MRes Paper

Student: Gabriele Filomena

Journal: Environment and Planning B: Urban Analytics and City Science

Word count: 4820

Journal Title
XX(X):1–22

Reprints and permission:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/ToBeAssigned
www.sagepub.com/
SAGE

A Computational approach to "The Image of the City"

Gabriele Filomena

Abstract

In *The Image of the City*, Lynch (1960) describes how individuals perceive and represent the complexity of urban artefacts. The most distinctive elements of the urbanscape, namely the legible ones categorised in paths, nodes, edges, districts and landmarks - give shape to the mental representation of the city, an entity on which orientation, spatial behaviour and human-environment interactions are based. His qualitative approach has stimulated research in spatial cognition, urban design, AI and robotics and still represents an essential pillar in the analysis of urban dynamics. Nevertheless, an explicit link between *The Image of the City* and GIS sciences is missing.

A quantitative and computational approach to *The Image of the City* is proposed with the aim of bridging this gap. Different perspectives in spatial cognition and GIS research are integrated, to obtain and depict an overall cognitive map, in which, presumably, the most salient elements are shared by a large part of the population. Nodes, paths and districts were identified employing network science techniques and following Space Syntax ideas about the relationship between spatial configuration, pedestrian movement and human-environment interaction. Relevant researches in landmark automatic detection were integrated with the information approach (Haken and Portugali 2003) to capture the complexity of points of reference in their visual, structural and semantic components, as conceptualised by Lynch and successive research on landmark cognitive salience. The methods were applied to the Congestion Charge Zone of London: the street network and a spatial dataset containing buildings' footprints were used as main data source.

Keywords

mental image, Lynch, cognitive maps, city, network, GIS

Introduction

In 1960 Lynch (1960) published *The Image of the City*, one of the most exhaustive and influential theories in spatial cognition and behavioural geography(Golledge and Stimson

1997; Portugali 2011). Lynch devotes himself to understanding how people perceive and represent the city, and from what external urban artefacts the mental image of the city arises. In other words, Lynch analyses two qualities of the built environment: legibility, ‘the ease with which its parts can be recognised and can be organised into a coherent pattern’ and imageability, ‘that quality in a object which gives it a high probability of evoking a strong image in’ the observer (Lynch 1960, 60).

Studying the city form of Boston, Los Angeles and Jersey City, the author finds out that individuals’ mental images can be overlapped to form a shared, community cognitive map. There is ‘consensus on the elements that enhance the identity and structure of a city’ (Nasar 1990, 42). Such skeleton is formed by five type of elements: paths, edges, nodes, districts, landmarks. Since the 70’s, the five elements have constituted the core of spatial cognition theories: these geographic elements mould the mental representations of the space, supporting orientation and movement within the complex environment. Siegel and White (1975) propose a well-known and comprehensive theory of the development of spatial knowledge. An initial declarative knowledge about landmarks and environment features (*landmark knowledge*) is followed by a procedural component, which contains information regarding the actions required for completing a path (*route knowledge*). Lastly, in the *configurational knowledge*, the other elements come into play; metric information and complex relations are stored. Successively, Lynch’s model has been reformulated in behavioural geography (Sadalla et al. 1980; Golledge et al. 1985; Presson and Montello 1988; Tversky 1993; Montello 1998). In particular, the paradigm of the anchor point theory (Golledge 1978; Couclelis et al. 1987) integrates Lynch’s perspective with empirical evidence on the hierarchical organisation of the spatial knowledge, processes of regionalisation and route segmentation.

Moreover, *The Image of the City* has deeply inspired research in environmental psychology (Devlin 2001). The mental image mediates in the interaction human-environment: ‘The environment suggests distinctions and relations and the observer (..), selects and organizes and endows with meaning what it sees’ (Lynch 1960, 6). Lynch has prompted the development of contemporary cognitive mapping research (Tversky 2003; Kitchin and Blades 2002), and facilitated the overcoming of the classic cognitive science paradigm: cognitive maps are today seen as mental constructs that guide the behaviour (Kaplan 1973; Kitchin 1994) or auto-organising systems that mediate the human-environment interaction (Portugali 1992).

Inevitably, this research trend has stimulated research in AI and robotics, where computational models such as TOUR (Kuipers 1978) and NAVIGATOR (Gopal et al. 1989), or neural network models (Kaplan 1976; O’Neill 1991) have been developed to reproduce and comprehend human mental processes. More recently, Raubal and Worboys (1999) have proposed a wayfinding simulation that integrates TOUR with embodied cognition theories (Johnson 1987). Nevertheless, while these approaches have allowed a better comprehension of human processes in the geographic space, there has not been a thorough attempt to integrate Lynch’s theory into GIS sciences, nor to support a quantitative formulation of *The Image of the City* relying on spatial datasets.

The aim of this work is to advance a potential framework to bridge the gap between cognitive mapping and GIS research, reuniting the study of the human cognition and the external environment, namely of the internal and the external representations. In the first part, a set of works that have attempted to reformulate Lynch's theory is reviewed. Thereafter, an integration of these different perspectives and their techniques is advanced. Finally, for each Lynchian element a computational method is proposed. The application of the methods in the central area of London is thence discussed.

Background

Space Syntax contribution

The relationship between the external space and the mental representation is the driving force of Space Syntax, a set of theories and techniques 'for the representation, quantification, and interpretation of spatial configuration in buildings and settlements' (Hillier et al. 1987, 363). In this perspective, the street layout and the configuration of the space have a strong impact on the development of mental representations (Kim and Penn 2004). The association between street configuration and cognitive mapping is not unprecedented and has been widely studied (Lynch 1960; Pailhous 1970; Freundschuh 1992; Timpf and Kuhn 2003; Richter 2009). What distinguishes Space Syntax research is the focus on topology rather than metric properties. Parameters concerning pedestrian movement are investigated through graph analysis, in a dual graph representation where axial lines (Hillier and Hanson 1984) - lines of sight - or road-centre lines (Turner 2007) are transformed into nodes and intersections into edges.

Within this community, Dalton and Bafna (2003) attempt to redefine Lynch's five elements through the constructs of axial lines and isovist (Benedikt 1979). In their view, Lynch pursues mainly the visual properties of the urban environment, neglecting the importance of structural aspects in spatial cognition. Therefore, they suggest to study and detect first order (spatial and structural) elements, that give shape to the mental representation, and second order (visual) elements, that enrich the image. The elements could be captured employing axial lines and isovists sorted in order of significance, so as to find the 'selective description of the city'. Nonetheless, the authors do not fully describe how to detect the elements; the transition from Lynchian, to Syntactical, first and second order elements appears inconsistent.

Jiang (2013) theorises that the scaling law of artefacts (Bettencourt et al. 2007) may support the identification of the primary elements in the city, the ones that form the skeleton of the cognitive map (Kuipers et al. 2003). He tested his hypothesises on paths, transforming streets into axial lines and ranking them by connectivity. Consistently with his assumptions, less connected streets are much more than well-connected and memorable streets, regardless the city examined and the street morphology. Provided that the scaling law regulates also the identification of nodes and landmarks, the author, however, does not indicate what properties should be measured for ranking them.

