7

Spatial representation: a cognitive view

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Approaches to the representation and modelling of geographical phenomena in digital form have expanded recently with the introduction of new perspectives, notably from cognitive science. The chapter reviews the roots of this cognitive perspective, and examines the impacts it is having on GIS. A formal model of topological relations between geographical objects is introduced, and used as the basis of a simple experiment with human subjects to show how its concepts are mapped into human cognition. Such experiments show promise for improved designs for easier-to-use systems.

1 INTRODUCTION

Most computer programs gain their meaning from the relationships between their internal formalisms and some aspect of the external world. Digital objects are used to represent entities in the real world, and computational procedures represent real-world processes. In the science of artificial intelligence, a representation has been defined as 'a set of conventions about how to describe a set of things' (Winston 1984: 21). Winston goes on: 'A description makes use of the conventions of a representation to describe some particular things'. The fidelity of these representations of entities and processes of the world is a key factor in the potential utility and usability of almost any computational system. Representation is a key concept in any application that uses computers.

This chapter provides a cognitive perspective on representations of geographical space, entities, and relationships that underpin geographical information systems. Representations of things geographical that have been developed in the cognitive sciences for use in those sciences will not be a focus here, but will be reviewed for what they may contain that is relevant to GIS. The review will concentrate on how a cognitive science perspective can inform the definition and design of digital objects to represent geography. It will also concentrate on graphic symbols that can represent those internal digital representations for presentation to and interaction with GIS users.

2 REALISM AND EXPERIENTIALISM

Many of the characteristics of the geographical world can be determined through objective methods such as measurement although human perceptions of the geographical world are also established through such cognitive functions as perception, reasoning, and memory. These two worlds, of measurement and cognition, are clearly compatible in many aspects. Even if there is no functional connection between them (as a phenomenologist might assert), experiences provide feedbacks that tune internal mental representations to match reality. This is a restatement of experiential realism, a philosophical stance outlined and named by Lakoff (1987). Experiential realism appears to be a good base for geographical representation in GIS (Couclelis 1988; Frank and Mark 1991; Mark and Frank 1996). Also, if mental representations exist, and are shaped both by the nature of human brains, bodies, and senses and by the nature of the world, then the same representations should be appropriate both to model spatial cognition and for scientific models of geographical phenomena. Thus the representations discussed in this chapter should not differ systematically from those in other chapters in this section; rather, different motivations and sources of evidence should lead to similar representational systems.

3 PERCEPTION, BEHAVIOUR, LANGUAGE, AND COGNITION

'Cognition' and 'cognitive' are words that refer to conscious thinking, including memory, reasoning, and perception. 'Perception' normally has a more narrow meaning, being used to refer to mental sensations and processes that relate to the senses and which occur in the direct presence of sensory stimuli (this psychological definition of perception differs from the common (mis)use of this term in the geographical literature to refer to any mental or cognitive phenomenon, as in 'environmental perception'). Some brain functions, and some brain controls of the body, are outside consciousness – motor skills are a good example. Such non-conscious processes are usually excluded from 'cognition'. Since human behaviour is a combination of perceptual inputs, conscious decisions, and motor acts, cognition is just one aspect influencing human behaviour. Since people's reasoning and decisions cannot be better than their knowledge of situations, cognitive factors often influence behaviour more than objective properties of the world such as distances or directions.

Language can be considered to be a very specialised form of behaviour, but it also appears to provide a unique window on mental processes. The relation between language and thought is, however, controversial. Decades ago, amateur linguist Benjamin Lee Whorf proposed an extreme level of interdependence between language and thought – that people think in language, and that native speakers of different languages think (reason) differently (Whorf 1940). In recent times, many linguists have attacked this conjecture, sometimes known as the Sapir-Whorf Hypothesis, claiming that it is false, and even ridiculous (cf. Pinker 1994). Whether or not language influences thought, it seems obvious that thought influences language, and that studying both the structure and the use of natural language describing spatial situations is a good way to study how people think about such situations. More specifically, distinctions made by language, and distinctions in spatial situations which must be made in order to account for linguistic differences, may reveal fundamentals of spatial representation that may be useful in GIS as well.

