any point in space is defined relative to other points in space
depth perception from motion parallax

or

depth perception from texture gradient

or

depth perception from occlusion

or

depth perception from retinal disparity (stereopsis)

: :

but which?
MAPPING SPACE IN THE BRAIN – RULE 2: DEFINE THE FRAME OF REFERENCE

**egocentric frames**
- retinal space
- eye position
- hand space

**arbitrary frames**
- allocentric (world-centered)
- route-centered
- object-centered
multiple single neuron recordings in behaving animals:

- Hippocampal pyramidal neuron
- Recording
- Occupancy counts
- Firing rate neuron 1
- Firing rate neuron 2

28-tetrode microdrive

Tetrode (braided set of 4 electrodes)

Relative-amplitude spike discrimination

Place field
tracking directional heading in the allocentric (world-centered) frame of reference: ‘head direction’ cells

– firing is tuned to the orientation of the animal’s head relative to the boundaries of the environment

– different neurons have different preferred directions (all directions are represented)
tracking directional heading: the ‘head direction’ cell

- firing is tuned to the orientation of the animals head relative to the boundaries of the environment (i.e., not to magnetic north)
- directional tuning may differ completely across two different environments provided that they are perceived as different

\[ \text{distance along axis} = \text{firing rate of a single head direction neuron} \]

Knierim et al., 1995

90-degree rotation of the environment boundary dominated by a single cue card

“N – heading” (relative to tracking camera)
tracking position in the world-centered (allocentric) frame of reference: the ‘place cell’
– firing is tuned to the position of the animal in the environment (the place ‘field’)
– different neurons map different positions (all directions are represented)
– rotation of the environment boundaries = rotation of the place fields
given that different hippocampal neurons bear different place fields, the firing rates of those neurons at any given time can be used to predict the animal’s position in the environment.

for a set of neurons, the firing rates across the full set describe the ‘pattern’ of activity across the full population – this is called a ‘population firing rate vector’.

all brain regions appear to register information according to such ‘population’ patterns.
mapping position in the environment by path integration: ‘grid cells’

– neurons of the medial entorhinal cortex exhibit multiple firing fields in any given environment
– such fields are arranged according to the nodes of a set of ‘tesselated’ triangles
– grids, like head-direction tuning and place cells firing fields rotate with the boundaries of the environment

Hafting et al., Nature, 2005
medial entorhinal cortex contains grid cells, grid X head-direction cells, and head-direction cells – each cell type is also velocity sensitive, thus allowing for determination of position according to path integration (i.e., tracking of direction and speed over time) all within one structure

Sargolini et al., Science, 2006
‘what’ (temporal) and ‘where’ (parietal) pathways in monkey and human

-damage to IT (TE + TEO) impairs object identification (but only via visual information)

-damage to parietal cortex (MT, MST, 7a, VIP, LIP) impairs visuospatial abilities (e.g., reaching to an object)

Moving from V1 along the what where pathway:
- progressive loss of retinotopy
- increasing receptive field sizes
- increasing generalization across stimulus features (e.g. size, shape, color, illumination)
along the ‘where’ pathway: area MST integrates optic and vestibular ‘flow’
area VIP of parietal cortex: bringing together personal spaces of the somatosensory and visual systems
parietal cortex neurons in behaving rats map path segments (e.g., start pt. to first R turn)
parietal cortex: a rather abstract frame of reference – the space defined by the route (i.e., the space defined by sequence of behavior changes and the spaces separating them)
together the triangles form an object the ‘top’ of which is perceived as indicated by the arrows – humans with damage to the right parietal cortex (and associated hemi-neglect) often fail to detect the gap in the triangle (red arrows) when it is on the perceived left side of the object (SE-NW) as opposed to the right (SW-NE)

Driver et al., Neuropsychologia, 1994
BOLD SIGNALS IMPLICATE HIPPOCAMPUS AND PARIETAL CORTEX IN NOVEL SCENE CONSTRUCTION

Hassabis et al., JNS, 2007