The Space Syntax approach has been questioned for excluding metric information from the analysis, heights of buildings and land use properties (Ratti 2004). Furthermore, although road-centre lines have been recently adopted (Turner 2007), axial lines, have obstructed the integration of space syntax techniques into GIS, and are not recognised as a shared cognitive construct (Jiang and Claramunt 2002; Jiang and Liu 2009). Nevertheless, the emphasis on configurational aspects is an illuminating argument in the transition towards a computational approach to cognitive maps. Cities hide regularities, informal geometries and implicit grids that mould and are moulded by spatial behaviour and people's mental representation. The internalisation of the urban configuration influences travel choices, orientation and pedestrian movement. Here, the attention to the topological properties of space and the concept of openness proposed by Lynch encounter: the perception of the street patterns is based on vista spaces and the representation of topological relationships (Hillier 2012).

The information approach

Haken and Portugali (2003) have offered a stimulating approach to cognitive mapping that integrates the synergetics approach (Haken 1983), contemporary trends in cognitive science, ecological psychology, urban geography with Lynch's theory. The researchers, on one side, make explicit the link between the concepts of imageability and *affordance* (Gibson 1979), and on the other, employ Shannon's information theory, for studying how the mental image is formed from specific urban elements. In this sense, legible cities are composed of informative and significant artefacts or urban configurations. City nodes, paths or districts are 'information carriers' that shape the image of the city. Here, the original measure of information (Shannon and Weaver 1949) - a form of entropy that quantitatively measures the unexpectedness of an event out of a possible number of messages, Z - is adjusted with an index that incorporates semantic information. This component represents the result of biological, cultural, social and pragmatic categorization processes.

Their theory follows the idea that city elements may be remembered for symbolic and social meanings (Appleyard 1969, 1970; Golledge and Spector 1978), but also for their pragmatic functions. The combination of these traits contributes to the legibility of the city and transform an object in an external representation. The drawback of such an approach is that it contemplates a measure of entropy, suitable for the city- or district-level but unfitting for computing individual scores of the elements.

Automatic landmark extraction in Geoinformatics

Sorrows and Hirtle (1999), refine the notion of landmark, formalising Lynch's descriptions. The authors differentiate visual landmarks - objects used as spatial points of reference for their visibility - from cognitive landmarks - relevant for their symbolic meaning; they are unusual for their cultural meaning - and structural landmarks - recognisable for their advantageous position in the space and their prominence. This work has inspired a vein of research in GIS community interested in the automatic identification of landmarks for wayfinding design and navigational support.

Raubal and Winter (2002), advance a model that measures buildings' salience in relation to perceptual and cognitive properties: location, shape, façade area, colour, visibility, cultural and historic importance. Winter ameliorates the model, recommending to consider 3d visibility as another property. Elias (2003) presents a similar approach based on machine learning algorithms that inspect geometric, topological and semantic attributes of buildings to establish landmark hierarchies. Finally, Winter et al. (2008) integrate the previous approaches to construct a hierarchy of landmarks based on prominence, uniqueness and salience. In particular, they emphasise the distinction between local-landmarks, salient at the neighbourhood or district level, and city-wide (global) landmarks.

Towards an Integration

The information approach has been partly unnoticed by the research community in spatial cognition, while GIS sciences still struggle to implement and accommodate Space Syntax techniques. Automatic landmark identification models are more successful (Richter 2013), presumably due to their applicability in navigation systems design. Nevertheless, internal and external representations are still far:

- Space Syntax has tackled the image of the city considering mostly the visual aspects and neglecting important implications regarding activities and the genuine human-environment interactions.
- Haken and Portugali's approach, whilst being based on the usage of geospatial dataset, drifts apart from GIS science, returning a macro-level index of legibility.
- Edges have received a little consideration, as another kind of landmark, while districts, have been translated in simple *Voronoi* partitions.
- More important, even in the successful approaches, the dataset was composed of small areas, was created ad-hoc by the researchers or it relied on questionnaires and less objective data.

The five elements

In the following sections, appropriate network science techniques are presented for the detection of nodes, paths and districts, from the street configuration. In addition, landmark detection was performed following Sorrow and Hirtle framework and the models described above. These approaches were enriched with an accurate visibility analysis and integrated with Haken and Portugali's theoretical formulation; semantic and pragmatic properties are here considered for the first time in a large geodataset. Finally, a set of rules to extract edges is described.

The analysis was performed on the central area of London, UK, as defined by the Congestion Charge Zone (figure 1), coherently with the idea that the image of the city revolves around the vividness of the elements located in the city centre. The analysis relied mainly on the street network and buildings footprints. The sources employed are:

- *OS Open Roads*[*]. The dataset contains motorways, A-roads, B-roads, minor and local roads

[*]Crown copyright and database rights 2017. Ordnance Survey (Digimap Licence)

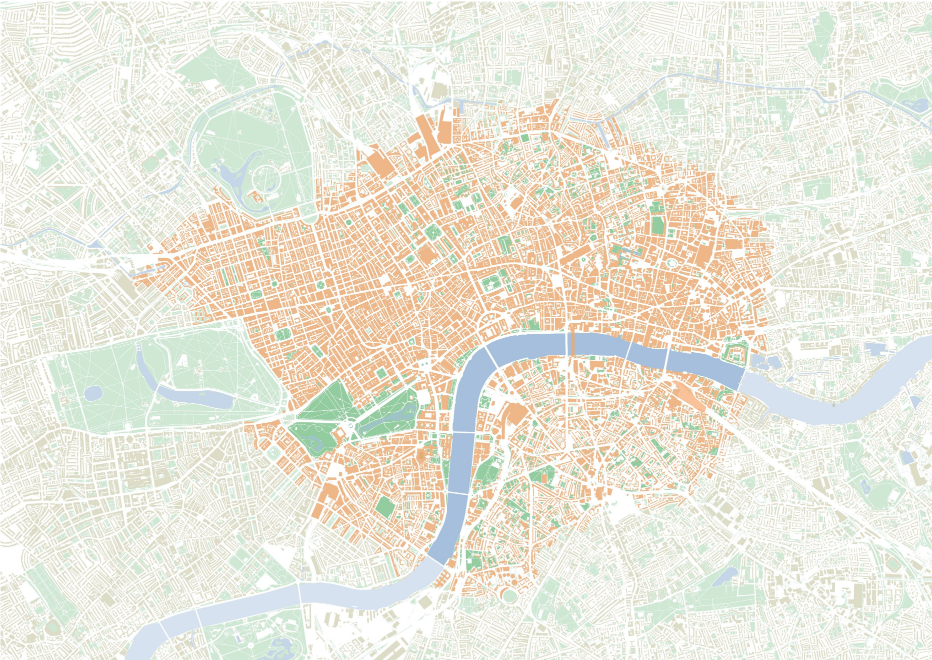

Figure 1. The area studied.

