A COMPUTATIONAL APPROACH TO "THE IMAGE OF THE CITY"

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Abstract

In the 1960 Lynch published *The Image of the City* (Lynch 1960), wherein he described 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.

In the present work, 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 the large part of the population. Nodes, paths and district 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 Haken and Portugali's (2003) information approach to capture the complexity of point of references 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.

I hereby declare that this dissertation is all my own original work and that all sources have been acknowledged. It is 11870 words in length.

At every instant there is more than the eye can see, more than the ear can hear, a setting or a view waiting to be explored (Lynch 1960, 1)

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AB – Angular edge Betweenness

EB – Euclidean edge Betweenness

CCZ – Congestion Charge Zone

POI – Point of Interest

SLA – Street-based Local Area

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Introduction

Motivation and research goal

In the decades after the publication of *The Image of the City* (Lynch 1960), Lynch's research on the formation of people's cognitive maps from a set of vivid elements of the city - categorised in landmarks, paths, nodes, edges and districts – has become of the most effective links between the study of the urban environment and research in behavioural sciences (Golledge & Stimson 1997; Portugali 2011). Concurrently, in the last 30 years, the availability of geospatial data, the advancement in geoinformatics, the growing computational power in computer science technologies and the necessity of understanding how people organise and employ geographic knowledge, have led GIS science towards a strong interest in cognitive mapping (Montello 2002; Montello 2009). Recently, in Introduction to Cognitive and Linguistic Aspects of Geographic Space (Frank, Mark & Raubal 2013), the editors argue that 'a generalisation of these (Lynch's) ideas could advance geographic thinking in general and GIS software in particular' (Frank et al. 2013, 3).

Although finding common ground between cognitive mapping and GIS should have been natural, there have been no attempts to translate the image of the city in a consolidated computational model. The importance of Lynch's contribution goes beyond a simple understanding of human cognition for designing navigational devices or for improving human-GIS interactions. Rather, as it is shown in section one of the present work, a formalisation of Lynch's concepts would allow comprehending how people represent the urban space and which elements they use to orientate and face the complexity of this environment. This is not just a philosophical conjecture; whereas here the emphasis is on the formulation of a complex theoretical framework, the aim is to offer an exhaustive set of tool to compute the image of the city, to extract, exclusively relying on geographic datasets (street network and buildings), *the five* Lynchian elements, and draw a shared skeleton of people's different cognitive maps. The central area of London was chosen as a case study.

Such approach might have different implications for urban planning policies, human cognition and wayfinding studies. Firstly, Lynch's method in its original version has been used to identify area of poor legibility (Nasar 1990; Nasar 1998; Luque-Martínez, Del Barrio-García, Ibáñez-Zapata & Rodríguez Molina 2007), where structural an architectural design choices hinder pedestrian movement, where there are a few possibilities of actions or low level of perceived safety and comfort. This framework implies a bottom-up approach that is not only unavoidable for studying and observing urban dynamics but, mostly, gives voice to humans' cognitive and social needs. Second, the necessity of reconsidering the concept of place, namely space as experienced by humans (Couclelis 1992), has been already indicated, for overcoming the incapability of GIS sciences to account for the way people perceive, represent and act in their environment (Jordan, Raubal, Gartrell & Egenhofer 1998). Lastly, cognitive maps organise the external complexity, simplifying and codifying human-environment interactions (Walmsley, Saarinen & MacCabe 1990); they include the knowledge about space (Kaplan 1976) and they support wayfinding behaviours (Golledge 1992b; Cadwallader 1976; Levitt & Lawton 1990). A computational approach to the mental image of the city may foster a new debate in spatial cognition and GIS research, enhance urban policies decision, and prompt the rise of new paradigms in pedestrian and traffic flow simulation.

Section 1. Imageability, the five elements and Spatial Cognition

A review of the concept of the image of the city, its importance in spatial cognition research and the development of computational models

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1.1 The image of the City

Lynch's interest in the city of the mind (Hospers 2010) revolves around the concepts of *legibility* – the ease whereby the parts of the cities are mentally recognised and organised – and *imageability* – the quality of a physical object (a building, an artefact) to raise in the observer a powerful mental image (Lynch 1960). A highly imageable city is well formed, vivid, remarkable and captivating.

The imageability of the city became the dependent variable of his research in Boston, Los Angeles and Jersey City; the built environment was the predictor. Lynch interviewed 60 subjects asking them to draw sketch maps of their city. People were instructed to describe distinctive elements of the cityscape, comment pictures and stroll with Lynch himself around the city. Several independent observers were instructed to detect the main elements of the cities. The analysis of the interviews brought Lynch to believe that the mental image is formed by the interrelations among five elements: paths, edges, districts, nodes and landmarks (Lynch 1960).

1. *Paths* are routes along which people usually move for reaching their destination. They include street, sidewalks, railways, public transport routes. All the other elements are arranged around them, geographically and semantically.
2. *Edges* are boundaries or barriers that break the continuity of paths. They help people to organise the physical elements of the built environment permitting to recognise different districts or phases easily.
3. *Districts* are quarters, neighbourhoods or city sections. They are remembered for their distinctive aspects of the inside, but they also serve as exterior references when they are endowed with remarkable visual features.
4. *Nodes* are strategic points wherein the observer can enter. They are junctions in the transport network that feed the street of the city and from which people travel. They include terminal stations, convergences of paths or changes in the structure of the city environment. They are the nerve centre of a district and concentrations of activities.

5. *Landmarks* are points that can seldom be accessed. Some of them might be spotted from different places and be used as distant references: dominant buildings, mountains, towers, domes, hills. Others are local and visible only from certain sites.

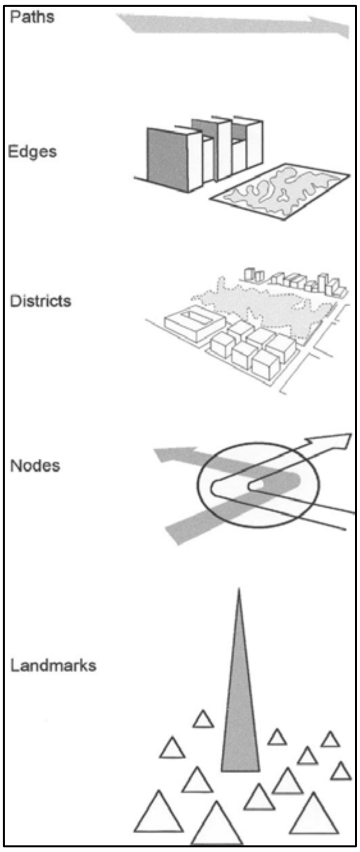


Figure 1: Graphical representation of Lynch's elements (Lynch 1960, 47-48)

Although these elements may be meaningless when considered singularly, all together they shape the image of the city. The visual quality of a city, relies on this physical elements and mould the mental image of the users: this is true not only for residents or people that have acquired spatial experience in a city but also for inexperienced visitor (Appleyard 1976; Francescato & Mebane 1973; Kaplan & Kaplan 1982; Nasar 1990; Gulick 1963; Milgram & Jodelet 1977).

1.2 Imageability and spatial cognition

Lynch's research is directed to the physical qualities of *identity* and *structure*. A functional image requires that its object is recognisable and distinguishable amongst others (identity) and related to the observer and with the surrounding elements (structure). Similarly, Golledge (1995b) proposes the concept of *occurrences*, core elements of the geographic space characterised by four traits: identity, location, magnitude and time. Permanence becomes a fundamental factor in the construction of the mental image: unambiguous objects of the geographic space, with a defined position, a consistent size and persistent in time, will likely form a substantial spatial representation. Indeed, the emergent features of the environment are organised by the observer through processes of meaning attribution. The individual experience leads to the formation of personal images of the city: differences emerge in how people perceive and give form to geographic concepts (Giannakopoulou, Kavouras, Kokla & Mark 2013). Nevertheless, it is possible to integrate the subjective experiences and depict a public-shared image of the city (see figure 2): 'There seems to be a public image of any given city which is the overlap of many individual images' (Lynch 1960, 46).

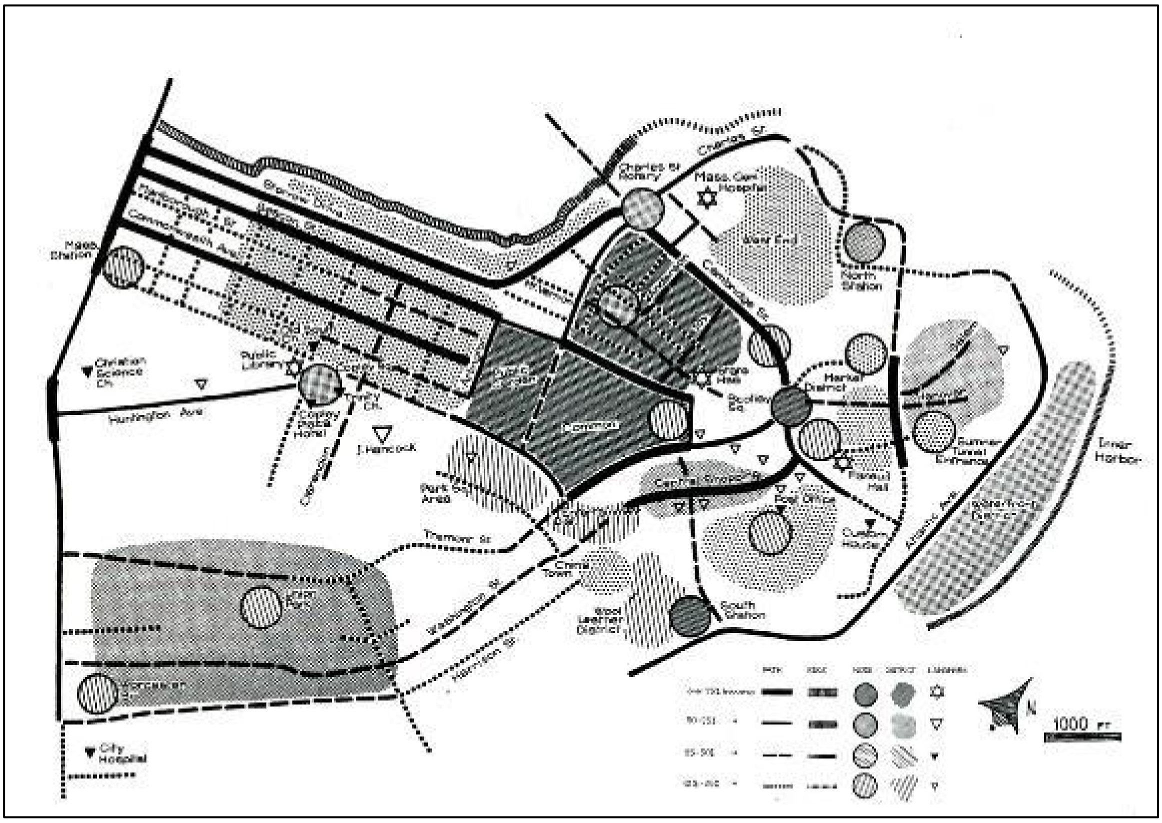


Figure 2: *Representation of the shared mental map of Boston (Lynch 1960, 147)*

The five elements and spatial knowledge acquisition

Behavioural and cognitive geographers have made The Image of the City a spatial cognition's pillar (Devlin 2001; Portugali 2011). This discipline focuses on the study of how people represent and interact with space, which mental processes are involved in the human-environment interactions and how the spatial knowledge is structured (Montello & Freundschuh 2005).

