Neural Representations of 3D Space

We have no direct way to sample 3D space with our visual or auditory systems, yet we must operate in a 3D environment.

3D representations of space must be computed in the brain – fascinating problems in neural computation.

Today: visual representation of 3D space

Next lecture: auditory representation of 3D space
2 Basic Classes of Visual Depth Cues

Pictorial cues: cues present in a single (static) view of a scene (e.g., occlusion, perspective, size, shading, etc)

Geometric cues: cues arising when a scene is viewed from multiple vantage points (binocular disparity, motion parallax)
An Image Rich in Pictorial Depth Cues
Street Art of Julian Beever
Binocular Disparity

L Eye  R Eye

Retinal Image

Motion Parallax

Retinal Image over Time

Δθ
Random-Dot Stereogram
Color Anaglyph Technique

Other Common Methods:
- Shutter glasses
- Polarizing filters

The red and blue lenses filter the two projected images, allowing only one image to enter each eye.
An Autostereogram
5.1.3. Ocular Dominance and Binocular Disparity

-Like those in the LGN, neurons in the input layer of V1 (layer 4C) are generally responsive to only one eye. Monocular neurons are clustered together, forming a pattern of stripes called *ocular dominance columns*.

-Elsewhere in V1, most neurons combine signals from the two eyes, and have a receptive field for each eye. These ‘binocular’ cells are the first neurons in the visual system that are able to make comparisons between the retinal images in the two eyes.

6.4 THE OCULAR DOMINANCE COLUMNS IN AREA V1 can be visualized by using a radioactive marker, tritiated proline. When the marker is injected into one eye it is transported via the LGN nucleus to the cortex. The radioactive uptake is revealed in this dark-field photograph. The light bands in this tangential section show the places where the radioactive marker was located and thus reveal the ocular dominance columns. Source: Hubel et al., 1978.

-5 mm
- Binocular neurons form the basis for depth perception. Objects at different distances from the viewer cast images onto different positions in the two retinae. These differences in position are called *binocular disparities*. The disparity of a point in 3D space is related to the depth of the point relative to where the eyes are fixated:

\[ \text{disp} \approx \frac{I \cdot z}{D^2} \]

where \( \text{disp} = \text{disparity} \), \( I = \) interpupillary distance, \( z = \) depth of object (relative to fixation), \( D = \) viewing distance
- V1 neurons are tuned for different ranges of binocular disparity (right). Such neurons code the position of objects in depth (relative to fixation plane).

- Disparity-selective neurons are found in many areas of visual cortex, including: V1, V2, V3, V3A, V4, IT, MT, MST.
Depth from Motion Parallax

- Objects at different depths produce different image motion in response to observer movement (motion parallax)

- Motion parallax can produce a reliable impression of depth in the absence of other cues (Rogers & Graham, 1979)

- However, motion parallax alone is not sufficient to specify the sign of depth (near or far)
For **NEAR** objects, image motion is in the **OPPOSITE** direction as observer motion.
Motion Parallax: Far Object

For **FAR** objects, image motion is in the **SAME** direction as observer motion.
Motion Parallax: Depth Sign Ambiguity

- Far object
- Near object

Eye Movement
Head Translation

Near

Near? Far?

Image motion

Visual image
Neural Coding of Depth from Motion Parallax?

- In the absence of pictorial cues (e.g., occlusion, size), neurons must receive an extra-retinal signal to compute depth sign from motion parallax.

- Psychophysical studies suggest that depth perception from binocular disparity and motion parallax may share a common neural substrate, but virtually nothing was known about the neural basis of depth from motion parallax.

- Do neurons combine visual motion signals with extra-retinal signals to code depth sign from motion parallax?
Experimental Design

Stimulus conditions
1) Motion Parallax
2) Retinal Motion
Example MT Neuron Selective for Depth Sign Based on Motion Parallax

Additional Example MT Neurons

**Near-preferring**
- MP: DSDI = -0.71
- RM: DSDI = 0.04

**Far-preferring**
- MP: DSDI = 0.65
- RM: DSDI = 0.21

Response (spikes/sec)

Simulated Depth (deg of equivalent disparity)
Extra-retinal Signals

- The task involves a passive head/body movement and a compensatory eye movement
- One potential source: vestibular/proprioceptive inputs related to head movement
- Second potential source: smooth eye movement command signals
- What is the source of the extra-retinal signal used to produce neural selectivity for depth sign from motion parallax?
Experimental Design II

Stimulus conditions
1) Motion Parallax
2) Retinal Motion
3) Head Only
4) Eye Only
Example Neuron
Nadler, Nawrot, Angelaki, & DeAngelis, *Neuron*, 2009

![Graph showing neuronal firing rate vs. simulated depth](image)

- Head Only: 0.26
- Eye Only: -0.67*
- Motion Parallax: -0.66*
- Retinal Motion: 0.01

*Note: Asterisks indicate statistically significant values.
• A smooth eye movement command signal (such as an efference copy of pursuit commands) disambiguates depth sign in the responses of MT neurons

• Vestibular/proprideceptive signals related to head translation do not

• Why?
Retinal motion ($d\theta/dt$) and eye rotation ($d\alpha/dt$) relative to the scene are necessary and sufficient information to compute depth from motion parallax.

Motion-Pursuit law
Nawrot & Stroyan (2009)

$\alpha$: eye orientation relative to scene
$\theta$: retinal image location relative to fixation

\[
\frac{d}{f} \cong \frac{d\theta/dt}{d\alpha/dt} = \frac{d\theta}{d\alpha}
\]

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