- *OS OpenMap Local (vector version)*. It includes a simplified representation of buildings footprints, and functional sites.
- *OS MasterMap - Topography Layer* (Ordnance Survey 2017) for water, road, green areas and railways structures surfaces.
- Supplementary dataset: the height of the buildings is included in free data-packs offered by *Emu Analytics*; The cultural and historic relevance is instead measured complying with Historic England[†] classification.

The extraction of each element is presented and discussed with reference to Lynch's considerations. Subjective observations are included to offer a personal validation of the results.

Nodes

Nodes are the strategic foci into which the observer can enter, and which are the intensive foci to and from which he is travelling. They may be primarily junction, places of a break in transportation, a crossing or convergence of paths. (..). Or they may be simply concentrations, which gain their importance from being the condensation of some use or

[†] historicengland.org.uk/listing/

physical character (Lynch 1960, 47). Space Syntax scholars have shown that elements

stored in people's cognitive map are related to centrality measures (Haq and Girotto 2003; Yun and Kim 2007). In this framework, topological properties of degree, closeness and betweenness (connectivity, global integration and choice) are usually computed employing a dual graph representation. However, Porta et al. (2006) argue that the primal approach is more effective in exploiting centrality indices to capture the skeleton of the urban structure and identify the crucial intersections.

'In theory, every ordinary street intersections are nodes, but generally they are not of sufficient prominence to be imaged as more than the incidental crossing of paths' (Lynch 1960, 75). Centrality acts as a driving force in the development of the urban structure, and central locations are prone to become genuine urban nodes (Newman and Kenworthy 1999). Thus, Lynch's nodes could be viewed as places that are structurally made to be traversed, nodes with the highest *betweenness centrality* in a network. Betweenness centrality was calculated in a undirected planar graph composed of 3799 nodes and 5297 segments, as:

$$C_i^B = \sum_{j,k \in G, j \neq k \neq i} \frac{n_{jk}(i)}{n_{jk}}$$

Where n_{jk} is the number of shortest paths (Euclidean metric) between the nodes j and k, and $n_{jk}(i)$ is the number of shortest paths between the nodes j and k that pass through i.

The result of the analysis is shown in figure 2. The measure selects some crucial nodes (16 nodes, value greater than 678266), as the two extremities of Waterloo Bridge, Trafalgar Square, Holborn Circus, the triangle formed by New Oxford Street, Southampton Row and Bloomsbury Way, High Holborn and Shaftesbury Ave junction, Tottenham Court Road station and several other intersections along Oxford Street. In this context, the nodes at the extremities of Waterloo Bridge play a fundamental role in linking the south and the north, while Holborn Circus and Trafalgar Square may be essential passing through nodes in the major roads network. Likewise, the analysis indicates also the relevance of the intersections along Oxford Street. Excluding the meeting point represented by Tottenham Court Road junction, the others may instead assume a role of critical-decision points. Finally, there is a remarkable absence of nodes in the southern region.

Paths

Paths are the channels along which the observer customarily, occasionally, or potentially moves. (..). People observe the city while moving through it, and along these paths the other environmental elements are arranged and related (Lynch 1960, 47).

Paths are the main lines of movement in the city; they guide people movement, acting as orienting devices. In low-legibility contexts, when a path is not characterised by vivid activities or peculiar properties, perceptual continuity comes into play: people rely

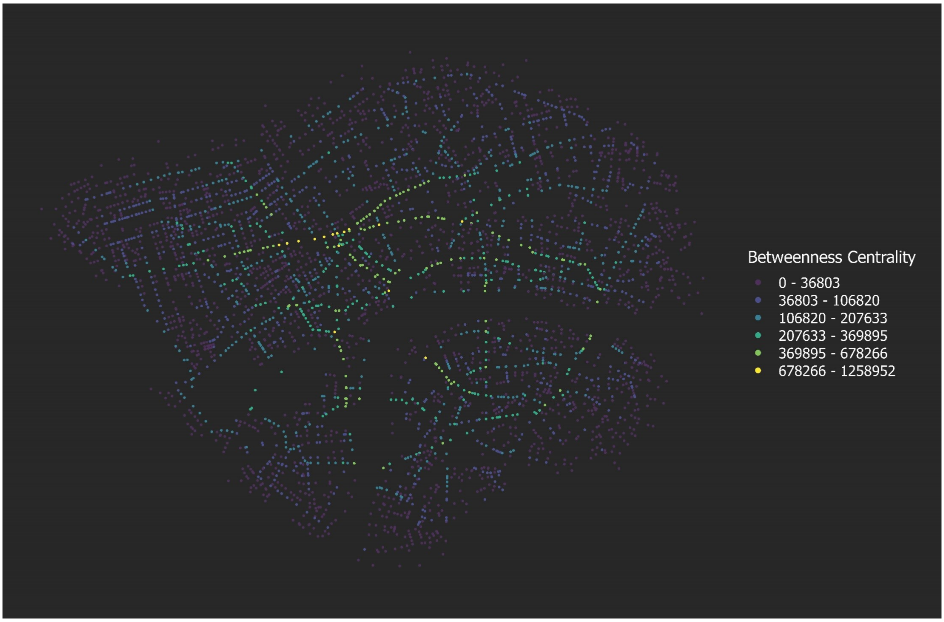

Figure 2. Street junctions coloured by betweenness centrality.

on this functional quality to successively travel across the city. This concept recalls the idea that people tend to choose routes that minimise the angular change rather than the distance (Sadalla and Montello 1989; Montello 1991; Golledge 1995; Hillier and Iida 2005). From a cognitive point of view, routes with fewer turns are easier to remember, especially in unfamiliar environments (Turner 2007; Mohsenin and Sevtsuk 2013; Cooper 2015). In this sense, angular betweenness is described as the best predictor of pedestrian and vehicular movement when only the street network is at the disposal of the researcher (Cooper 2015). In contrast with the Euclidean shortest path, based on Euclidean distance, this is a topological measure. Thus, betweenness centrality, as defined above, was computed for nodes in a dual graph representation. In this case, street segments were represented by nodes, intersection by edges. Besides, the amplitude of the angle of incidence formed by two segments was assigned to the corresponding edge as weight (see figure 3).

Figure 4 displays a skeleton of the major paths formed by 650 segments (values between 246012 and 2687304). The Inner Ring Road assumes a moderate importance, while the A40 stands out from the rest of the map. The A201, through Blackfriars Bridge, the A4200 (Kingsway, Southampton Row), and the Strand emerge as relevant directrices as well. Paths in the south are well-defined, despite the absence of preeminent nodes in the region; here, St George's Circus acquires a crucial function. Overall, a regular system comes to light: paths in central London are long streets, with an individual character; minor roads act as 'measuring devices'. It is noteworthy that, while in the north paths go

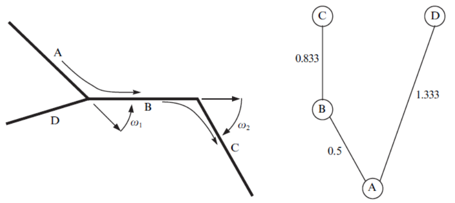

Figure 3. Angle of incidences and weights in a dual graph representation (Turner 2007, 542).