Siegel and White (1975) explicitly employ the concept of landmark in their comprehensive theory of the structure of the spatial knowledge. Deeply inspired by Lynch's work, they identify three structures that are developed sequentially: *landmark knowledge* derives from 'unique patterns of perceptual events at a specific location' (Siegel & White 1975, 23). This knowledge contains information regarding the features of a place and path-maintaining devices. *Route knowledge* represents the sequence of actions required for completing a path between different point of references. Finally, *survey knowledge*, integrates the route and the landmark knowledge creating complex and configurational relationships, storing metric information (Goldin & Thorndyke 1983) and categorising spatial elements in geographic regions (Golledge, Dougherty & Bell 1995). Through this bird-eye view and holistic perspective (Hirtle & Hudson 1991) the other elements come into play: 'Once routes with termini become interrelated into a network-like assembly, the gaps are gradually filled in and become Lynch's districts, edges, and nodes' (Siegel & White 1975, 30).

Since this work, landmarks have become a central and recurring element in spatial knowledge theories. While the seventies theories (Siegel & White 1975; Golledge & Spector 1978) might have been approximative in defining the features of points of references, Sorrows and Hirtle (1999), refine this notion describing three types of landmarks: *visual landmarks*, objects that are used as spatial reference points for their size and their visibility, in contrast with the surrounding environment; *cognitive landmarks*, relevant for their meaning, they can be prototypical or peculiar (for instance: buildings with historic and/or cultural meanings); *structural landmarks*, recognisable for their position in the space; they are placed in advantageous positions and easily accessible.

Human movements add to the declarative and cognitive valences of landmarks an experiential and procedural significance (Golledge 1992a). Wayfinding behaviour is a motivated activity in which the agent, through complex cognitive processes, complete a route between an origin and a destination point. In the urban spaces, the structure of the road network affects the cognitive representation of the environment (Lynch 1960; Freundschuh 1992), and travel choice activities (Timpf & Kuhn 2003; Richter 2009). However, despite the broad availability of navigation tools, humans still prefer to use cognitive information acquired by direct experience (Golledge, Jacobson, Kitchin & Blades 2000). This phenomenon demonstrates the involvement of the body and the sensorimotor system in spatial cognition processes and the fact that humans do not exclusively take the shortest or the fastest paths. Rather, their decisions are influenced by other factors such as angular deviation minimisation (Golledge 1997; Sadalla & Montello 1989; Mohsenin & Sevtsuk 2013;

Cooper 2015), number of turns, shortest or longest leg first, scenery and emotional connotations (Golledge 1995a).

The empirical results obtained within the paradigm of the *anchor point theory* (Golledge 1978; Couclelis, Golledge, Gale & Tobler 1987), according to which processes of regionalisation, route segmentation and recognition of salient reference points form an integrate a 'skeletal hierarchical' (Couclelis et al. 1987, 99) representation of the space, reinforce the value of Lynch's model but also raise the issue on how to integrate the five elements in a systematic and comprehensive model (Gale, Doherty, Pellegrino & Golledge 1985; Golledge & Stimson 1997).

In light of these developments, AI and robotics attempt to model spatial knowledge in the framework of the computer metaphor. The TOUR model is designed as 'a psychological model of human common-sense knowledge of large-scale space' (Kuipers 1978, 131) that makes use of Lynch's five elements for acquiring information from the external environment. Besides ELMER (McCalla, Reid & Schneider 1982) and TRAVELLER (Leiser 1987), developed to emulate human itineraries, NAVIGATOR (Gopal, Klatzky & Smith 1989) is well-known for being based on empirical results (Golledge, Smith, Pellegrino, Doherty & Marshall 1985) and for comparing its performance with human behaviour. The connectionist paradigm (Rumelhart, Smolensky, McClelland & Hinton 1986) has instead inspired Kaplan's (1976) neural network model and the biologically based model introduced by O'Neill (1991) in which the hierarchical network of neurons represents connections among external spatial entities (nodes, cities, regions). The more recent CASIMIR (Schultheis & Barkowsky 2011), revises Golledge and colleagues' (Golledge et al. 1985) models of spatial knowledge.

1.3 Cognitive maps

The computational models mentioned have profoundly enhanced the comprehension of mental processes in spatial cognition, but they neglect the actual interaction with the external environment. Paths, edges, districts, nodes and landmarks support the movement within the built environment, but there is indeed something more: 'The image is an organiser of facts and possibilities (..). Distinguishing and patterning the environment may be a basis for the ordering of knowledge' (Lynch 1960, 126), it is the result of nonlinear, two-way processes. Cognitive maps differ from geometric representations, physical or cartographic, where space is metric and uniform (Tversky 2003); rather, they are mental constructs that guide the behaviour (Kaplan 1973; Kitchin

1994), auto-organising systems that mediate the human-environment interaction (Portugali 1992). Therefore, the external environment must be brought back at the heart of the discussion.

With these intents, recent frameworks have tried to offer an integrated complex models: Raubal and Worboys (1999) enrich TOUR with a computational implementation of the notions of affordance and image schemata (Johnson 1987). Haken and Portugali's *Synergetic Inter-Representation Networks* model (Haken & Portugali 1996; Portugali 2002; Portugali 2004b; Portugali 2010) combines Lynch's idea on external artefacts with connectionism, embodied cognition (Lakoff 1987; Varela, Thompson & Rosch 1991) and ecological psychology (Gibson 1979). However, a computational approach to cognitive mapping that, more than contemplating a set of rules or symbolic information about the environment, includes spatial datasets or uses geospatial representations of cities is still missing.

Section 2. Computational and GIS approaches to The Image of the City

Designing the theoretical framework

In the last decades, *Space Syntax* (Hillier & Hanson 1984), a 'set techniques for the representation, quantification, and interpretation of spatial configuration in buildings and settlements' (Hillier, Hanson & Graham 1987, 363) has been one of the most prolific approaches to the study of spatial behaviour (Penn 2003; Bafna 2003; Montello 2007) and has revitalised the discussion about the complex relationship between environmental properties and spatial cognition. In this section, Space Syntax's reconceptualization of Lynch's theory is presented along with the information approach to the image of the city and state of the art in automatic landmark identification research. Nowadays, these three veins of research represent the starting points for formulating a geo-computational approach to the image of the city

2.1 Space Syntax contribution

This framework is based on the notion of visual accessibility and studies the relation between spatial configuration and the consequent mental representations (Kim & Penn 2004). Spatial configuration is investigated in an abstract format, focusing on topology rather than on metric properties, using graph analysis (Hillier & Iida 2005; Penn 2003). Traditionally, the network is drawn as a series of lines of sight – *axial lines* (Hillier & Hanson 1984) – so as to build an axial map: a representation that 'consists of the fewest and the longest sets of lines of sight and of access that pass through all the open spaces in an urban area and minimises the number of changes of direction between any other pair of lines' (Kim & Penn 2004, 487), with the scope of predicting movement patterns.

The Syntactical Image of the City

Dalton and Bafna (2003) seek to describe and formalise Lynch's elements through the concepts of axial lines and *isovists* – set of points that form a visibility area from an observer point (Benedikt 1979): 'By precisely defining the relationship between the axial line and the isovist, it can be shown that all of Lynch's elements may be redefined using a single, coherent family of tightly-related spatial entities' (Dalton & Bafna 2003, 1). In their view, Lynchian elements miss the structural component of the city image. Indeed, mental maps are structured by way of hierarchical processes: first order (spatial and structural) elements shape the mental representation, while second order (visual) elements perfect it. Axial lines (for paths, edges and districts) and the isovists (for node and landmarks) techniques may be exploited to capture these aspects and, successively, sorted along a continuum. This process would allow identifying a 10% of core elements, a 'selective description of the city' (Dalton & Bafna 2003, 20) or 'skeleton map' (Kuipers, Tecuci & Stankiewicz 2003),

Despite the inspiring premises, the authors do not completely formalise their approach. Their distinction between first order elements (paths, nodes, districts) and visual (edges, landmarks) is confusing and arbitrary: axial line and isovists could be used for both first and second order elements, and they do not allow for many aspects of the human-environment interaction. The authors neglect the extensive literature on the role of landmarks in environmental cognition and spatial behaviour, blaming Lynch of having overlooked spatial and structural properties of elements. In addition, some limits as keeping out metric considerations, the height of buildings and land use properties from the model (Ratti 2004), or the cognitive inconsistency of the axial line notion (see below), are inherent to Space Syntax approach.

In the same branch of research, Jiang (2013) unfolds Dalton and Bafna's vision, employing the scaling law of artefacts (Rui Carvalho & Alan Penn 2004; Bettencourt, Lobo, Helbing, Kühnert & West 2007). In this perspective, the image of the city arises from this property: 'In an imageable city (..), small city artefacts are far more common than large ones; or, alternatively, low-density locations are far more common than high-density locations' (Jiang 2013, 1552). The minority of relevant and meaningful elements would represent the skeleton of the image, the head of a heavy-tailed distribution, while the remaining elements, the tail, would represent the less important, redundant and superficial artefacts (see figure 3).

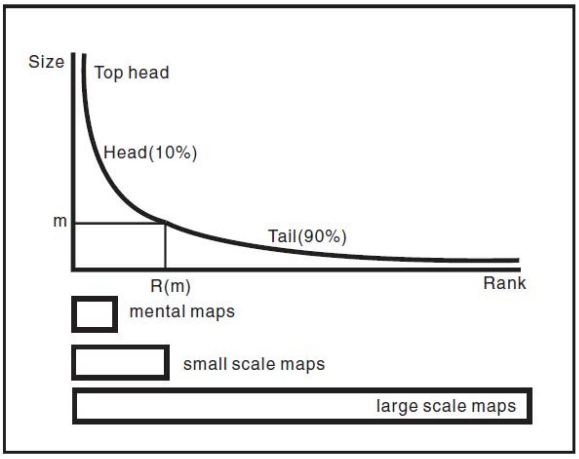


Figure 3: Cognitive and cartographic mapping in the scaling framework. m is the mean of an attribute, R(m) is the rank of m (Jiang 2013, 1564)

Jiang has tested his hypothesis on paths, interpreted as axial-lines ranked by connectivity (number of intersections per street). The researcher found out that the number of less connected streets is much bigger than the well-connected ones and that the distribution of streets in classes is similar across cities, despite their different morphologies (see figure 4). Jiang introduces a mathematical model to extract the Lynchian elements from their relative categories, but, except for paths, he does not suggest how to rank the other elements, namely which properties to take into consideration.

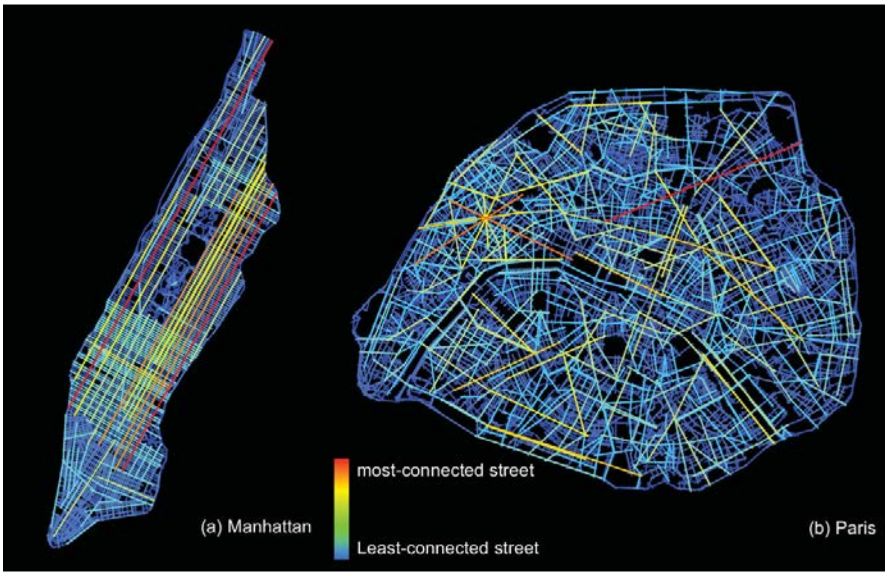


Figure 4: Most legible paths, Manhattan and Paris (Jiang 2013, 1562)

2.2 The face of the city is its information

Within the theoretical framework mentioned above, Portugali and Haken (Haken & Portugali 2003; Portugali 2004a) have employed information theory to describe pattern recognition processes in the identification of the preeminent elements of cities: ‘What is it in the geometrical and semantic elements in the face of the city that make them landmarks, edges, districts, paths and nodes — so much so that they afford remembering, city imaging and orientation more than other urban elements?’ (Haken & Portugali 2003, 388).