4 ENTITIES, FIELDS, AND PHENOMENA

The first problem in representation is to decide what is to be represented. What things exist? To put this more formally, what is the ontology of geographical space? This chapter will follow the terminology of the US Spatial Data Transfer Standard (SDTS). 'Entities' are things in the real world; 'objects' are things in the digital world. Digital objects and associated attributes and values represent geographical entities. The distinction between entity and object makes explicit the difference between things and their representations in a formal system.

4.1 Entities versus fields

Many geographical phenomena are best described scientifically as fields. Good examples are topographic elevations, air temperatures, and soil moisture content. A 2-dimensional field may be defined as any single-valued function of location in a 2-dimensional space. Fields can be classified according to the levels of measurement (data types) of the dependent variable. Two of the most important types are continuous fields, in which the dependent variable is measured on an interval or ratio scale, and discrete fields, with nominal dependent variables. It appears that any geographical phenomena can be represented either as a field or as a collection of digital objects. However, in many cases one approach is a much better basis for efficient computation; also, one may be a better model of people's mental representations of the phenomena. For example, a set of states or provinces within a country would commonly be represented in GIS as a set of areal objects, or as a set of linear objects that form their boundaries. However, the same phenomenon could also be represented as a discrete 2-dimensional field where each point in space is mapped into the nominal category indicating which state it falls in. Fields can be digitally represented by vector approaches, but often are represented by raster data structures.

Whether the entity or the field model is more appropriate is particularly interesting for topographic elevations. Topographic data normally are represented in GIS as fields, either through gridded digital elevation models (DEMs) or as triangular tessellations (TINs: see Hutchinson and Gallant, Chapter 9). Although TINs are often placed in the vector GIS class, they still represent a field. However, in discourse, people normally communicate about terrain in terms of features such as hills, ridges, valleys, gullies, canyons, etc. Thus, a commonsense GIS, capable of being used by untrained people, should be able to handle queries about 'this hill' or 'that canyon'. However, this is not just an issue for easy-to-use GIS: a lot of field data from the pre-Global Positioning System (GPS) days – such as the labels on biological specimens in museums – have location specified only by feature names and descriptions, such as 'on the east ridge of Sumas Mountain' (see also Seeger, Chapter 30; Shiffer, Chapter 52; and Smith and Rhind, Chapter 47). A system to geocode such museum locality data automatically would have to be able to recognise ridges and mountains. Technically, either an objects or a fields model could be used internally in a GIS; the other model could then be presented to users as a 'view'.

4.2 Dimensionality: points, lines, and areas

It has become standard practice to classify geographical entities according to their dimensionality as points, lines, or areas. This typology is especially prevalent in cartography. For the conventional wisdom of US cartography there is arguably no better place to look than the various editions of *Elements of Cartography* by Arthur H Robinson and his various colleagues at the University of Wisconsin. In the second edition, Robinson (1958: 137) wrote about four kinds of geographical quantities (point, line, area, and volume) and three kinds of cartographic symbols (point, line, and area). Robinson discusses 2-dimensional data in a chapter on 'Mapping quantitative point, line, and area data', and separates volume data under the title 'Mapping 3-dimensional data'. Campbell's textbook (1984) follows an almost identical chapter subdivision, with chapters on 'Mapping spatial variations: points, lines, and areas' and on 'Mapping spatial variations: surfaces'. It is not surprising that GIS follows the same basic classification, using dimensionality as the highest level of subdivision for geographical objects (cf. Fegeas et al 1992).

It is interesting that cognitive and linguistic works also use such a classification, apparently without knowledge of the cartography and GIS literatures. For example, in Herskovits' (1986) study of the prepositions in English, she uses exactly the same classification based on dimensionality; as does Talmy's classic work on the relation between language and the structure of space (Talmy 1983). Evidently, although entities must be 3-dimensional to have a real physical existence in a 3-dimensional world, it is common if not universal for people to conceptualise some geographical entities as points, others as lines, and still others as areas (regions).

4.3 Entities with uncertain boundaries

Whereas some geographical entities have distinct or crisp boundaries, many lack these and instead are 'bounded' by transition zones (Fisher, Chapter 13). The frequency of such indistinct boundaries is one of the most distinctive things about geographical entities, compared with manipulable (table-top) entities. The frequency of geographical entities with indistinct boundaries has been known for some time, yet vector GIS is tuned to represent entities with crisp boundaries, whereas raster GIS does not represent entity boundaries at all. Thus, formal methods for the representation of geographical entities with uncertain or graded boundaries is an important new research topic in GIS (cf. Burrough and Frank 1996). Fuzzy set theory represents a possible approach to modelling entities with graded boundaries, but it has problems (see Fisher, Chapter 13). Fuzzy membership functions can be the dependent variables in membership fields, perhaps represented by rasters, but it is not clear whether a full range of GIS functions can be based on such data or whether results of such implementations would be either cognitively acceptable or scientifically valid. Much work in implementation, testing, and human subjects' evaluation lies ahead.