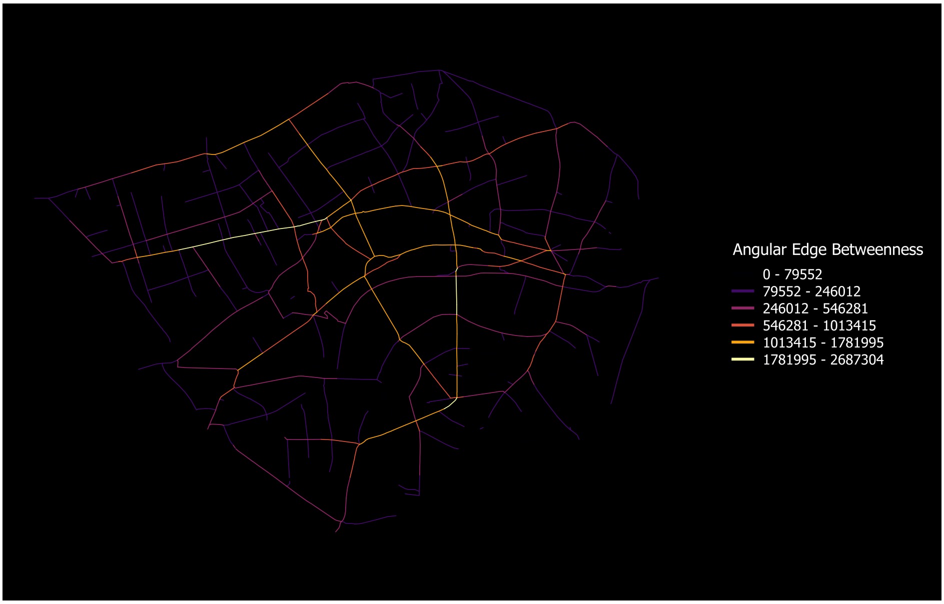

Figure 4. Segments coloured by angular edge betweenness.

from the east to the west, in the south, they move towards the north. In a sense, primary paths follow the patterns around them; they are coherent with the general structure.

Districts

Districts are the relatively large city areas which the observer can mentally go inside of, and which have some common character. They can be recognized internally, and occasionally can be used as external reference (Lynch 1960, 66). The characteristics that determine districts are thematic continuities which may consist of an endless variety of components (Lynch 1960, 67).

Districts are 'thematic units' used by individuals to refer to 'fuzzy entities' (Montello et al. 2011, 186), with imprecise boundaries. Therefore, formulating membership criteria entails a choice amongst different alternatives and implementations. In this discussion, it is assumed that the different districts of central London can be identified analysing the road layout. Indeed, Space Syntax suggests that the topology of the street network is associated with people perception of places and regions: Law (2017) illustrates a process for generating sub-graph from the street topology applying community detection techniques. The so formed Street-based Local Areas (SLA) (Turner 2007) are regions whose internal homogeneity has social and functional foundations (Girvan and Newman 2002).

In the present discussion, the *modularity optimisation* function is adopted to extract SLA. This algorithm optimises modularity, an index that measures the goodness of a network division, defined as:

$$Q = \frac{1}{2m} \sum (A_{ij} - \frac{K_i K_j}{2m}) \delta(C_i, C_i)$$

'Where A is the adjacency matrix; m is the total number of edges; K_i and K_j represent the degree of the subgraphs i and j; δ is a Kroneckar Delta function which equals 1 when its arguments are the same, 0 otherwise' (Law 2017, 167)

Modularity computes the difference between the edges within a community and the expected numbers of edges in a network with the same structure but random connections (a sort of null model). When the number of within-community edges is nothing more than random, the structure of the communities is poor and Q = 0. Otherwise, greater the difference, greater the modularity Q, stronger the division. The implementation of the modularity optimisation technique follows these steps:

1. Every node is a sub-graph.
2. Every node joins the neighbours with the highest modularity score in a subgraph. All nodes are checked.
3. The nodes in the same sub-graph form a new super vertex.
4. The first step is repeated until the modularity cannot be optimised anymore.

The function was run in an undirected dual graph representing the Greater London Area street network. 86527 segments were transformed in nodes, linked by 182225 edges. The partitions were computed for an unweighted network (figure 5) and a network were weights were based on the angle of incidence, as described above (figure 6). The results are compared with a subdivision of London in functional districts (figure 7), provided by the web-page *wikitravel.org/en/London*.

The role of the Thames is recognised only by the topological network. In the angular condition, the South Bank partition extends towards the other side of the river. The topological subdivision differentiates between Bloomsbury and Holborn but clusters Bloomsbury with Soho, Covent Garden and Leicester Square. Westminster and South Bank are instead well-defined. The angular network is capable to group Soho, Covent Garden and Leicester square together, separately from Bloomsbury. This condition generates more detailed and accurate partitions also when it comes to distinguishing amongst Bloomsbury, Holborn and the City.

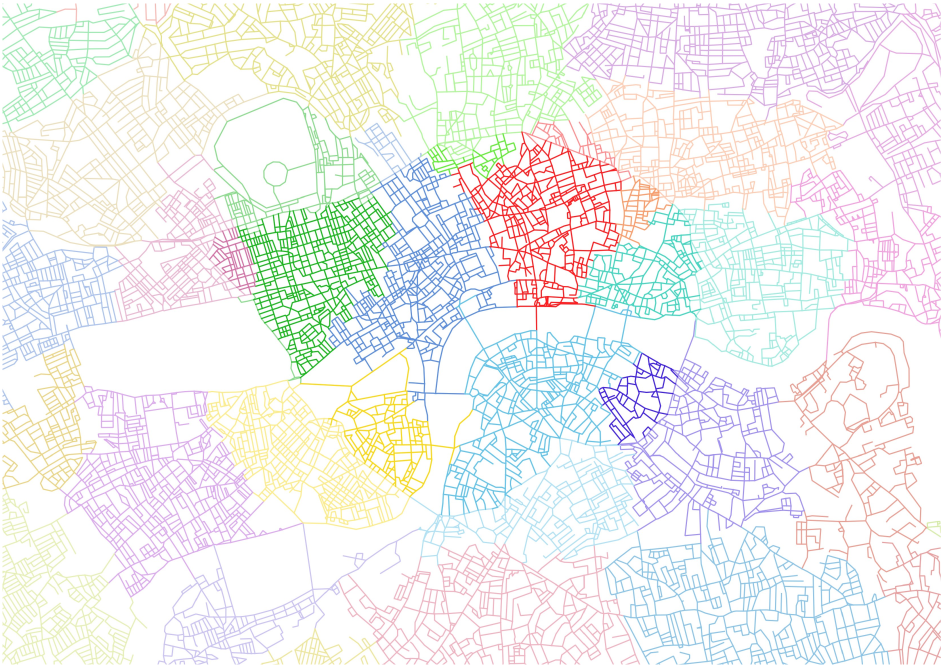

Figure 5. Street-based Local Area (SLA) - Topological partition.

Landmarks

Landmarks are point references considered to be external to the observer. They are more easily identifiable, if they have a clear form; if they contrast with their background; and if there is some prominence of spatial location (Lynch 1960, 78-79).