Haken and Portugali (Haken 1988; Haken & Portugali 2003) argue that the computation of the information transmitted by urban elements may indicate what artefacts model the image of the city. In their model, the original measure of information introduced by Shannon and Weaver (1949) – a form of entropy that quantitively measures the *unexpectedness* of an event out of a possible number of messages, Z (equation 1) – is adjusted with the index *j* that takes into consideration semantic differences amongst the objects (equation 2):

1.

$$I = \ log_2 \, Z$$

2.

$$i = \sum_{j=1}^{N} p_j \, log_2 p_j$$

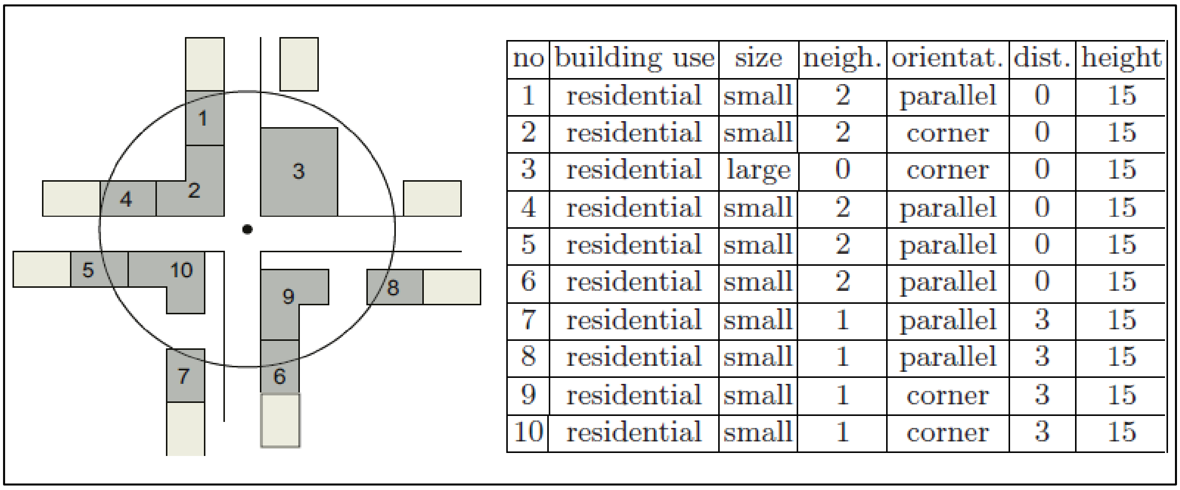
For example, *j* may represent differences in the aesthetic properties of the edifices through categories as Victorian houses, skyscrapers or terraced houses. Semantic information (Haken 1988) gives sense to the flow of Shannonian Information across open and complex systems: ‘We actively ‘‘select’’ the elements that convey the highest value of information. We are actively ‘‘landmarking’’, ‘‘edging’’ elements’ (Haken & Portugali 2003, 400). It is the outcome of categorisation processes based on innate humans’ properties, cultural values and actions. A crucial aspect of this framework is Gibson’s concept of *affordance*: ‘The affordances of the environment are what it offers the animal, what it provides or furnishes. (..). It implies the complementarity of the animal and the environment’ (Gibson, 1979: 127). A city element, beyond its appearance and its geometry, could be considered a landmark for its symbolic meanings (Appleyard 1969; Appleyard 1970; Golledge & Spector 1978), for possible actions and recalled experiences (Haken & Portugali 2003). All these aspects contribute to making the city legible and transforming an object in a cognitively connoted, an external representation (Haken & Portugali 2003; Portugali 2011; Portugali 2004a).

The information approach extends the concept of the image of the city, providing a complete computational approach to cognitive and urban dynamics. However, it should be noted that *i* (see equation 2) is a measure of entropy that may refer to an entire city or specific districts, rather than a sort of individual score for ranking buildings, paths or other elements.

2.3 Automatic identification of landmarks

In the last 15 years, several researchers in computer science, geoinformatics and wayfinding have sought to automatically identify landmarks for supporting navigation and wayfinding behaviours. The first approach, proposed by Raubal and Winter (2002), has widely influenced the following works. Inspired by the conceptualisation offered by Sorrow and Hirtle (1999), the researchers illustrate a model for measuring buildings saliency in relation to perceptual and cognitive properties: location, shape, façade area, colour, visibility, cultural and historic importance. The model has been enriched by Winter (2003) that indicates advance visibility as another significant factor in landmark salience.

Likewise, Elias (2003) presents an approach designed to automatically extract landmarks using machine learning techniques, inspecting semantic, geometric and topological attributes of buildings. Figure 5 shows a synthetic dataset used by the author and the relative categorisation of the properties. Her research has the merit to include in the analysis topological properties and land-use information.



no	building use	size	neigh.	orientat.	dist.	height
1	residential	small	2	parallel	0	15
2	residential	small	2	corner	0	15
3	residential	large	0	corner	0	15
4	residential	small	2	parallel	0	15
5	residential	small	2	parallel	0	15
6	residential	small	2	parallel	0	15
7	residential	small	1	parallel	3	15
8	residential	small	1	parallel	3	15
9	residential	small	1	corner	3	15
10	residential	small	1	corner	3	15

Figure 5: Elias (2003, 384) test data and categorisation

Winter and colleagues (Winter, Tomko, Elias & Sester 2008) integrate the previous approaches to construct a hierarchy of landmarks based on prominence, uniqueness and salience. The contribution of their work lies in the distinction between local-landmarks, salient at the neighbourhood or district level, and city-wide landmarks (global landmark). They assume that each local-landmark creates a field of dominance, a region where the influence of a landmark is higher than the effect of any other building. Thus, the authors first identified the points of reference and subsequently obtained *Voronoi* partitions with landmarks as seeds. A landmark hierarchy is derived from the frequency of selection. Moving up in the hierarchy, neighbour cells are compared to find the most striking landmarks and to create new Voronoi partitions (figure 6).

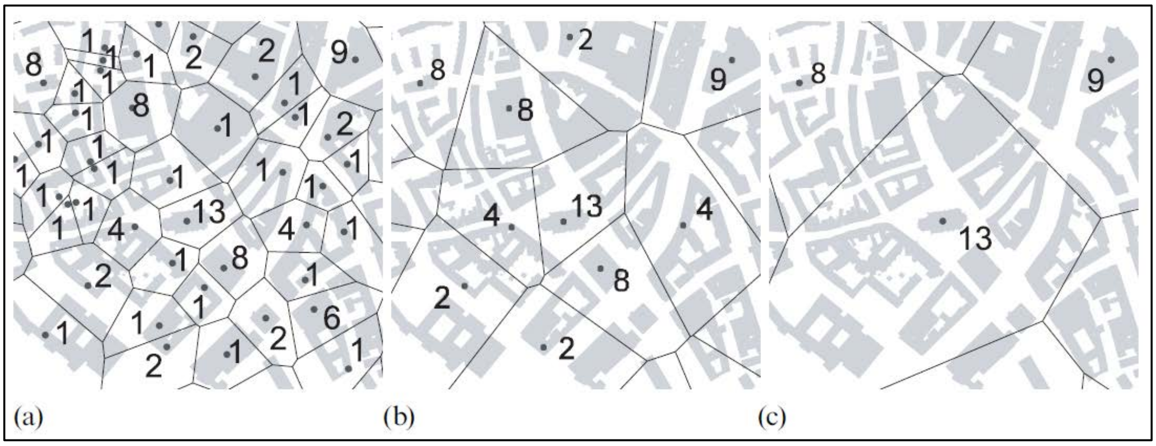


Figure 6: Landmarks and dominance regions (Voronoi partitions) with different levels of detail: a) base level; b) level 1; c) level 2 (Winter et al. 2008, 390)

Apart from the relative good reception of automatic landmark identification approaches for navigation systems (Richter 2013), the majority of these works have not achieved the integration that Frank and colleagues (Frank et al. 2013) hoped for. The information approach has been partly unnoticed by the research community in spatial cognition, while GIS community still struggles to implement and accommodate Space Syntax techniques. The limits already described can be summarised here:

- Space Syntax has tackled the image of the city considering mostly the visual aspects and neglecting important implications for what concerns activities and genuine human-environment interaction.
- Portugali and Haken approach, whilst being based on the usage of geospatial dataset, drifts apart from GIS science, returning a too general and macro-level measure of legibility.
- Whereas paths and landmarks have been widely investigated, fewer words have been spent for edges and nodes, sometimes considered as a type of landmark, or for districts, reduced to Voronoi partitions, at best.
- 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, making the model not completely automated and replicable.

Joining GIS and cognitive science may still seem a mirage, but indeed these different and apparently incompatible perspectives are a concrete starting point.

Section 3. Towards an integration

Methodology and data

The main flaw of the set of works presented in the previous section is not having proposed a model able to consider all the five elements. Yet, their diversities, and the potentials of the techniques they have proposed encourage to pursue a more comprehensive vision. In this section, the implications of network analysis in spatial cognition are introduced. Appropriate network science techniques are presented for what concerns the detection of nodes, paths and districts from the street layout. Afterwards, a comprehensive landmark detection approach is illustrated, referring to visual, structural, semantic and properties of buildings. Finally, before presenting the dataset used for studying the central area of London, a set of possible rules for edge identification is posited.

3.1 Network Analysis: Nodes, paths and districts

The Syntactical approach emphasises how the configurational aspects of urban spaces influence and mould spatial behaviour in the city. Cities hide a mathematical order that has developed along with discontinuous growth patterns. Even the more common organic cities, a result of uncontrolled bottom-up processes, have an informal geometry, produced by deformed grids, aggregation of buildings, shape and orientation of edifices and movement patterns in the city (Hillier 2012). Seeing, moving and interacting with the environment, an individual starts to relate and to internalise the spatial configuration: one knows where he or she is likely going to meet other people or to find an amenity in the urban configuration (Hillier & Hanson 1984; Blanchard & Volchenkov 2009). For Hillier and Iida (2005), this is inevitable: the properties of the urban network influence the accessibility of some places, their identification and the plan to reach them.

Furthermore, in this context the concept of view of a path, or the openness of space, described by Lynch (1960) resurfaces. The sense of openness and the visibility of landmarks, reinforce the image of a path and are at the base of the daily naïve geography: human perception of the street patterns is indeed based on vista spaces and the representation of topological relationships (Hillier 2012). Looking at figure 7, the configuration a) permits to identify a main street and to reach destinations along it easily. The configuration b) instead has a slightly different structure that makes the urbanscape a sort of labyrinth, impeding movement.