4.4 Entity types

Classification is a fundamental cognitive process, and it is widely held that categories lie near the heart of cognition (Lakoff 1987; Rosch 1973, 1978). Categories carry a great deal of generic, or default, characteristics of entities and allow people to 'know' some aspects of novel situations. Geographical entities are no exception, and classification of geographical entities into categories is a well-known process both in everyday thinking and in scientific work. Various subfields of geography have developed elaborate classifications for kinds of landforms, vegetation assemblages, settlements etc.

Mark (1993) described a cognitive theory of categories and showed how such a theory could form a sound basis for entity types in geographical data interchange standards such as the US SDTS and other data standards. Using an example of inland water bodies, Mark showed that the conceptual boundaries between adjacent categories of water bodies in two closely related European languages (lake, pond, lagoon in English compared with lac, étang, lagune in French) did not match up. The category of water bodies classified as étangs in French might be considered to be lakes or ponds or lagoons in English. In standard English, lakes are distinguished from ponds mainly by size and lagoons are distinguished mainly by their position relative to the sea. On the other hand, the distinction between *étang* and *lac* in French seems to be mainly one of water quality with étangs having stagnant water. A weakness of Mark's analysis is that it was based on dictionaries and examples, rather than on human subjects' data. Clearly, further research is required. The example points to the relation of geographical categories to cognition, and to the potential of cultural differences in geographical entity type definition, which could be an impediment to cross-cultural geographical information exchange.

5 SPATIAL RELATIONS

Spatial relations are what distinguish spatial information from other information. Spatial relations are often encoded in human natural language by closed-class linguistic elements, typically prepositions in western European languages. 'Closed-class' means that there is a relatively small and fixed set of words (lexicon), and thus a limited number of categories that can be distinguished. Spatial relations also can be expressed through verbs that describe trajectories or other spatial actions.

Mathematically, in a metric case, there is an infinite continuum of possible spatial relations between any two entities. Topological characteristics of a situation are invariant under certain transformations. There is evidence that many of the cognitively important spatial relations are entirely or predominantly topological. Because of combinatorial principles, even a small number of topological distinctions can lead to a large number of mathematically-distinct topological spatial relations. Most work on formalising spatial relations, both in GIS and in cognitive science, has relied on researchers' intuitions as to which relations are worthy of distinction and which are not. Some cognitive principles for motivating formal models of spatial relations are presented in this section (5.1–5.4).

5.1 Topology and metrics

Topology may be defined as 'those properties of geometrical figures that are invariant under continuous deformation' (McDonnell and Kemp 1995). Many spatial relations between objects are topological in nature, including adjacency, containment, and overlap. It has long been known that topological spatial relationships are learned by humans at a very early age, well under one year (Piaget and Inhelder 1956). Metric information such as size, shape, distance, or direction can also be very important cognitively, but is often used to identify entity types. Metric aspects of spatial relations often refine, rather than define, spatial relations. The relative roles of topological and metric properties in defining spatial relations in reasoning or language is complex. Some terms indicate relations which are purely topological, and in those cases metric properties may be irrelevant – 'within' and 'enters' are probably examples of this. In other cases, metric properties such as distance or direction, expressed either quantitatively or qualitatively, may determine the meanings of various terms, for example 'north of' or 'near' both normally refine the 'disjoint' topological relation, and are ill defined for non-disjoint entities.

5.2 Spatial relations between disjoint objects

It seems that spatial relations between disjoint entities, which neither touch nor overlap, are characterised by a system of distinctions that is essentially independent of the system used to describe and classify spatial relations for non-disjoint entities. This section (5.2) deals with disjoint entities, and the following section will deal with the other case.

5.2.1 Distance

Distance may be pure Euclidean distance. In natural language, 'hedge' words such as 'about' are often associated with approximate numerical distance.

