infer transfer of motion from one object to another — a transfer of the object property of momentum. This implies adaptation of a perceptual relationship rather than an adaptation of an object property *per se*. But if that inference is derived from experience (induction), even at a perceptual level as advocated by Helmholtz and Southall [13], it is not clear why repeated evidence of collisions should undermine it. Furthermore, object properties, and presumably their relations, are properly tied to objects rather than spatial locations. A full explanation of causal adaptation will need to outline what type of retinotopically specified representation is altered in the neural pathway between the stimulus and the ensuing percept. Nevertheless, this new paradigm offers a way to study the perception of causality through adaptation, opening up many new avenues of investigation.

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Neural Odometry: The Discrete Charm of the Entorhinal Cortex

A recent study finds that the grid reference system in entorhinal cortex, used for computing distances during self-localization, has a discretized and modular organization. This has implications both for how the system develops and also for how it functions.

Kathryn J. Jeffery

In order for a map to work it needs a metric grid reference (Figure 1A): this has turned out to be just as true for the brain as for a mariner's chart. The brain's map grid reference is located in the entorhinal cortex, in which it was recently discovered that neurons are tuned to a combination of distances and directions [1]. The result of this tuning is one of the most striking patterns observed in neurobiology: the hexagonal polka-dot pattern formed from patches of activity (or 'firing fields') laid down by the cells as the animal moves around the environment (Figure 1B,C). This pattern has led to the name 'grid cells' for these neurons, and they are thought to serve as a distance-measuring device (like a car's odometer) for the navigation system.

Grid cells are hard to find and record, and so initial studies were only able to sample a few at a time. These early studies observed that the scale of grids (the distance between the firing fields; Figure 2A green bars) increases steadily from the dorsal-most to ventral-most regions of entorhinal cortex [1,2], providing capacity for the brain to represent spaces of different sizes. These studies also seemed to find that the orientation of the grids was coherent across the whole population for a given animal in a given environment, leading to the conclusion that the system acts as an integrated whole. Now, Stensola *et al.* [3] have used an improved method of neuronal recording that allows the sampling of many neurons at once (186 in their best ensemble), and found that, rather than acting as a single integrated unit, the cells appear to be organized in a modular fashion, with the modules behaving quasi-independently. This surprising result constrains not only our models of how the system wires up in the first place, but also of how it operates in adulthood.

This modularity finds expression in a number of ways. First, the increase in the scale of the grids from dorsal to ventral entorhinal cortex is not continuous but, surprisingly, discrete. A hint of this was first reported by Barry *et al.* [4] after recording small numbers of grid cells at a time, and Stensola *et al.* [3] have confirmed this with their large data set. Although absolute grid scale was evenly distributed across animals, the ratio between the scale of one set of grid cells (one module) and the next appears similar across scales and also across animals, at around 1.42, though there is considerable variation. Although these discretized scales increase from dorsal to ventral entorhinal cortex, there is overlap, such that a given dorso-ventral level contains cells expressing grids of more than one scale. All in all, there seem to be four or five of these scale modules in a given animal, although more may be revealed with further study of the most ventral regions (not sampled in this experiment).

A second kind of modularity was observed in the orientations of the grids, which are evidently not coherent, as first thought, but which also appear to vary discretely. Since orientation is thought to be conveyed by a class of compass-like neurons known as head direction cells [5], this suggests that the connection between a given grid cell and the head direction system is partly informed by the local network architecture and is not entirely random.
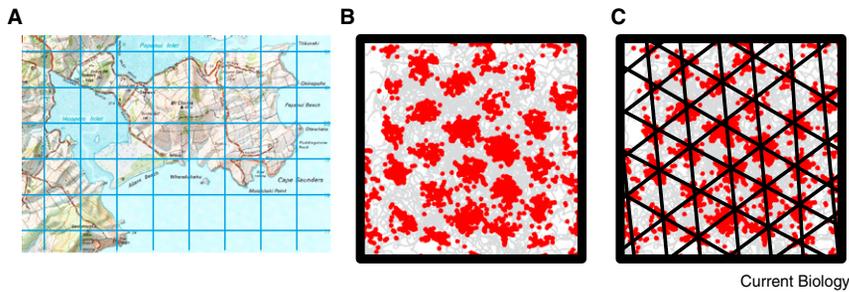
Figure 1. Maps, grids and grid cells.