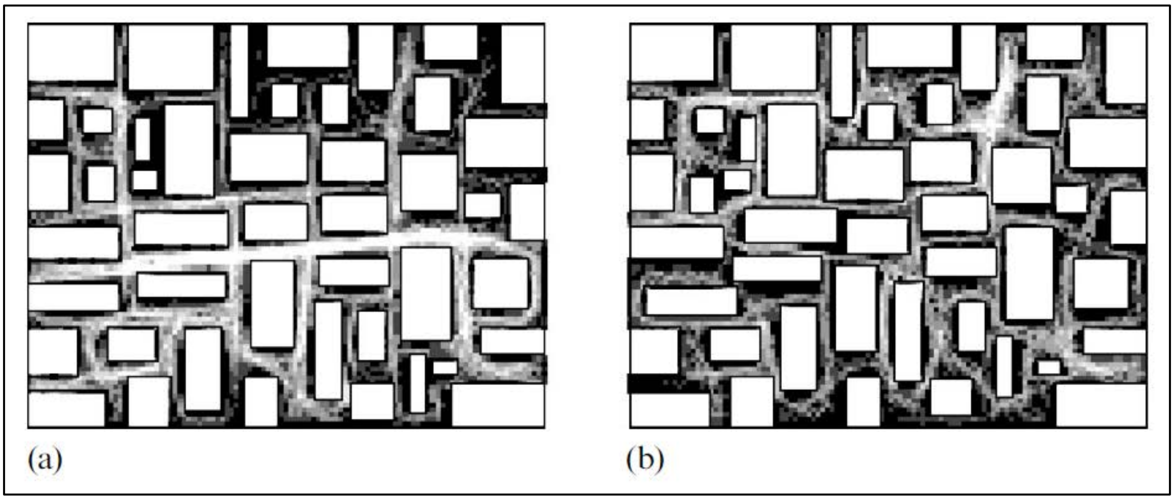


Figure 7: Traces of agents moving randomly in two similar arrangements of buildings and streets (Hillier 2012, 20)

These arguments support the idea that some city elements could be retrieved employing graph theory: a network can be redefined as a graph in which nodes and edges have attributes and network science techniques are applicable.

Primal and Dual approaches, axial lines or segments?

How to translate these considerations into a network representation brings to two different perspectives. The classic one, called *primal graph* or object-based graph (Blanchard & Volchenkov 2009; Porta, Crucitti & Latora 2006a), looks more intuitive and sees intersections as nodes and roads, or any other kind of linear relationships, as edges. In this view, the city emerges from interactions between objects, locations and elements that are represented by nodes linked by streets. The urban elements are located in a Euclidean plane, where relationships are based on Euclidean geometry. The primal approach has been widely used for its simplicity: the distance between two places is just represented by the linking edge. In addition, it takes into account geographical aspects, allowing comparisons between different urban structures (Crucitti, Latora & Porta 2006b).

The *dual graph* is one of the main Space Syntax techniques and converts streets into nodes and intersections into edges (Porta et al. 2006a). Hence, measures of accessibility are not based on the Euclidean concept of distance anymore but topologic distances, like the number of turns or least angle change (Hillier & Iida 2005). It is a non-planar topological transformation that replaces one-dimensional elements with zero-dimensional nodes respecting spatial hierarchies. Since streets are mapped regardless their metric length, this representation permits to compare street networks regardless their geographical extensions (Porta et al. 2006a, 854).

In the analysis of the street configuration, another debate concerns what unity should be analysed: axial lines or roads? Jiang and Claramunt (2002) claim that the notion of axial line leads to theoretical and practical limitations: axial lines are not a cognitive concept, and there is no reason to believe that they belong to a shared knowledge. Incongruences between GIS representations and axial lines properties still exist, beyond computational and derivation issues (Jiang & Claramunt 2002; Jiang & Liu 2009). Jiang and Liu (2009) also show that street-based analyses can predict traffic flows more precisely than axial lines. These questions have encouraged Space Syntax to turn to the use of road centre lines, instead (Turner 2007).

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Nodes and Paths

Space Syntax has shown that the imageability of a street is associated with the topological properties of degree, centrality and betweenness. Indeed, several studies have found out that the places drawn in people's sketch maps are related to centrality measures (Haq & Girotto 2003; Yun & Kim 2007). However, according to Porta and colleagues (Porta, Crucitti & Latora 2006b), the primal approach is more effective in exploiting centrality indices to capture the skeleton of the urban structure, to capture the most crucial intersections of paths, movements and flows. Lynch's nodes could be viewed as 'places that are structurally made to be traversed (*betweenness centrality*), places whose route to other places deviates less from the virtual straight route (*straightness centrality*)' (Crucitti, Latora & Porta 2006a). Centrality is an index that conveys a location's advantage in urban areas: there is a relation between the intensity of land use, as retail and service amenities, and centrality measures (Porta, Strano, Iacoviello, Messora, Latora, Cardillo, Wang & Scellato 2009).

Betweenness centrality and straightness centrality were employed to identify the major nodes in a primal undirected graph, where edges were weighted with Euclidean distance. These measures can differentiate between primary and secondary nodes and catch the urban structure effectively (Crucitti et al. 2006b; Crucitti et al. 2006a), without exhibiting the *border effect* that characterises closeness centrality (Tomko, Winter & Claramunt 2008; Porta et al. 2006b). In betweenness centrality, a node is central when it lies between many other nodes; it is the intermediary of others (Freeman 1977; Freeman 1978). Straightness centrality compares the length of the path between two nodes with the straight line that links them (Vragović, Louis & Díaz-Guilera 2005), capturing a centrality that refers to ‘being more directly reachable’ (Porta et al. 2006b, 708). The betweenness centrality of a node is:

3.

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

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*. Straightness centrality (Latora & Marchiori 2001; Vragović et al. 2005; Crucitti et al. 2006b) was computed for a node *i* as:

4.

$$C_i^S = \sum_{j \in G, j \neq i} \frac{d_{ij}^{Eucl}}{d_{ij}}$$

Where d_{ij}^{Eucl} represents the Euclidean distance along a straight line between the nodes *j*, *i* and d_{ij} is the length of the shortest path between the same nodes.

Finally, against the relation between nodes and concentrations of uses, the *reach centrality* (Sevtsuk & Mekonnen 2012) was calculated. The measure contemplates the assignment of attributes (e.g. number of activities, population, employees in an area) to nodes and ‘accounts for opportunities that are reachable along the actual street network as perceived by pedestrians’ (Sevtsuk & Mekonnen 2012, 294) . In the present work, the weight of a node represented the number of services (as commercial activities, sports centres, libraries, etc.) in a Euclidean buffer of 50 meters. Therefore, the reach centrality of a node j, indicates the number of other nodes reachable from *i*, at the shortest path distance of *r*:

5.

$$C_i^R = \sum_{j \in G, d[i,j] \leq r} W[j]$$

where *d[i,j]* is the shortest path distance between *i* and *j* and *W* is the weight of a destination node *j*. The radius was fixed at 600 meters, a measure that has proven to be related to pedestrian travels within the city (Cooper 2015).

Betweenness measures have been portrayed as better predictors of urban movement than closeness centrality, especially when an angular metric is applied (Turner 2007; Hillier & Iida 2005). In contrast with the Euclidean shortest path, based on metric distance, the idea that people choose routes that minimise the angular change – angular shortest past – has been strengthening in the last years widespread (Sadalla & Montello 1989; Montello 1991; Golledge 1995a; Hillier & Iida 2005; Turner 2007). The reason is purely cognitive: routes with fewer turns are easier to remember, especially within an unfamiliar environment, and for what concerns vehicular traffic, major roads are designed to avoid high angular deviations (Cooper 2015). People may appeal to these two heuristics depending on their knowledge (Turner 2007) and on the scale considered: distance minimisation is used by experienced individuals in local decision-making contexts. Conversely, with an imperfect knowledge and for longer travels, angular minimisation is preferred (Cooper 2015). Therefore, *edge betweenness* was computed both with Euclidean and angular metrics, for each road segment, to obtain the set of the most, allegedly, memorable and travelled paths. Edge betweenness centrality is a generalisation of the betweenness centrality (Freeman 1977), to measure the importance of an edge in a network. Coherently with the formula 3, betweenness centrality of an edge is simply the sum of the fraction of all the shortest paths that pass through it. In a primal graph representation, edge betweenness was computed with edges weights based on Euclidean distance. Subsequently, the centroids of the street were obtained, transformed in nodes and linked by edges to form a dual representation. In this context, an edge acts as the junction between two street segments and has a weight equal to the amplitude of the angle of incidence formed by them, in radian (see figure 8). In both cases the graph is undirected; it is assumed that traffic flows in both directions.

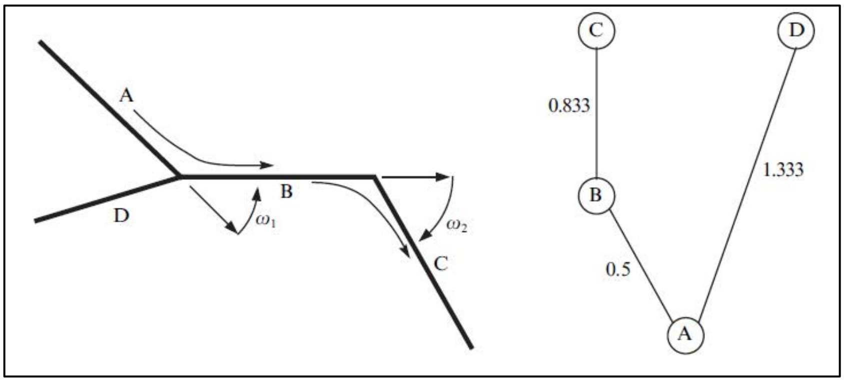


Figure 8: Angle of incidences and weights in a dual graph representation (Turner 2007, 542)

Districts

Lynch argues that a city could be mentally reorganised and its part clustered through mental associations and meaning attributions: people build, transform and mould a place; they share connections between places and categorise spaces and city elements giving birth to a common and implicit knowledge (Dalton 2007). How to automatically identify these areas then? Space Syntax suggests that the topology of the street network has a relation with people perception of places and regions: Law (2017) has recently studied the effects of *Street-based Local Areas* (SLA) (Turner 2007) on socioeconomic factors exploiting the notion of community structure (Girvan & Newman 2002) and the dual graph representation. The formation of SLA entails the use of community detection technique to define a set of different subgraphs (regions), 'that maximises internal ties and minimises external ties using strictly the topology of the graph' (Law 2017, 167) from the street network. The spatial homogeneity that emerges in this way has social and functional foundations (Girvan & Newman 2002).

In this work, the *modularity optimisation algorithm* (Blondel, Guillaume, Lambiotte & Lefebvre 2008) is adopted. This function optimises *modularity* (Newman & Girvan 2004), a measure of the quality of a particular division of a network, looking for structures that maximise it. 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 weak and Q = 0. Otherwise, greater the difference, higher the modularity Q, stronger the division.

6.

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

'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, 168).

For large datasets, the multi-level implementation (Blondel et al. 2008) of the 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 modularity optimisation function was run in an undirected dual graph in three different conditions:

1. The network was unweighted, thereby merely topological.
2. The Euclidean distance between two streets was assigned to the linking edge: sum of the lengths of *segment A segment B*, divided by two (Turner 2007).
3. Weights were based on the incidence angle of the segments, as described above.

3.2 Landmarks

The identification of the landmarks was performed by enriching and systematising Raubal and Winter's seminal work. Also, Elia's (2003) considerations on the topological relations of each building with the surrounding area, and visibility, as suggested by Winter (2003), were included in a complex and variegated analysis. The maximum height of a building was used for computing the visibility in *ArcScene*:

- 446 Junctions in a simplified network composed only of major roads were used as observer points.
- From every point, *sight lines* to each building were constructed, with a sampling distance along the perimeter of the edifice of 10 meters.
- The intervisibility of the sight lines was determined considering the building layer as a possible source of obstructions (see an example in figure 9).
- Only the resulting visible lines were kept, and the longest one for each building was extracted and used as unscaled visibility score.