Even more commonly, distance may be given in qualitative rather than metric terms, dividing distances into perhaps just three categories: 'at', 'near', and 'far'. There may be gender differences in the tendency to use or rely on metric distances, compared with landmarks. Concepts such as 'near' are ill defined, and Robinson and his colleagues (Robinson and Lundberg 1987; Robinson and Wong 1987) worked on calibrating the meaning of 'near' using fuzzy set theory.

5.2.2 Direction

Direction also may be either qualitative or quantitative. Direction is an orientation specified relative to some reference frame (see section 5.2.3). Again, in everyday speech, directions seem normally to be specified qualitatively, typically in either four or eight directions. For science and navigation, more precise metric measures of directions are needed, normally specified in degrees from some arbitrary direction. Frank (1992) has discussed qualitative reasoning about cardinal directions, and has shown that eight directions are an adequate basis for most spatial reasoning.

Ideally, directional relations are thought of as being between points. Directions are not so straightforward between spatially-extended entities, since a large range of directions may exist, between any point in one entity and any point in the other. Peuquet and Zhan (1987) discussed this problem and provided heuristic rules for computing the direction relation between extended entities. However, there were apparently no human subjects tests to evaluate whether the algorithm's conclusions match human intuitions or the usage of directional terms. The approach advocated in this chapter requires eventual cognitive testing with human subjects before the heuristics developed by Peuquet and Zhan can be considered to be effective and workable representations (see also Peuquet, Chapter 8).

5.2.3 Reference frames

Various reference frames are used in discourse and spatial reasoning. Geographically, in many cultures, a reference frame based on cardinal directions seems dominant for outdoor ('geographical') spaces, whereas viewer-centred or object-centred reference frames often dominate for bodily or tabletop ('manipulable') spaces and entities (Mark et al 1987). But even in speech communities that typically use cardinal directions in geographical space, it is common to describe location as being, say, 'in front of the library', which invokes a directional reference frame centred on and oriented to the library. Systems to use and understand many spatial terms, especially directional, will have to accommodate multiple reference frames and switching contexts. Individuals may need to switch among these reference frames during discourse or spatial reasoning. Preferences among multiple available reference frames vary with situation, scale, and culture, with a few cultures typically using cardinal directions even indoors and for body parts, and with others failing to have orthogonal geographical coordinate schemes equivalent to cardinal directions (Pederson 1993).

5.3 Spatial relations between non-disjoint objects

This section discusses topological spatial relations between entities using a particular formal model termed the 9-intersection (Egenhofer and Kuhn, this volume; Egenhofer and Herring 1994). This model is based on very simple views of spatial entities: each entity is defined to have an interior, a boundary, and an exterior. The exterior fills the 'universe', except for the parts of that universe occupied by the entity itself and its boundary. Uses of the 9-intersection, and the discussions of it in this chapter, have been restricted to entities in a 2-dimensional space, although it can also be applied to spaces of fewer or more dimensions.

The simple form of the 9-intersection model tests each 'part' (interior, boundary, exterior) of one spatial entity against each such part of the other and simply records which of the nine possible intersections (3×3) are empty and which are not. With two possible 'states' for each of nine possible intersections, this model could distinguish 2^9, or 512, spatial relationships. However, if continuity constraints are placed on the entities involved, the number of possible spatial relations is greatly reduced. The 9-intersection model offers no improvement in explanatory or descriptive power for region–region relations, compared with previous models. For a pair of regions, eight spatial relations can be distinguished, as shown in Figure 1. For two simple unbranched line segments, however, the 9-intersection model distinguishes 33 different topological spatial relations. It seems unlikely that people distinguish that many relations and we advocate human subjects testing to sort out how these 33 relations are organised in cognitive and linguistic systems.

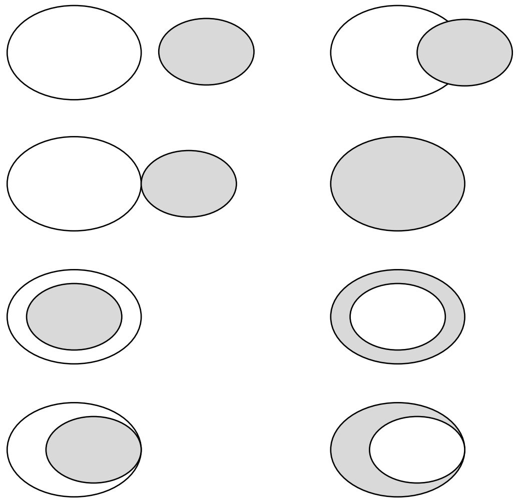

Fig 1. The eight distinct spatial relations between two simply connected 2-dimensional objects in a 2-dimensional space, according to the 9-intersection model.