The present work follows Sorrows and Hirtle's framework in the distinction of three type of landmarks: visual, structural and cognitive (pragmatic and cultural meanings). Indeed for Lynch, an edifice may become a landmark when it stands out from the background; when there is a contrast. Nevertheless, in his view, activities and historic references may contribute to reinforcing the legibility when visual attraction is insufficient. Therefore, Raubal and Winter's set of techniques was enriched to allow for topological relations amongst the buildings, visibility, semantic and pragmatic aspects. The components considered were visual, structural and topological, semantic and pragmatic.

Visual properties included height, façade area and visibility of the buildings. The maximum height of a building was used for computing the visibility in ArcScene, using 446 major junctions as observer. For each edifice, the longest unobstructed (visible) line was kept and used as a coarse value of visibility.

For what concerns structural and topological properties, openness was computed as a 2d area of open space around a building, in every direction. The minimum distance

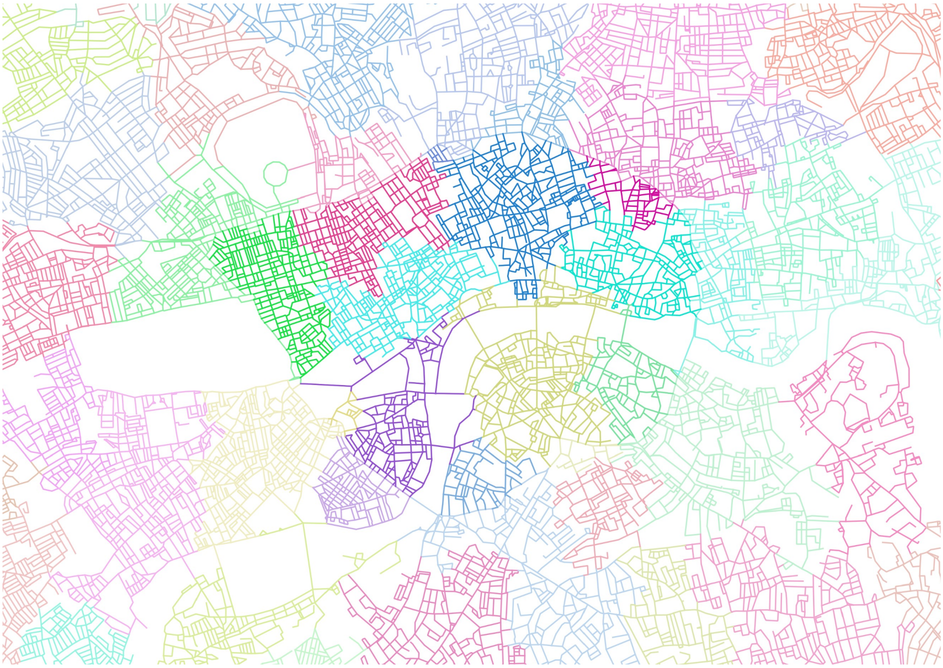

Figure 6. Street-based Local Area (SLA) - Angular weights partitions.

from the road, the number of adjacent buildings and the extension of the polygon were included in this analysis.

The cultural meaning of a building was obtained summing the score of listed historic elements located within its boundaries. Finally, pragmatic significance was calculated following a simplification of the approach proposed by Haken and Portugali, as an index of unexpectedness:

$$Ps_b = 1 - N_b/N$$

Where, in a buffer of 200 meters around the building b, N_b is the frequency of the land use class of b and N is the number of buildings. Such index of unexpectedness may indicate the pragmatic importance of a place for the observer or its peculiarity in a functional sense. The scores of the indexes were scaled and combined in the relative component, and, subsequently, in the overall score, on the basis of the weights specified in table 1. Figure 8 shows the scores of the buildings for each component. Figure 9 is coloured by the overall scores.

The maps show that the southern region is marked by a cross low legibility. In that region, there is a strong homogeneity in terms of visibility, rather mediocre, and structural attraction. Only the buildings along the river stand out from this dullness. The north-east of the city has a similar trend: in this area, there is a complete absence of points of

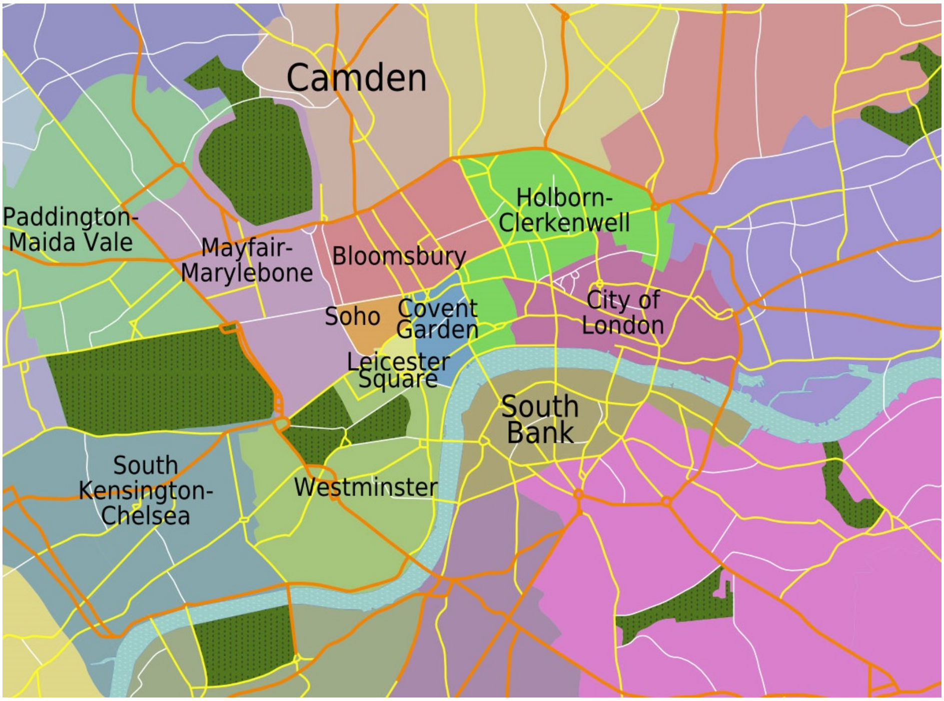

Figure 7. Functional districts in central London.

Table 1. Landmark extraction: properties and weights.