Figure 9: Visible sight lines from an observer point in ArcScene, Congestion Charge Zone, London.

Concerning the structural and topological properties, openness was computed as a 2d area of open space around a building, in each direction (most extended circular buffer obtainable, without obstructions). The minimum distance from the road, the number of adjacent buildings and the extension of the polygon were included in this analysis. The latter is a measure, introduced by Raubal and Winter (2002), that includes the area and the 2d shape factor of the building.

The semantic component was calculated following the precise categorisation offered by *Historic England*. The listed buildings geo-dataset includes different kinds of edifices and sites (from castles, bridges and ruins to railway stations and pubs) that are recognised as being of special architectural or historic interest. The entries are classified according to different levels of importance:

- Grade I (one) of exceptional interest.
- Grade II* (two star) particularly important.
- Grade II (two) of special interest.

For each building, the cultural salience was computed summing the scores of all the points contained in its boundaries.

Moreover, the pragmatic significance was calculated following a simplification of the information approach proposed by Haken and Portugali (2003), as an index of unexpectedness:

7.

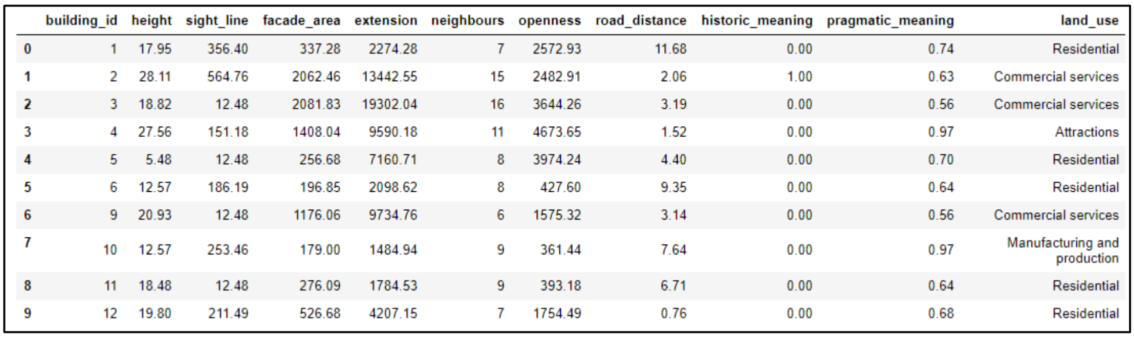
$$Ps_b = 1 - \frac{N_b}{N}$$

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. This simple measure may enhance the vividness of a building in two ways: on the one hand, a building with a commercial function, surrounded for example by residential edifices or accommodation structures, assumes relevance for its inherent affordances; on the other hand, a peculiar categorisation as ‘military’ or ‘industrial’ use, even if not pragmatically attractive to the observer, might become significant in discerning a building from the background.

Finally, the scores of each property were scaled and combined in the relative component, and in the overall score, according to the assigned weights. The table below, summarises the properties, the methods used and the weights. Figure 10 and 11 show a sample of the dataset used.

Component	Property	Measurement	Property Weight	Component Weight
Visual attraction	Height	$\gamma = max(height)$	0.20	0.50
	Visibility	$v = max(sight.lines)$	0.50	
	Façade Area	$\alpha = height * width$	0.30	
Structural and Topological attraction	Extension	$\theta = cell_{size} * \frac{longside}{shortside}$	0.30	0.30
	Neighbours[1]	$\vartheta = num_{adjacentbuildings}$	0.20	
	Openness	$p = AreaMaxBuffer$	0.30	
	Distance from the Road	$d = min(distance_{road})$	0.20	
Semantic meaning	Cultural and historic importance	$c = sum(score_{elements})$	1.00	0.10
Pragmatic meaning	Land Use	$Ps = 1 - \frac{Frequency(Building_{Landuse})}{Nr(Neighbours_{200mt})}$	1.00	0.10

Table 1: Landmark computation: properties and weights



	building_id	height	sight_line	facade_area	extension	neighbours	openness	road_distance	historic_meaning	pragmatic_meaning	land_use
0	1	17.95	356.40	337.28	2274.28	7	2572.93	11.68	0.00	0.74	Residential
1	2	28.11	564.76	2062.46	13442.55	15	2482.91	2.06	1.00	0.63	Commercial services
2	3	18.82	12.48	2081.83	19302.04	16	3644.26	3.19	0.00	0.56	Commercial services
3	4	27.56	151.18	1408.04	9590.18	11	4673.65	1.52	0.00	0.97	Attractions
4	5	5.48	12.48	256.68	7160.71	8	3974.24	4.40	0.00	0.70	Residential
5	6	12.57	186.19	196.85	2098.62	8	427.60	9.35	0.00	0.64	Residential
6	9	20.93	12.48	1176.06	9734.76	6	1575.32	3.14	0.00	0.56	Commercial services
7	10	12.57	253.46	179.00	1484.94	9	361.44	7.64	0.00	0.97	Manufacturing and production
8	11	18.48	12.48	276.09	1784.53	9	393.18	6.71	0.00	0.64	Residential
9	12	19.80	211.49	526.68	4207.15	7	1754.49	0.76	0.00	0.68	Residential

Figure 10: Sample of the dataset of the buildings, before the landmark identification

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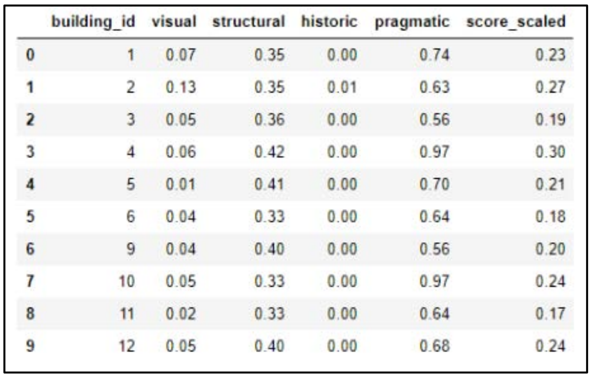
[1] Included buildings outside the region considered in this work



	building_id	visual	structural	historic	pragmatic	score_scaled
0	1	0.07	0.35	0.00	0.74	0.23
1	2	0.13	0.35	0.01	0.63	0.27
2	3	0.05	0.36	0.00	0.56	0.19
3	4	0.06	0.42	0.00	0.97	0.30
4	5	0.01	0.41	0.00	0.70	0.21
5	6	0.04	0.33	0.00	0.64	0.18
6	9	0.04	0.40	0.00	0.56	0.20
7	10	0.05	0.33	0.00	0.97	0.24
8	11	0.02	0.33	0.00	0.64	0.17
9	12	0.05	0.40	0.00	0.68	0.24

Figure 11: Sample of the dataset, after the application of weights

3.3 Edges

Edges, or barriers, have rarely been the subject of automatic extraction algorithm. They are associated with lack of paths or hindrance to pedestrian flows, but there is a substantial disinterest in their detection. Raubal and Winter suggest to detect boundaries computing the extent θ of each building (see table 1), but this formalisation does not satisfy completely the definition of boundary given by Lynch: whereas a complex of edifices might hamper spatial behaviour, rivers, railways and others linear[2] geographic elements are the main barriers represented in cognitive maps. Thus, in the present discussion the following elements were considered edges:

- Boundaries of major parks.
- Railway structures as bypasses or other visible structures.
- River and watercourses.
- Roads with large carriageways[3].

3.4 Data sources

The analysis was performed on the Central area of London, United Kingdom, as defined by the Congestion Charge Zone[4]. This choice follows both practical and geographical reasons. To begin with, the analysis of

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[2] In a perceptual sense.

[3] *OS MasterMap Highways Network - Routing and Asset Management* had been used for extracting streets width, but the number of missing values did not permit to rely on this technique. Thus, the extraction is purely manual and based on the author's judgement.

[4] tfl.gov.uk/modes/driving/congestion-charge/congestion-charge-zone

the whole extension of Greater London Area would be highly demanding in terms of computational resources. Secondly, as expressed by Lynch, the image of the city is usually developed from meanings and experiences that take shape in the central areas: elements in the city centre are more vivid, and they incorporate more semantic information. The analysis relied mainly on the street network and buildings footprints:

- Districts, Nodes and Paths: *OS Open Roads*. The dataset contains motorways, A-roads, B-roads, minor and local roads as classified by the National or Local Highway authority, as well as unclassified roads. All the segments included inside the CCZ polygon, or less than 50 meters away, were included.
- Landmarks: *OS OpenMap Local (vector version)*. It includes a simplified representation of buildings footprints and functional sites. Compared to similar products and other mapping services, *OS OpenMap Local Map* is developed after a process of generalisation wherein scale and complexity of the representations are reduced. This representation is supposed to be more coherent with cognitive categorisation and simplification processes.
- Edges: water, road, green areas and railways structures surfaces, are extracted from the *OS MasterMap Topography Layer* (Ordnance Survey 2017a).

Finally, other supplementary datasets were used for enriching the analysis: the height of the buildings is contained in free data-packs offered by *Emu Analytics*. The Cultural and historic relevance is instead measured complying with Historic England classification. Historic England is a public organisation that manages and maintains The National Heritage List for England (NHLE)[5]. The distribution of services and their functional classification were extracted by the *OS Points of Interest Database* (Ordnance Survey 2017b).

In the next figures, the CCZ, the simplified street network used and its dual representation are displayed.