(A) A map, with overlaid grid of orthogonal lines used for calculating distances. (B) The activity of an entorhinal grid cell from the Stensola *et al*. [3] experiment, recorded as a rat foraged around a 2 m square box. The grey lines represent the cumulative path of the rat throughout the trial and the red dots indicate action potentials fired by the neuron. Note that the neuron concentrated its activity in evenly spaced patches ('firing fields'), producing an unusual polka-dot pattern over the floor of the box. (C) When the grid cell's firing fields are connected by imaginary lines, these form a triangular or hexagonal grid. The grid array of firing fields may be used by the brain's navigation system to calculate distances, by analogy with the orthogonal grid in (A). (Panels (B) and (C) modified with permission from [3].)

In other words, cells within a module seem to be in agreement about which head direction cells to respond to. Importantly, cells of a given scale tended to have the same grid orientation as each other and those of different scales had different orientations: orientation modularity and scale modularity are thus aligned.

Third, grids also showed modularized distortion. Distortion refers to the slight squashing of a grid that makes its hexagonal pattern not quite perfectly symmetrical (Figure 2B). Stensola *et al*. [3] observed that grid cells that were alike in scale and orientation tended to squash their grids in the same direction, while those of a different scale and orientation (that is, belonging to a different module) were squashed in a different direction. Intriguingly, the axes of distortion were at right angles in a square environment but not in a circular one, suggesting an influence of environmental boundaries on the geometric properties of the grids. When the experimenters then induced further distortion by compressing the environment along one of its axes, turning it from a square to a rectangle, they found that grids either compressed accordingly or remained rigid, and again, grids from cells in a given module tended to behave the same way.

Interestingly, the modules that showed compression tended to be those with the large scale whereas the modules that resisted compression (so that their grids were truncated in the smaller box) tended to be those with a smaller scale. Why this should be the

case is not clear, but it may be that modules containing small grids only receive short-range influence from the boundaries, are hence are only influenced by one boundary (the one they remain 'attached' to), while modules containing larger grids receive longer-range boundary inputs and can

thus be affected by all the boundaries at once.

And finally, the temporal firing properties of the cells showed a modular organisation: the periodic firing known as theta rhythm was more similar in frequency for cells within a module than for cells between modules.

Taken together, these findings indicate that the brain does not have one single map grid but several — four or five, or even more — that operate partly independently. This is an important finding for two reasons. First, it helps inform models of how grids are generated. Such models [6] have assumed some kind of coordinated interaction between neurons that are competing for dominance in firing by supporting their colleagues (cells with the same firing field locations) and/or suppressing their competitors (those with offset firing fields), with grids emerging as the compromise solution. The finding that grids are modular suggests that these co-ordinated networks operate somewhat in isolation from each other, and yet the similarity in the module scale ratios
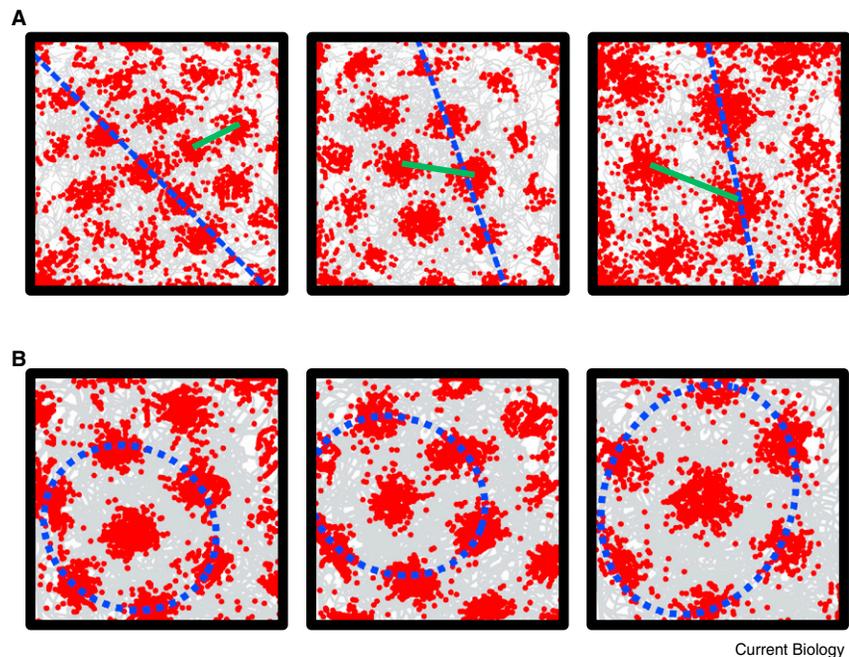

Figure 2. Modularity of grid cells.