Component	Property	Property Weight	Component Weight
Visual	Visibility	0.50	0.50
	Façade area	0.30	
	Height	0.20	
Structural	Extension	0.30	0.30
	Openness	0.30	
	Neighbours	0.20	
	Road Distance	0.20	
Semantic	Cultural Importance	1.0	0.10
Pragmatic	Land Use	1.0	0.10

reference and the vividness is poor. Distinctive landmarks are also rare in the western part. However, this region is composed of more attractive and stimulating buildings. Indeed, most of the landmarks are distributed in the City - with a cluster of points of reference formed by a group of visible skyscrapers - along the river - as in Westminster - or in the northern part - with the railway stations, Euston and BT towers. In particular,

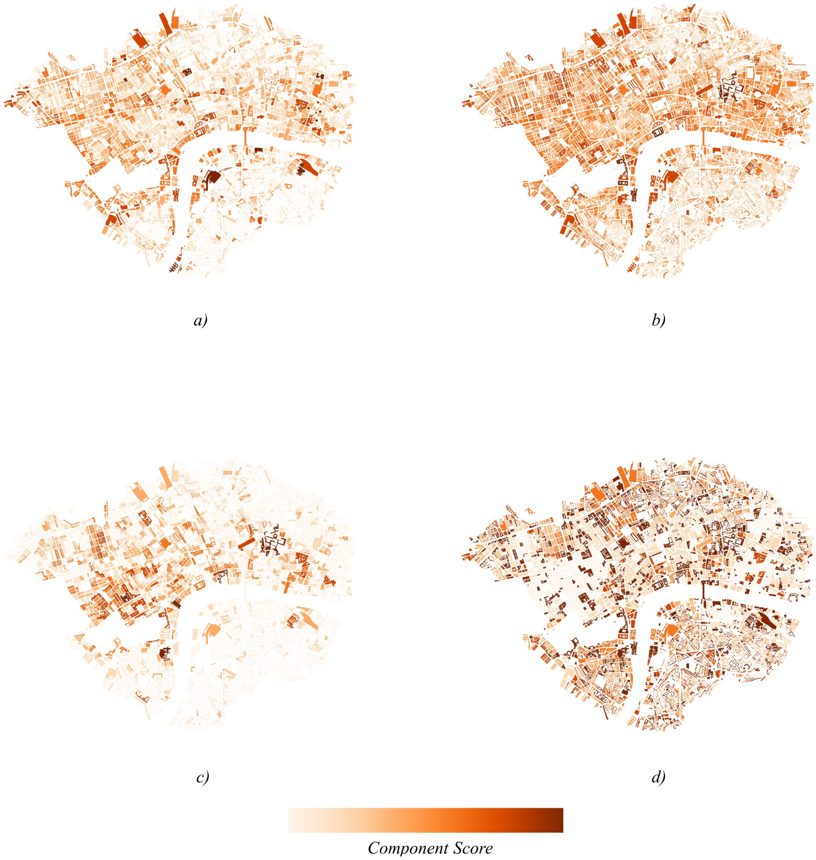

Figure 8. Buildings coloured by a) visual component, b) structural c) semantic d) pragmatic scores.

points of reference in Westminster support the idea that structural, pragmatic and cultural aspects come into play when visibility properties are mediocre. The opposite is true in the City, where there is a scarcity of semantic meanings and the landmarks are mostly visual.

Edges

Edges are linear elements not considered as paths: they are usually, boundaries between two kinds of areas. They act as lateral references. Those edges seem strongest which

Figure 9. Buildings coloured by overall scores.

are not only visually prominent, but also continuous in form and impenetrable to cross movement (Lynch 1960, 62).

Edges have generally been ignored in spatial cognition literature. Whereas Raubal and Winter (2002) reduce them to simple landmarks, Tomko and Winter (2013) describe their cognitive salience in wayfinding processes and cognitive mapping. They are authentic organising features whose primary trait is linear continuity. Nevertheless, this is not an isolating property: edges could be permeable and crossable, they can coincide and align with paths.

Here, the following linear and continuous elements were extracted:

- Boundaries of major parks.
- Railway structures as bypasses or other visible structures.
- River and watercourses.
- Roads with large carriageways.

In figure 10, the Thames splits the centre of London into two macro-areas. This division is not only geographical but even associated with different levels of vividness and centrality. Yet, somehow the river transmits the legibility of the north to the south bank. This barrier works as a seam. Conversely, the railway probably plays a more powerful role in terms of regionalisation. The network of bridges and bypasses, perhaps, compensates for the absence of landmarks, guiding urban flows towards the north but

Figure 10. Primary edges in central London.

also destructing the perceptual continuity in the region. Lastly, while Euston Road and Hyde Park delimit the city centre to the north and the west, the eastern border is probably blurrier.

The image of the city

The elements operate together, reinforcing each other reciprocally, giving coherence and structure to the image. This is not an external process but a complex of reciprocal interactions between the observer and the city. In figure 11 , all the districts (angular weights) and edges are displayed along with nodes, paths, and main landmarks (highest scores cluster).

The measures implemented in this work permitted to portray a well-defined network of paths that encounter each other in a group of central and crucial nodes. Although the south has penury of landmarks, several paths start in this region for reaching the northern nodes. Landmarks, scattered at the extreme north, along the river and in the east, support the movement of people towards more legible and thriving areas. Here, the north-east sector emerges as an area with a modest cognitive salience: this district is not traversed by major paths and building are not particularly informative. Presumably, this kind of contexts evoke a blurry and imprecise mental representation. On the contrary, area such as Soho, Covent Garden and Leicester Square, even though devoid of landmarks, are

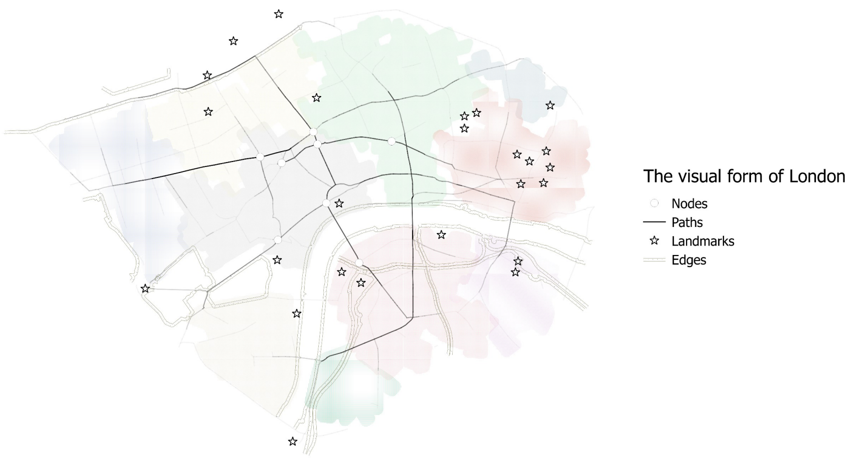

Figure 11. The image of the city, London.

concentrations of activities, traversed by dominant paths and nearby the major nodes. Furthermore, edges play an ambiguous role, fragmenting the region, but also reinforcing or spreading legibility around them.

Conclusion

The intent of the work is to advance a theoretical framework and a set of tools to integrate GIS and cognitive sciences. In Lynch view, the elements recognised and cited by a large number of subjects form the community mental images of Boston, Los Angeles and Jersey City. Here, the mental image of London was drawn ranking artefacts on the basis of network or geospatial measures. A complete geo-computational approach to The Image of the City was presented for the first time and tested on a large urban dataset, allowing for properties disregarded in the past research. However, the techniques implemented are not definitive and could be further enhanced and complemented. In particular, the public transport network should be taken into consideration for determining crucial nodes, beyond the street junctions. In this direction, as suggested by Tomko and Winter (2013), the image of the city could assume different structures depending on the mean of transport used by the observer. In other words, accessibility factors should be accounted for in the analysis. As mentioned, districts may be detected looking at other dimensions, like ethnicity or social factors, while edges may require a more precise formalisation.