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[5] historicengland.org.uk

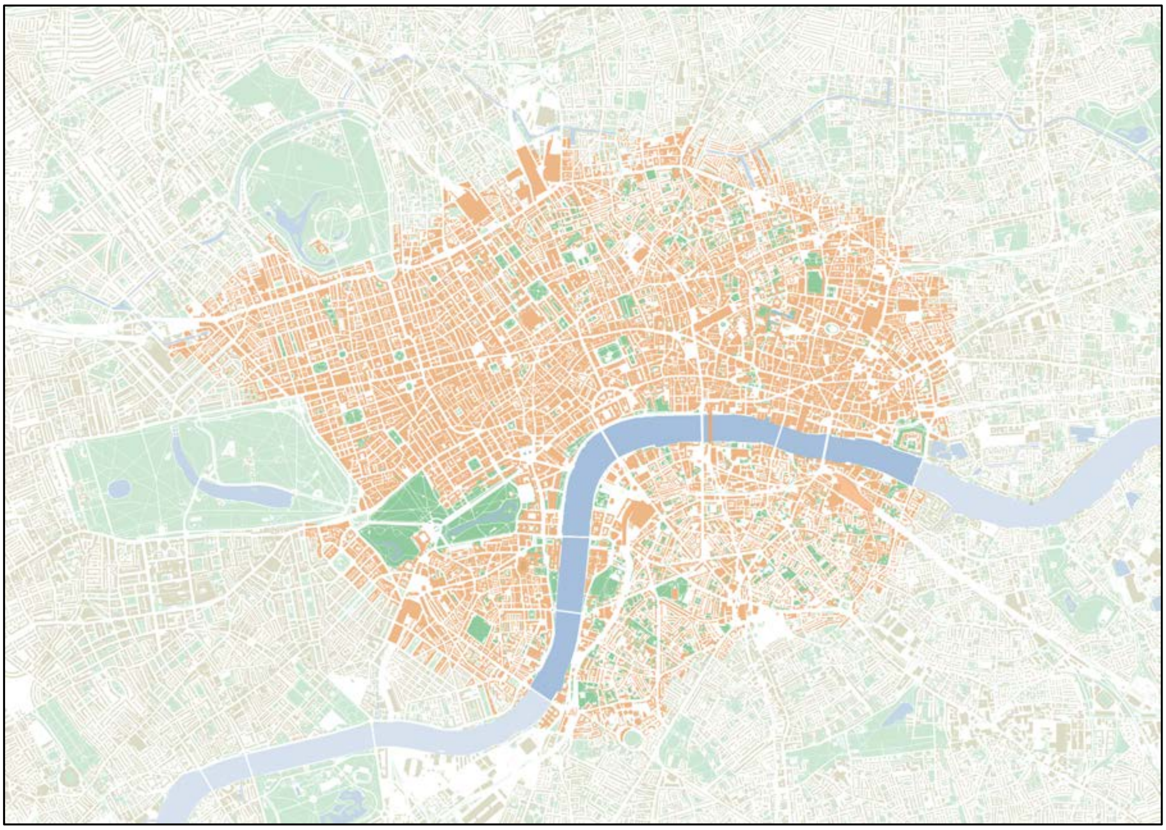

Figure 12: The area studied

Figure 13: The street network used in this work: Primal graph representation

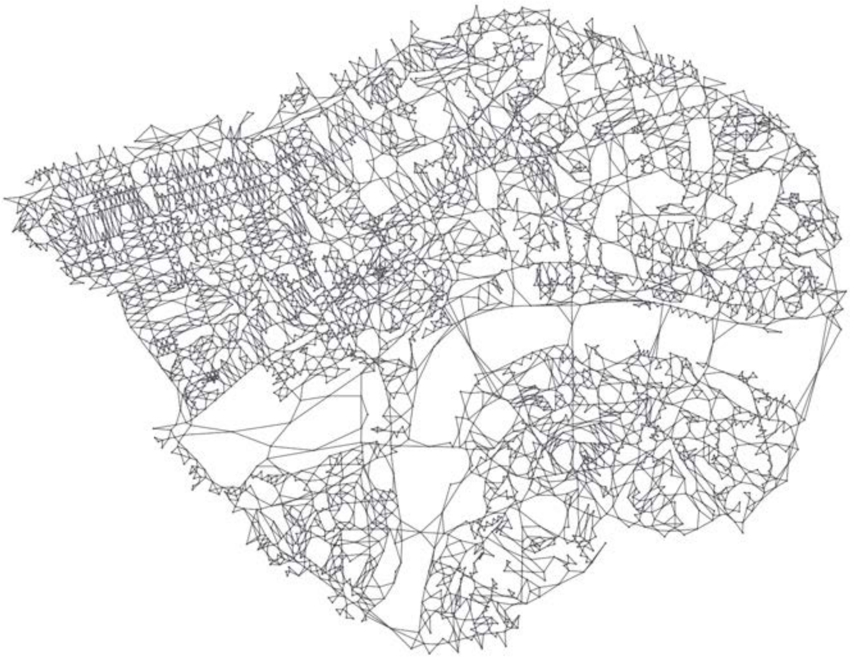

Figure 14: The street network used in this work: Dual graph representation

3.5 Statement of ethic

This work did not make use of sensitive information. The author exclusively employed the street network of London's CCZ and polygons representing buildings and other elements of the city. The primary analysis relied on completely open data that does not include personal aggregated information, either. For this reason, Ordnance Survey[6] does not specify privacy policy about the data collection process.

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[6] www.ordnancesurvey.co.uk/privacy.html

Section 4. The case study

Analysis and discussion

In this section, the results of the analysis are presented and discussed with reference to Lynch's considerations. Some subjective observations are included to comment the elements identified, and offer a personal validation of the results. As the main scope of the present work is to find appropriate methods to extract Lynchian elements, a solid validation would require the employment of external judges, qualitative interviews or recognised functional maps. Therefore, the elements extracted do not necessarily coincide with possible results. Nodes, paths and landmarks were ranked by the indexes presented and clustered with the jenks natural break optimisation for visualisation purposes.

4.1 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 physical character' (Lynch 1960, 47).*

Nodes are key places in perceptual, spatial and behavioural terms. They could be arrival points, entrance to different parts of the city or the major paths, or decision points, namely intermediate steps along a route. Furthermore, as Lynch mentions, their prominence is also due to the concentration of 'some use', as activities, services or events. Thereby, their notoriety assumes a functional and pragmatic meaning.

'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). The challenge is to distinguish imageable nodes from ordinary intersections and to capture the complex properties reported by Lynch. In this sense, betweenness, straightness and reach centrality measures were calculated in a planar graph composed of 3799 nodes and 5297 segments. For each measure, a map with nodes coloured by centrality values is displayed.