Line–region relations offer an interesting intermediate level of complexity and resolution. Egenhofer and Herring (1994) showed that 19 spatial relations are possible between a line and a region. These relations have formed the basis for a program of cognitive evaluation of spatial relations that Mark and Egenhofer have been conducting over the last several years. This work will be reviewed next as a case study.

5.4 Case study: spatial relations between lines and regions

As noted above, the simple (Boolean) version of the 9-intersection model distinguishes 19 spatial relations between a simple, unbranched line and a simply connected region without holes. Intuition would suggest that people would rarely distinguish that many spatial relations. However, such intuitions may be wrong, and human subjects testing is essential to determine what distinctions are actually made in language or spatial reasoning. Tests of users' reactions to spatial relations in queries or reasoning situations apparently have not been performed. However, tests using language have been done by Mark, Egenhofer and colleagues, and this work will be summarised here to demonstrate the value of subjects testing combined with formal models.

Mark and Egenhofer first explored the cognitive validity of the 9-intersection relations using a grouping task (Mark and Egenhofer 1994b). All of their experiments so far have been performed with a geographical context of a road and a park. A park outline shape was kept constant for all experiments, and roads were placed in 38 different positions, two for each 9-intersection relation. Subjects were asked to put drawings into groups so that the same phrase or sentence could be used to describe all drawings in the group. Subjects were native speakers of English, Mandarin, or German. The experiment produced two main findings: first, topologically identical drawings (according to the 9-intersection) were almost always grouped together by any subjects; but second, subjects grouped topological relations in a very wide variety of ways (Mark and Egenhofer 1994b). Beyond the 9-intersection classes, individual differences dominated the results, and cultural or linguistic differences, if present, could not be detected given the small sample sizes and the within-group variance. Tendencies for relations different in only one of the nine intersections to be grouped together were used by Egenhofer and Mark (1995) as part of an evaluation of conceptual neighbourhoods for spatial relations. However, different experimental protocols were needed to get at more subtle differences in cognitive representations of spatial relations.

Mark and Egenhofer designed an agreement task and a drawing task. In the drawing task, subjects were presented with blank outlines of a polygon said to be a park, with a sentence under each drawing. They were asked to draw a line to represent a road that had the spatial relation indicated in the sentence. This test was applied to 32 English subjects, each of whom was asked to draw 64 sentences, and 19 Spanish-speaking subjects who drew 43 sentences (Mark and Egenhofer 1995). Such a protocol tends to identify prototypical configurations. Respondents produced a total of more than 2800 drawings; 88 per cent of which fell into just five spatial relations, roughly equivalent to 'inside', 'outside' (disjoint), 'enters', 'crosses', and 'goes to'. Sharif (1996) analysed the geometry of the drawings by the English language subjects and found that there were many empirical regularities in the spatial relations drawn.

In the agreement task, subjects were presented with a road–park map and a sentence (such as 'the road crosses the park') and were asked to evaluate the degree to which the sentence described the spatial relation between the road and park shown in the map (Mark and Egenhofer 1994a). This task was much more controlled, and produced useful results. It has been applied to 12 sentences in English (see Mark et al 1995 for a summary of most of this work) and one sentence in Spanish; Abrahamson (1994) also used the same stimuli and experimental protocol for five sentences in Norwegian. A total of more than 550 subjects have been tested for English sentences, and about 90 subjects for the Spanish sentence. When responses are averaged for each map–sentence pair, across all subjects within a language, and rescaled to a 0–1 scale, the values can be interpreted as the 'membership' of that map in the fuzzy set of all configurations described by, for example, 'the road crosses the park'. Correlations between mean agreements to different sentences, across all maps, can be interpreted as a measure of the similarity in meanings of the sentences tested. The mean agreement values can also be related to other parameters describing the configurations, in efforts to explain subjects' responses and perhaps to characterise the meanings of the sentences themselves.