Moreover, an accurate validation of the model is required. On on side, qualitative interviews or functional maps could be used to evaluate the results presented. On the other side, O-D matrices regarding pedestrian and traffic flows, or Points of Interest check-in datasets, might give indications on paths and nodes, besides indicating how to calibrate weights in the landmark extraction.

In conclusion, it was showed that a transition from *The Image of the City* towards the computational image of the city is feasible and inspiring. The present work encourages to tackle cognitive mapping research from a multidisciplinary perspective, not only in academia. The computational image of the city could indeed provide support in urban planning policies, through the identification of low-legibility areas (activities, movement and orientation), in wayfinding design, and in pedestrian-vehicular simulation models.

References

Appleyard D (1969) Why buildings are known. *Environment and Behavior* 1(2): 131–156.

Appleyard D (1970) Styles and methods of structuring a city. *Environment and Behavior* : 100–117.

Benedikt ML (1979) To Take Hold of Space: Isovists and Isovist Fields. *Environment and Planning B: Planning and Design* 6: 47–65.

Bettencourt LMA, Lobo J, Helbing D, Kühnert C and West GB (2007) Growth, innovation, scaling, and the pace of life in cities. In: *Proceedings of the National Academy of Sciences of the United States of America*, volume 104. ISBN 0027-8424, pp. 7301–7306. DOI: 10.1073/pnas.0610172104.

Cooper CH (2015) Spatial localization of closeness and betweenness measures: a self-contradictory but useful form of network analysis. *International Journal of Geographical Information Science* 29(8): 1293–1309. DOI:10.1080/13658816.2015.1018834.

Couclelis H, Golledge RG, Gale N and Tobler W (1987) Exploring the anchor-point hypothesis of spatial cognition. *Journal of Environmental Psychology* 7(2): 99–122. DOI:10.1016/S0272-4944(87)80020-8.

Dalton RC and Bafna S (2003) The syntactical image of the city: A reciprocal definition of spatial elements and spatial syntaxes. In: *Proceedings, 4th International Space Syntax Symposium*. London, pp. 1–22.

Devlin AS (2001) *Mind and maze: Spatial cognition and environmental behavior.* Praeger Publishers/Greenwood Publishing Group. ISBN 0-275-96784-0 (Hardcover).

Elias B (2003) Extracting Landmarks with Data Mining Methods. Springer, Berlin, Heidelberg, pp. 375–389. DOI:10.1007/978-3-540-39923-0{_}25.

Freundschuh SM (1992) Is there a relationship between spatial cognition and environmental patterns? In: Frank A, Campari I and Formentini U (eds.) *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*. Heidelberg: Springer, pp. 288–304. DOI: 10.1007/3-540-55966-3{_}17.

Gibson JJ (1979) *The Ecological Approach to Visual Perception*. Boston, MA: Houghton Mifflin. ISBN 9781848725775.

Girvan M and Newman MEJ (2002) Community structure in social and biological networks. *Proceedings of the National Academy of Sciences of the United States of America* 99(12): 7821–7826. DOI:10.1073/pnas.122653799.

Golledge RG (1978) Learning about urban environments. In: Carlstein T, Parks D and Thrift N (eds.) *Timing space and spacing time*. London: Arnold, pp. 76–98.

Golledge RG (1995) Path selection and route preference in human navigation: A progress report. In: Frank AU and Kuhn W (eds.) *Spatial information theory. A theoretical basis for GIS: International conference COSIT '95*. Berlin: Springer, pp. 207–222.

Golledge RG, Smith TR, Pellegrino JW, Doherty S and Marshall SP (1985) A conceptual model and empirical analysis of children's acquisition of spatial knowledge. *Journal of Environmental Psychology* 5(2): 125–152. DOI:10.1016/S0272-4944(85)80014-1.

Golledge RG and Spector AN (1978) Comprehending the urban environment: Theory and practice. *Geographical Analysis* 10(4): 403–426. DOI:10.1111/j.1538-4632.1978.tb00667.x.

Golledge RG and Stimson R (1997) *Spatial behavior: A geographic perspective*. New York: Guilford.

Gopal S, Klatzky RL and Smith TR (1989) Navigator: A psychologically based model of environmental learning through navigation. *Journal of Environmental Psychology* 9(4): 309–331. DOI:10.1016/S0272-4944(89)80012-X.

Haken H (1983) *Synergetics: An Introduction*. Berlin: Springer-Verlag. ISBN 9783642074059.

Haken H and Portugali J (2003) The face of the city is its information. *Journal of Environmental Psychology* 23(4): 385–408. DOI:10.1016/S0272-4944(03)00003-3.

Haq S and Girotto S (2003) Ability and intelligibility : Wayfinding and environmental cognition in the designed environment. In: *Proceedings, 4th International Space Syntax Symposium*. London, pp. 1–20.

Hillier B (2012) Studying Cities to Learn about Minds: Some Possible Implications of Space Syntax for Spatial Cognition. *Environment and Planning B: Planning and Design* 39(1): 12–32. DOI:10.1068/b34047t.

Hillier B and Hanson J (1984) *The social logic of space*. Cambridge: Cambridge University Press. ISBN 9780511597237. DOI:10.1017/CBO9780511597237.

Hillier B, Hanson J and Graham H (1987) Ideas are in things: an application of the space syntax method to discovering house genotypes. *Environment and Planning B: Planning and Design* 14(4): 363–385. DOI:10.1068/b140363.

Hillier B and Iida S (2005) Network effects and psychological effects: a theory of urban movement. *Spatial Information Theory. COSIT 2005. Lecture Notes in Computer Science, vol 3693.* .

Jiang B (2013) The Image of the City out of the Underlying Scaling of City Artifacts or Locations. *Annals of the Association of American Geographers* 103(6): 1552–1566. DOI: 10.1080/00045608.2013.779503.

Jiang B and Claramunt C (2002) Integration of Space Syntax into GIS: New Perspectives for Urban Morphology. *Transactions in GIS* 6(3): 295–309. DOI:10.1111/1467-9671.00112.

Jiang B and Liu C (2009) Street-based topological representations and analyses for predicting traffic flow in GIS. *International Journal of Geographical Information Science* 23(9): 1119–1137. DOI:10.1080/13658810701690448.

Johnson ML (1987) *The body in the mind: The bodily basis of meaning, imagination, and reason*. Chicago: University of Chicago Press. ISBN 9780226403175.

Kaplan S (1973) Cognitive maps in perception and thought. In: Downs RM and Stea D (eds.) *Image and environment: Cognitive mapping and spatial behavior*. Chicago: Aldine, pp. 63–78.

Kaplan S (1976) Adaptation, structure & knowledge. In: Moore GT and Golledge RG (eds.) *Environmental knowing*. Stroudsberg: Dowden, Hutchinson & Ross, pp. 32–45.