(A) Co-modularity of orientation and scale. The three plots are from three different, simultaneously recorded cells from three different modules from Stensola *et al*. [3], depicted as in Figure 1. Note the difference in scale (shown by the green bars) and also in orientation of the grids (dotted blue lines). (B) Modularity of grid distortion. The distortion is shown by connecting the centres of the outer fields in a hexagonal array and seeing that these form an ellipse (blue dotted line) rather than a circle. Note that the ellipses in the different modules have different orientations. (Both panels modified with permission from [3].)

across different scales suggests, by contrast, that there is some kind of 'cross-talk' between modules. One possibility is that modules constrain each others' formation by the same kind of cooperative/competitive dynamic that generates grids in the first place. That is, perhaps modules are the end product of the brain's attempt to organise continuously varying grid scales and orientations within the same interacting cell population, by analogy with the way in which discrete political parties emerge from society's attempts to organise the underlying continuum of political views. Studies of grid formation during development may help answer this question.

The second question raised by the findings is a functional one: do these modules serve a purpose? It is not yet clear why independent modules would be a useful organisational feature for a map grid, but one possibility is that different modules have different roles,

such as perhaps to represent spaces of different sizes. Alternatively, perhaps the variation in size and orientation serves to break up the otherwise repeating pattern that forms when homogeneous grids combine, allowing unique spatial patterns to emerge in the downstream neuronal population, the hippocampal place cells [7].

Clearly, there is much still to discover about this fascinating system. Whatever the origin and function of the discrete organization of entorhinal cortex, its discovery will be important in shaping our understanding of how the brain's grid reference develops and functions. Not only that, it may also advance our understanding of organizational principles in cortical systems more generally.

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Integrative Cell Biology: Katanin at the Crossroads

A new study showing a functional and physical interaction between the ROP effector RIC1 and the microtubule severing enzyme katanin brings together auxin signaling and microtubule ordering in *Arabidopsis* pavement cells.

Olivier Hamant[1,2]

The nexus between upstream signaling receptors and downstream effectors is often thought to rely on complex cascades. In fact, only portions of such transduction pathways have been identified so far and the exact topology of these cascades remains to be fully characterized. A new study, recently published in *Current Biology* by Lin, Cao *et al.* [1] provides an interesting example in which a rather simple pathway causally links auxin perception, Rho GTPase activation, katanin activity, microtubule ordering and finally cell shape in plants.

The epidermal cells of most plant leaves — pavement cells — exhibit a very peculiar puzzle shape, with necks and lobes. While the biological function associated with this shape remains elusive, these cells represent excellent systems to investigate the

processes controlling morphogenesis and polarity. Mechanistically, it has been proposed that the bundling of microtubules in necks (Figure 1) reinforces the cell wall, *via* the deposition of cellulose along the microtubule tracks. Like a balloon with local thickenings, the presence of turgor pressure coupled with local wall reinforcements promotes the formation of outgrowths between the area where microtubules bundle, hence the jigsaw puzzle shape of these cells. The regulatory pathway that is behind this original microtubule pattern has been investigated thoroughly in the past decade, notably highlighting the essential role of the small Rho GTPase in plants (ROP) [2].

As also observed in animal cells, the Rho GTPases play a crucial role in polarity establishment in plants. In pavement cells, the activation of ROP6 and its effector RIC1 in the necks

promotes the bundling of microtubules in these areas [3]. Interestingly, auxin, *via* one of its receptors, ABP1, can activate ROP6 and ROP2 (Figure 1) [4]. ROP2 preferentially promotes actin assembly in the lobes through its effector RIC4, and this actin assembly locally inhibits the internalization of the auxin efflux carrier PIN1, which is then trapped at the membrane where ROP2 is further activated by extracellular auxin [5]. As ROP6 does not exhibit such a feedback loop on PIN1, this network is in principle sufficient to generate initial heterogeneities that can then build up into morphological changes between these different cellular zones.

Lin, Cao *et al.* looked at the other end of the cascade, that is, the link between RIC1 and microtubule bundling [1]. They found that RIC1 interacts with, and potentiates, the microtubule-severing protein katanin (Figure 1). This is a remarkable result for two main reasons. Firstly, katanin is well-characterized biochemically — it has been shown to cut microtubules in all kingdoms [6] and this activity has been related to many biological functions, including chromosome segregation (*e.g.,* [7]), cell shape (*e.g.,* [8]), growth heterogeneity [9], hormone