The most solid data are for the English sentence 'the road crosses the park' (about 150 subjects) and the Spanish 'la carretera cruza el parque' (about 90 subjects). These are plotted in Figure 2, and the simple correlations between the means by diagram is 0.985 (97 per cent of variance in common). Not only are the means related to topology in about the same way, but geometric variations also reduce agreement for the English-speaking and Spanish-speaking subjects in almost exactly the same way.

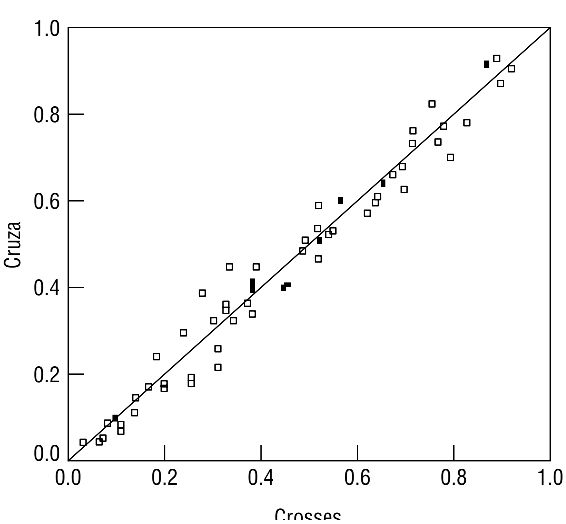

Fig 2. Mean agreement values for 'cruza' against 'crosses'.

The results of all this testing has been a general confirmation of the validity of the 9-intersection model. However, the relations it distinguishes must in most cases be aggregated in order to make intuitive spatial relations. Previous work on formal models of spatial relations has generally assumed, either explicitly or implicitly, that the relations distinguished form a uniform set of equally distinct spatial relations. In the new model, the same 'primitive' spatial relation might be an element in two or more cognitive spatial relations. This result requires both a powerful formal model of spatial relations, and human subjects testing, using several protocols, to confirm or refine the formal models.

6 SUMMARY AND PROSPECTS

Experiential realism appears to bridge the gap between naive realism and developmental models of cognition. Cognition is related to perception, language, and behaviour. The exact relation of language to cognition is controversial, with some believing that language shapes cognition, whereas others see cognition as being independent of language. Whatever the relation, language is certainly related to culture, and makes an excellent site for the study of certain aspects of cognition.

Both entities and fields exist in cognitive models. Entities are typically conceptualised as being organised by dimensionality: points, lines, areas, volumes. Entities are often thought of as having indistinct boundaries, a fact which is at odds with typical GIS representation schemes. Entities are also categorised, and since many aspects of nature form a continuum, categories may be relatively arbitrary and thus subject to cultural differences. Spatial relations, on the other hand, seem to be very similar in disparate cultures and languages. Cognitive spatial relations are predominantly topological but metric factors such as distance and direction often refine the relations and characterise prototypical relations. A case study, that of spatial relations between lines and regions, was used to describe the value of research approaches combining formal models and human subjects testing.

There is a very real sense in which all representations are cognitive. Mathematics is, after all, a formalisation of how at least some people think. The cognitive view of spatial relations, however, emphasises the importance of human subjects testing, preferably under laboratory controlled conditions, in defining the nature of the spatial representations that are needed for geographical information systems and spatial analysis.

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And cognitive representation about space is one of the important fields in Geographic Information Science (Montello 2000), which has formed the following cognitive image schemata (Fabrikant & Buttenfield 2001): (1) container, which has an interior, an exterior, and a boundary, (2) Surface, continuous data are modelled on a surface.Â views of space describe the connectivity and adjacency of geographic features, (7) center-periphery, thiessen polygon maps delineate functional regions.Â Secondly, cognitive image schemata based on the geographic spatial cognition under the three spatial frameworks play important roles in guiding to determine the correlative and corresponding spatial predicates, which should be based on the integrating tightly epistemic logic with ILP. Cognitive spaces provide a domain-general format for processing in the hippocampal-entorhinal region, in line with its involvement beyond navigation and memory. Spatial navigation serves as a model system to identify key coding principles governing cognitive spaces. An important question concerns the extent to which firing properties of spatially tuned cells are preserved in cognitive spaces. Technological advances such as calcium imaging will clarify coding principles on the population level and facilitate the translation to human cognitive neuroscience.