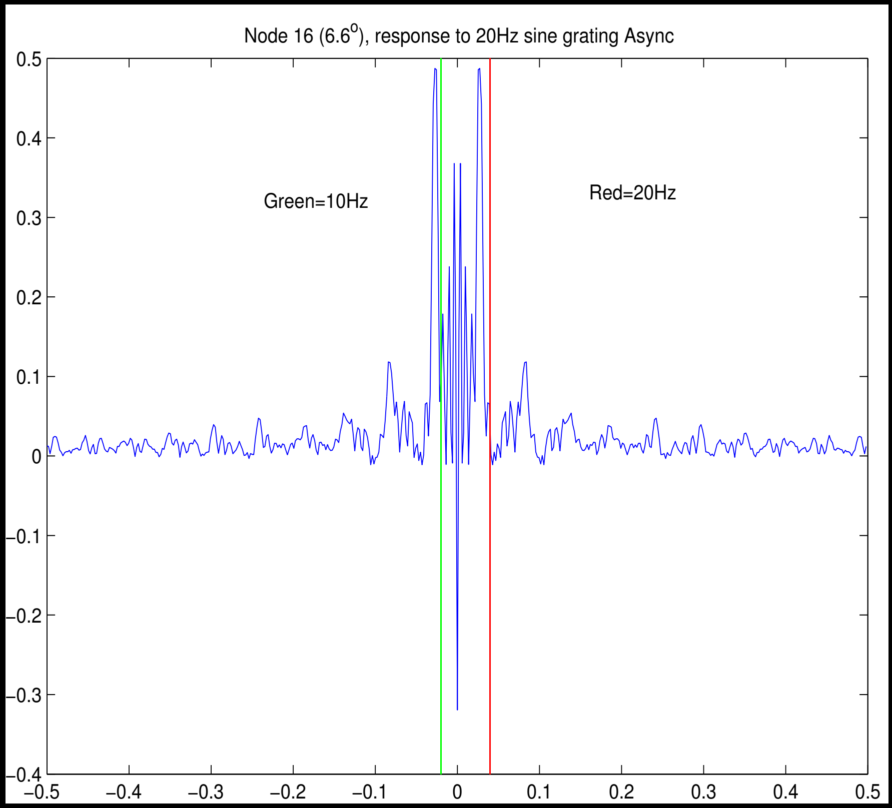
- 1D Fourier transform in time for each RF was taken of synchronous and asynchronous models for each of the major angles (horizonal and vertical)
- Synchronous transform indicates large magnitude of zero or near-zero frequency
- Asynchronous transform indicates more distributed amplitude over larger ranges of frequency
- Comparison of normalized synchronous and asynchronous FFT show large differences in frequency response between 10 and 20Hz for the “tracking” RF nodes

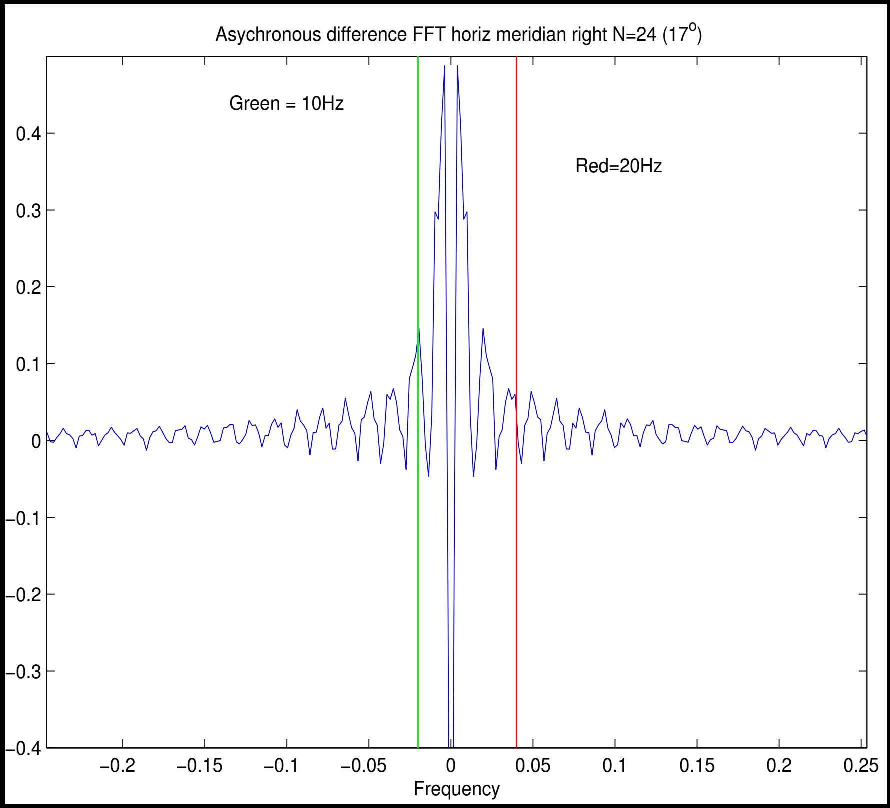
Fourier comparison



- Y-axis represents RF node (eccentricity) from the periphery to the fovea on the right-hand horizontal meridian $\theta = 0^o$
- Areas of red indicate large differences between synchronous and asynchronous
- Differences occur between 10 and 20Hz starting at 6^o eccentricity

Closer look at Fourier comparison





- Left: Red and green lines represent 10 and 20Hz respectively. Peaks occur in between
- Right: Peak appears to be centered on 10Hz

Summary

- Experiments worked as predicted
- Synchronous sampling at 30Hz can not track a 20Hz signal (undersampling)
- Asynchronous model tracks 20Hz signal, at a trade-off, foveal RFs do not respond to signal, peripheral do beginning around 6^o visual angle
- Improvements:
  - Find realistic scale for RF size
  - Include refractory period and center surround for ganglion layer

References

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