Kim YO and Penn A (2004) Linking the Spatial Syntax of Cognitive Maps to the Spatial Syntax of the Environment. *Environment & Behavior* 36(4): 483–504. DOI:10.1177/0013916503261384.

Kitchin RM (1994) Cognitive maps: What are they and why study them? *Journal of Environmental Psychology* 14(1): 1–19. DOI:10.1016/S0272-4944(05)80194-X.

Kitchin RM and Blades M (2002) *The cognition of geographic space*. London: I.B. Tauris.

Kuipers BJ (1978) Modeling spatial knowledge. *Cognitive Science* 2(2): 129–153. DOI:10.1207/s15516709cog0202{_}3.

Kuipers BJ, Tecuci DG and Stankiewicz BJ (2003) The Skeleton In The Cognitive Map: A Computational and Empirical Exploration. *Environment & Behavior* 35(1): 81–106. DOI:10.1177/0013916502238866.

Law S (2017) Defining Street-based Local Area and measuring its effect on house price using a hedonic price approach: The case study of Metropolitan London. *Cities* 60: 166–179. DOI:10.1016/j.cities.2016.08.008.

Lynch K (1960) *The image of the city*. Cambridge, MA: MIT Press.

Mohsenin M and Sevtsuk A (2013) The impact of street properties on cognitive maps. *Journal of Architecture and Urbanism* 37(4): 301–309. DOI:10.3846/20297955.2013.866864.

Montello DR (1991) Spatial Orientation and the Angularity of Urban Routes. *Environment and Behavior* 23(1): 47–69. DOI:10.1177/0013916591231003.

Montello DR (1998) A new framework for understanding the acquisition of spatial konowledge in large-scale environments. In: Egenhofer MJ and Golledge RG (eds.) *Spatial and temporal reasoning in Geographic Information Systems*. New York: Oxford University Press, pp. 143–154.

Montello DR, Goodchild MF, Gottsegen J and Fohl P (2011) Where's Downtown? Behavioral Methods for Determining Referents of Vague Spatial Queries. *Spatial Cognition & Computation* 3(2-3): 185–204.

Nasar JL (1990) The evaluative image of the city. *Journal of the American Institute of Planners* 56(1): 41–53. DOI:10.1080/01944369008975742.

Newman P and Kenworthy JR (1999) *Sustainability and cities : overcoming automobile dependence*. Washington, DC: Island Press. ISBN 9781559636605.

O'Neill M (1991) A biologically based model of spatial cognition and wayfinding. *Journal of Environmental Psychology* 11(4): 299–320. DOI:10.1016/S0272-4944(05)80104-5.

Ordnance Survey (2017) OS MasterMap Topography Layer [GML geospatial data], Using: EDINA Digimap Ordnance Survey Service.

Pailhous J (1970) La représentation de l'espace urbain: L'exemple du chauffeur de taxi. *Presses Universitaires de France* 10.

Porta S, Crucitti P and Latora V (2006) The Network Analysis of Urban Streets: A Primal Approach. *Environment and Planning B: Planning and Design* 33(5): 705–725. DOI: 10.1068/b32045.

Portugali J (1992) Geography, environment and cognition: An introduction. *Geoforum* 23(2): 107–109. DOI:10.1016/0016-7185(92)90009-S.

Portugali J (2011) *Complexity, cognition and the city*. Understanding Complex Systems. Berlin, Heidelberg: Springer-Verlag. ISBN 3642194508. DOI:10.1007/978-3-642-19451-1.

Presson CC and Montello DR (1988) Points of reference in spatial cognition: Stalking the elusive landmark. *British Journal of Developmental Psychology* 6(4): 378–381. DOI: 10.1111/j.2044-835X.1988.tb01113.x.

Ratti C (2004) Space Syntax: Some Inconsistencies. *Environment and Planning B: Planning and Design* 31(4): 487–499. DOI:10.1068/b3019.

Raubal M and Winter S (2002) Enriching wayfinding instructions with local landmarks. In: Egenhofer MJ and Mark DM (eds.) *Geographic information science. Second international conference, GIScience 2002*. Berlin: Springer, pp. 242–259.

Raubal M and Worboys M (1999) A Formal model of the process of wayfinding in built environments. In: Freksa C and Mark DM (eds.) *Spatial information theory. Cognitive and computational foundations of geographic information science: International conference, COSIT '99*. Berlin: Springer, pp. 1–21.

Richter Kf (2009) Adaptable path planning in regionalized environments. In: Hornsby KS, Claramunt C, Denis M and Ligozat G (eds.) *Spatial information theory: 9th International conference, COSIT 2009*. Berlin: Springer, pp. 453–470.

Sadalla EK, Burroughs JW and Staplin LJ (1980) Reference points in spatial cognition. *Journal of Experimental Psychology: Human Learning and Memory* 6(5): 516–28.

Sadalla EK and Montello DR (1989) Remembering changes in direction. *Environment and Behavior* 21(3): 346–363. DOI:10.1177/0013916589213006.

Shannon CE and Weaver W (1949) *The mathematical theory of communication*. Urbana, IL: University of Illinois Press.

Siegel AW and White SH (1975) The development of spatial representations of large-scale environments. *Advances in Child Development and Behavior* 10: 9–55.

Sorrows ME and Hirtle SC (1999) The nature of landmarks for real and electronic spaces. In: Freksa C and Mark DM (eds.) *Spatial information theory. Cognitive and computational foundations of geographic information science: International conference, COSIT '99*. Berlin, Heidelberg: Springer-Verlag, pp. 37–50.

Timpf S and Kuhn W (2003) Granularity transformations in wayfinding. In: Freksa C, Brauer W, Habel C and Wender KF (eds.) *Spatial cognition III. Routes and navigation, human memory and learning, spatial representation and spatial learning*. Berlin: Springer. ISBN 3-540-40430-9, pp. 77–88. DOI:10.1007/3-540-45004-1{_}5.

Tomko M and Winter S (2013) Describing the functional spatial structure of urban environments. *Computers, Environment and Urban Systems* 41: 177–187. DOI:10.1016/j.compenvurbsys.2013.05.002.

Turner A (2007) From Axial to Road-Centre Lines: A New Representation for Space Syntax and a New Model of Route Choice for Transport Network Analysis. *Environment and Planning B: Planning and Design* 34(3): 539–555. DOI:10.1068/b32067.

Tversky B (1993) Cognitive maps, cognitive collages and spatial mental model. In: Frank A and Campari I (eds.) *Spatial information theory. A theoretical basis for GIS: International conference COSIT '93*. Berlin: Springer, pp. 14–24.

Tversky B (2003) Structures of mental spaces: How people think about space. *Environment and Behavior* 35(1): 66–80. DOI:10.1177/0013916502238865.

Winter S, Tomko M, Elias B and Sester M (2008) Landmark hierarchies in context. *Environment and Planning B: Planning and Design* 35(3): 381–398. DOI:10.1068/b33106.

Yun YW and Kim YO (2007) The Effect of Depth and Distance in Spatial Cognition. In: *Proceedings, 6th International Space Syntax Symposium*. Istanbul, pp. 1–14.