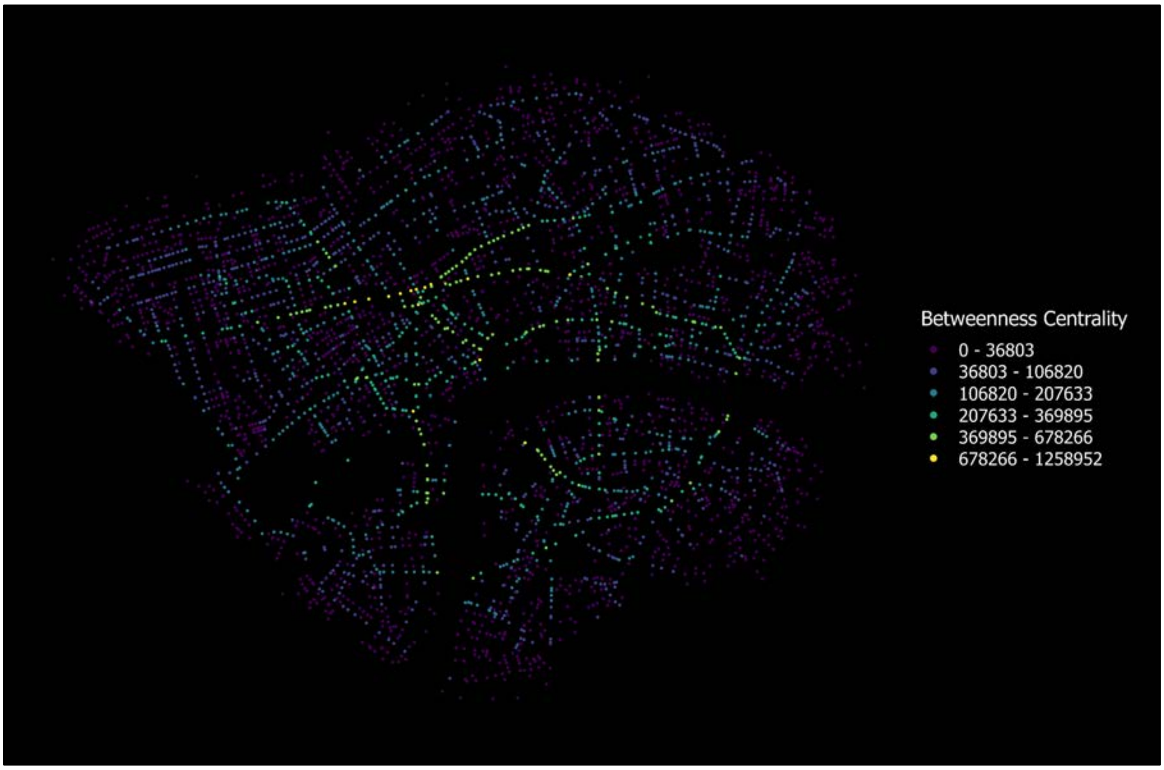

Figure 15: Street junctions coloured by betweenness centrality

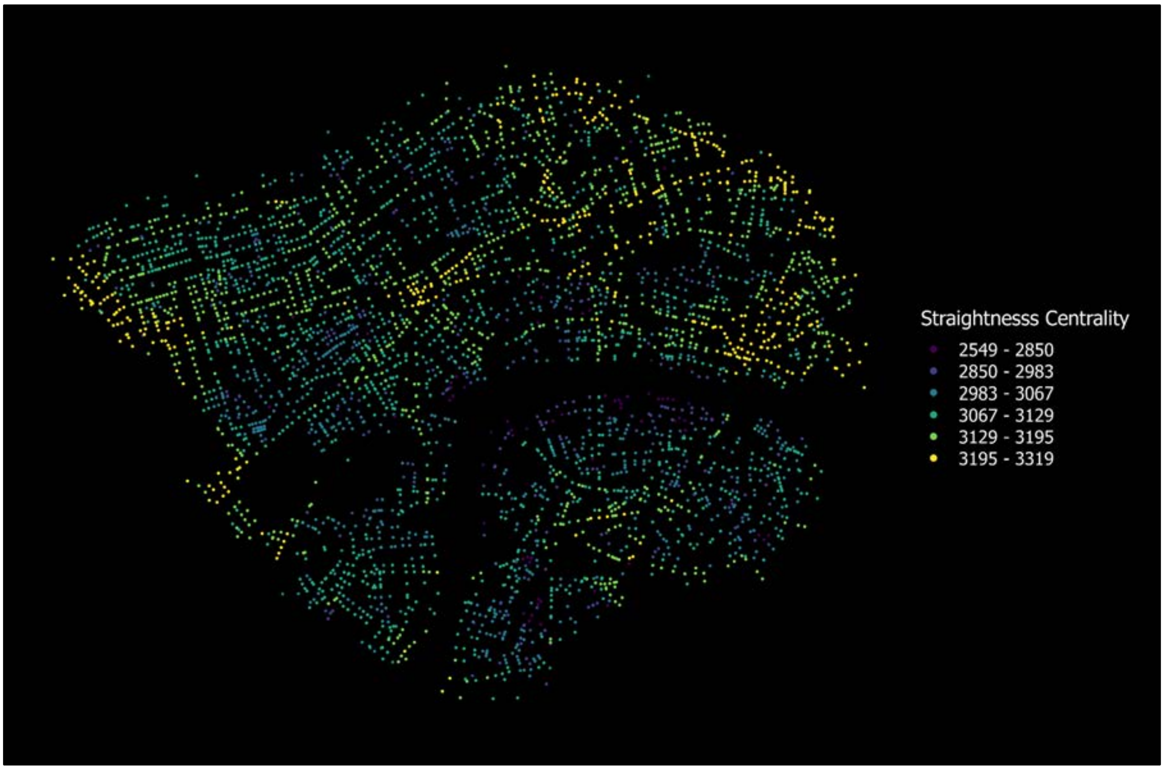

Figure 16: Street junctions coloured by straightness centrality

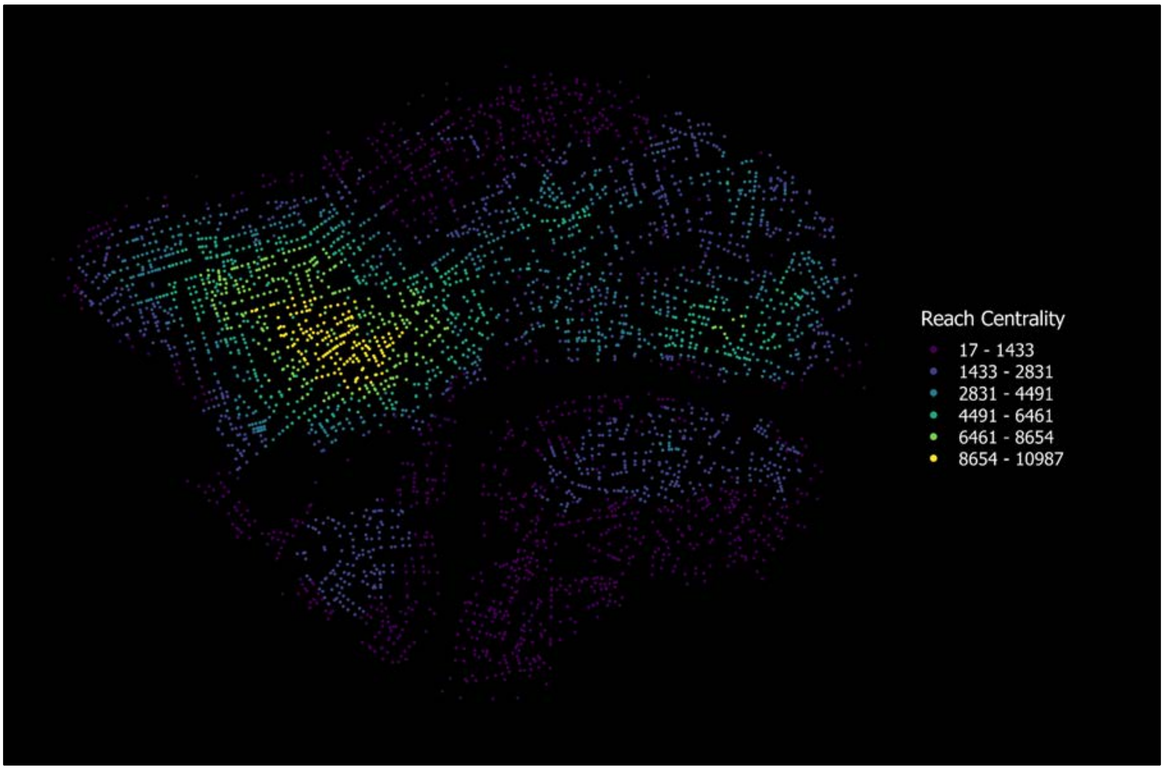

Figure 17: Street junctions coloured by reach centrality

From a quick comparison, betweenness appears a more selective measure compared to straightness and reach centrality. The nodes in the highest cluster are much less compared to the most critical nodes identified with the other measures. Straightness scores are particularly high along some parts of the Inner Ring Road, in The City and the south of Newington. The widespread high straightness scores may indicate that the street morphology permits to reach different points with rather straight routes. Even though straightness may be a decisive factor in terms of traffic flows, at least in this context it does not allow to select a set of outstanding nodes. The same could be said for the reach centrality: while it reveals a poverty of services in the South Bank, compared to the more flourishing Soho and Covent Garden, it does not constitute a compelling measure of imageability. Rather it might be useful for identifying penury in services to the public[1]. The graphs below show how reach and straightness centrality are benevolent in terms of high scores, compared to betweenness: in the last measure, the 90% of the nodes have a value lower than 200000. Approximately, that means that the three highest clusters in the relative map contain less than the 10% of the

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[1] In this index, neighbouring nodes may obtain similar values. Thus, the results probably indicate centrality at the district level, rather than node. Nevertheless, the weight of nodes could be manipulated, or the analysis may be conducted only considering junctions amongst major roads.

nodes. On the contrary, in the straightness values, just the highest cluster contains the 20% of the nodes, while in reach centrality the two highest clusters contain more than 10% of them.

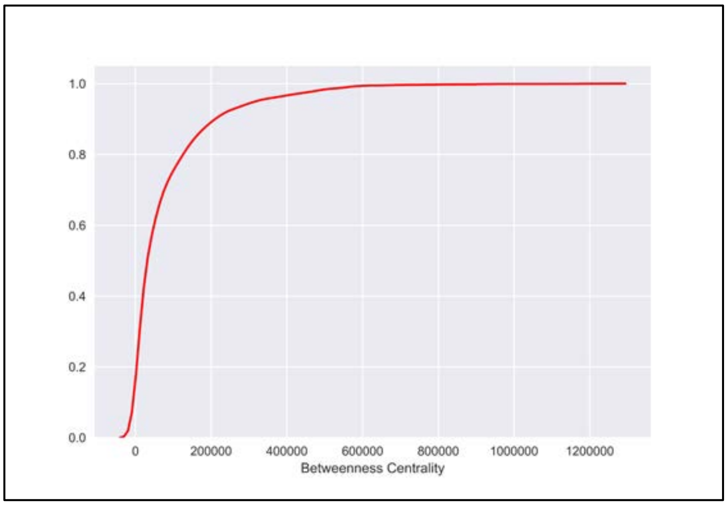

Figure 18: Cumulative probability distribution: Betweenness Centrality

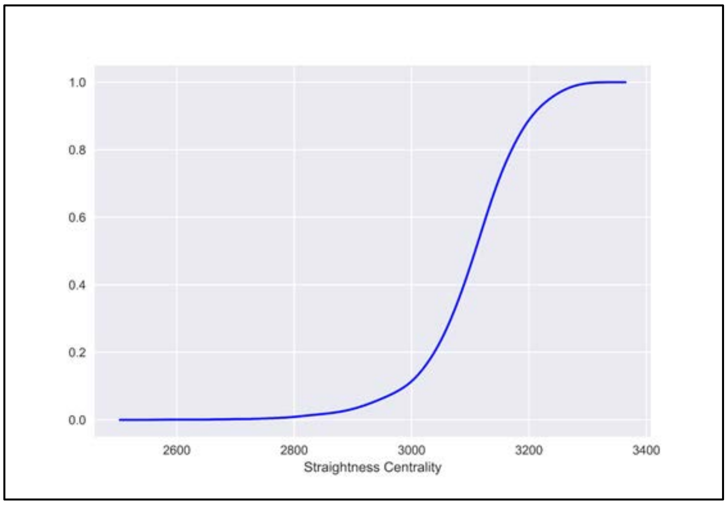

Figure 19: Cumulative probability distribution: Straightness Centrality

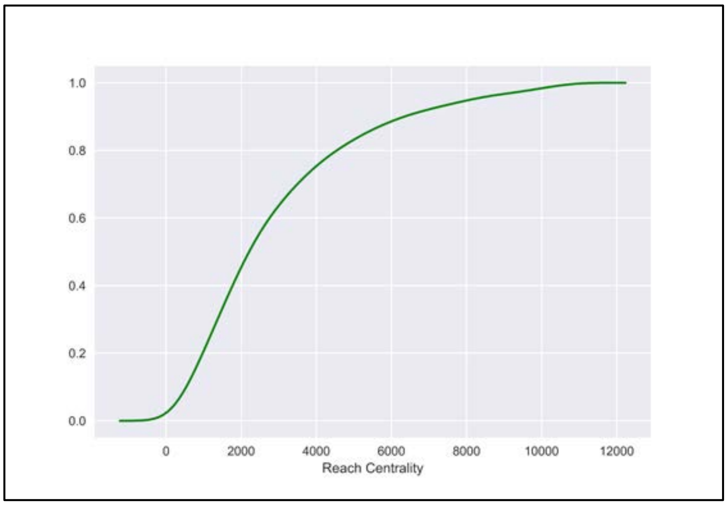

Figure 20: Cumulative probability distribution: Reach Centrality

Therefore, betweenness values offer more insights: 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 junctions along Oxford Street were detected as the main nodes in the street network. Waterloo Bridge performs an important function of link between the two regions divided by the Thames; it may represent an arrival point from the southern parts of the city and, perhaps, of the country. Holborn Circus, on the other side, is the junction of 5 major roads and represents an unavoidable pass-through when it comes to reaching specific places. In addition, Trafalgar Square is likely well impressed in the community cognitive map of London; the nearby Charing Cross railway station reinforces the strength of the square, in a transport accessibility perspective, and sketches a sort of triangle of nodes along with the Waterloo roundabout and up to the end of the Strand in front of King’s College. Finally, the copious series of nodes in Oxford Street, where Tottenham Court Road station stands out, already suggests the great importance that this street takes on in the path structure. Cognitively speaking, it is hard to believe that all the junctions in Oxford Street are as much legible as they are central. Nevertheless, one may think that those nodes assume their relevance along the route to other destinations, becoming decisions points or fundamental, intermediate steps. Figure 22 displays the crucial nodes of central London, namely the 16 nodes with a betweenness centrality value greater than 678266. Presumably, the greater number of streets and junctions in the north-west region, along with the street morphology of the area considered, contribute to the absence of relevant nodes in the south[2].

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[2] Measures of local betweenness (600, 800, 1000 meters) were calculated without obtaining more promising results.

Figure 21: Main nodes in London: Trafalgar Square, Tottenham Court Road Station, Waterloo Bridge south end, Holborn Circus

Figure 22: Main nodes detected with betweenness centrality

4.2 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 can be major access lines and well-defined routes along barriers. These directrices of movement become automatic orienting devices. People trust memorable streets and their spatial qualities. Analogously to nodes, the prominence of a street may be due to the activities that take place along its sidewalks, or to the proximity to areas designed to specific scopes, or with peculiar properties. When this is not the case, what can make a difference cognitively is continuity, a 'functional necessity'. Especially in low-legibility contexts, people rely on this perceptual quality to travel across the city and follow their routes. Continuity is associated with a sense of openness and command: it gives the feeling of being able to arrive at the destination. In this discussion, the concept of continuity and the focus on people's movement solicited the computation of two measures of edge betweenness: Euclidean (EB) and angular (AB).

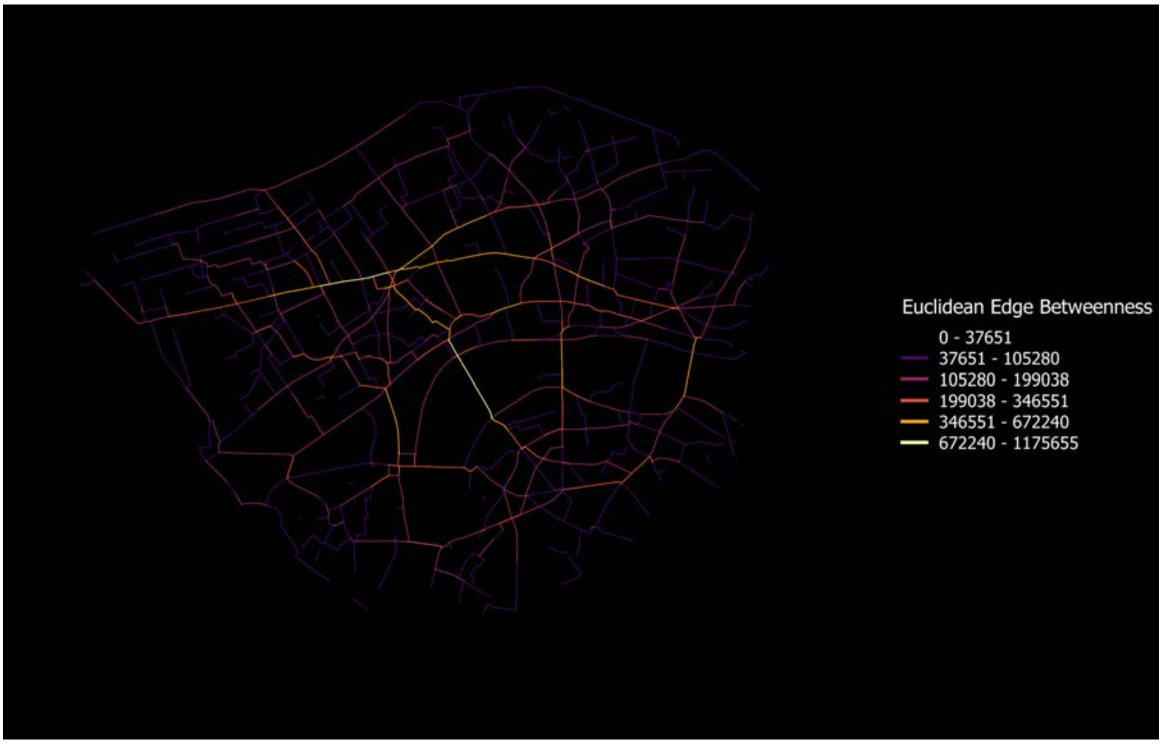

Figure 23: Segments coloured by Euclidean edge betweenness

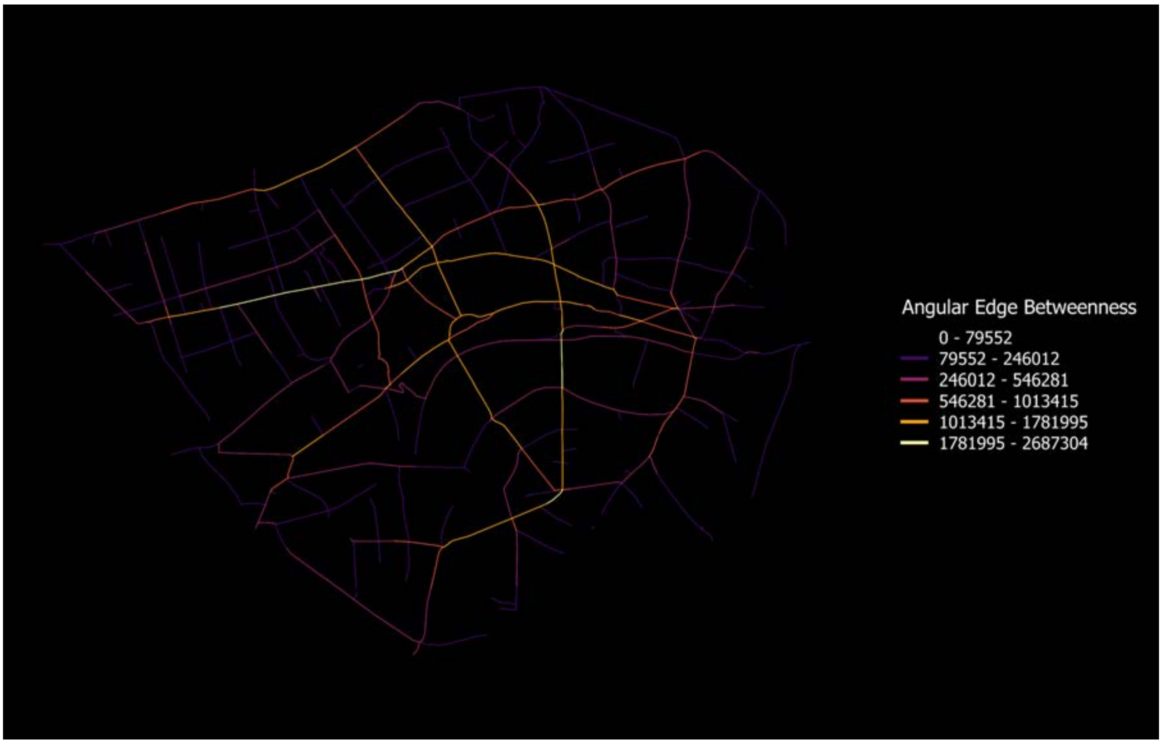

Figure 24: Segments coloured by angular edge betweenness

The figures 23 and 24 delineate basic structures of primary paths that are likely to be traversed by a substantial number of people. The two representations share some common traits but distinguish themselves for other aspects. The Inner Ring Road, the border of the area considered, has a similar relevance in both maps, especially in the northern region. The A40 (Oxford Street, Holborn and Theobald Road), as emerged from the node analysis, stands out from the rest of the skeleton distinctly. However, besides these roads and the A301, Waterloo Road, the first measure neglects relevant directrix captured by AB: the A201 through Blackfriars bridge, an almost straight connection between the south and the north, and the A4200 (Kingsway, Southampton Row). Also, the Strand emerges more clearly from the second analysis. Paths in the southern region are well-defined, and St George's Circus acquires a crucial function. On the contrary, Euclidean distance minimisation causes in the north-west region a proliferation of paths that implicate a series of turns. The fewest turn criterion is another good predictor of the urban movement that Euclidean centrality measures cannot account for.

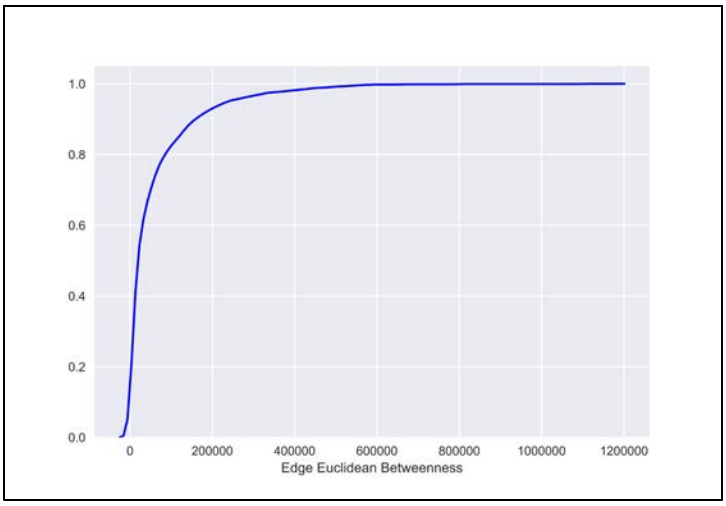

Figure 25: Cumulative probability distribution: Edge Euclidean Betweenness

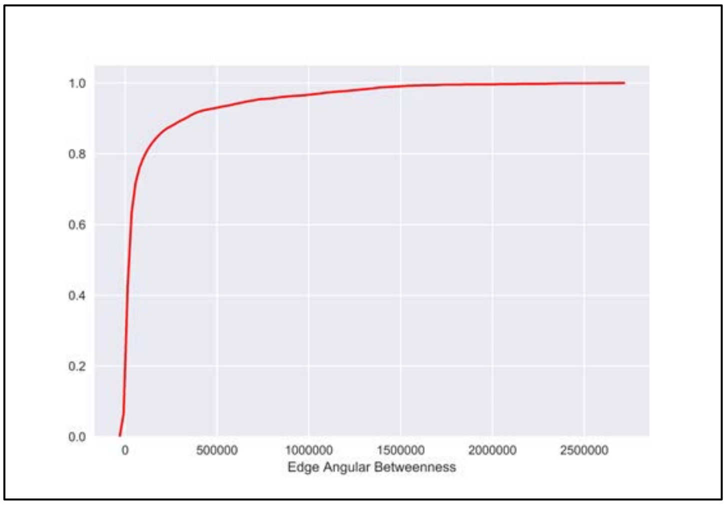

Figure 26: Cumulative probability distribution: Edge angular Betweenness

The graphs above show that there is no noticeable difference regarding selectivity: only a few segments constitute the paths map. Nonetheless, AB ignores some paths highlighted by the EB, delineating a skeleton formed by actual major roads. AB also detects paths with stronger identities, associated with a precise pair of origin and destination points. These routes connect directly specific roundabout or junctions vividly. On the contrary, in the EB map, paths are sometimes interrupted, they dissolve gradually. Most of the AB paths are long streets with an 'individual character'; intersecting roads that act as 'measuring devices'. It arises a geometrical system that 'impose regularity' to the surroundings in a coherent way, without causing spatial confusion. The visible segments in the angular edge betweenness skeleton (figure 27) are 650, with a value between 246012 and 2687304.

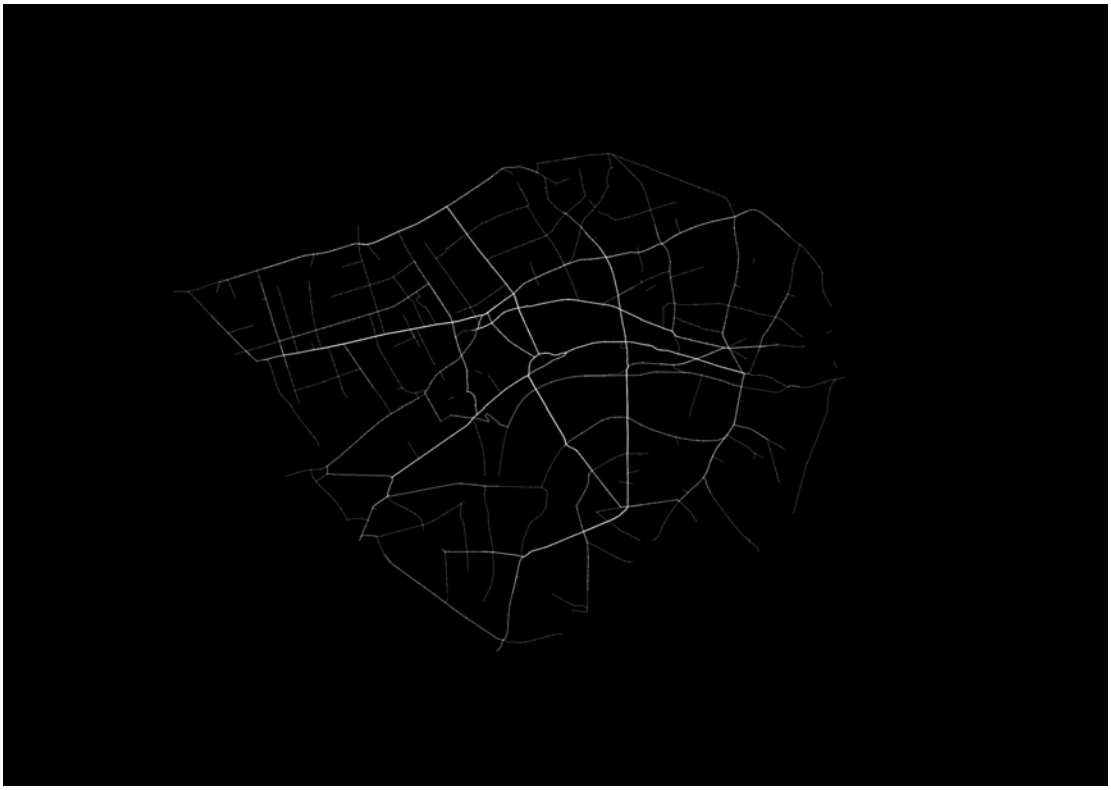

Figure 27: The skeleton of path designed by the angular edge betweenness (intensity represent variation)

4.3 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: texture, space, form, detail, symbol, building type, use, activity, inhabitants, degree of maintenance, topography (Lynch 1960, 67).*

A complex operationalisation would be required to comply with Lynch's definition of district. Indeed, their cognitive nature and the fact that they emerge from the intertwining of different dimensions, make every computational approach partial or unsatisfying. 'Districts are thematic units' used by citizens to refer to 'fuzzy entities' (Montello, Goodchild, Gottsegen & Fohl 2011, 186). Usually, the boundaries of these regions are not precise, and it is hard to formalise membership criteria.

Here, the focus is on the street topology. It has been hypothesised that different street patterns could produce the formation of geographic entities in people's cognitive maps. The modularity optimisation function was run in an undirected dual graph. The analysis was conducted on the Greater London Area[3] to extract the areas from their global context. 86527 segments were transformed in centroid-nodes, linked by 182225 edges. The divisions produced by the three different conditions, topological (fig. 28), Euclidean distance (fig. 29) and angular weights (fig. 30), are compared with a subjective functional and social representation of districts, proposed in the London Wikitravel page[4] (fig. 33), and, briefly, with London administrative boundaries, boroughs (fig. 31) and boroughs (fig. 32).

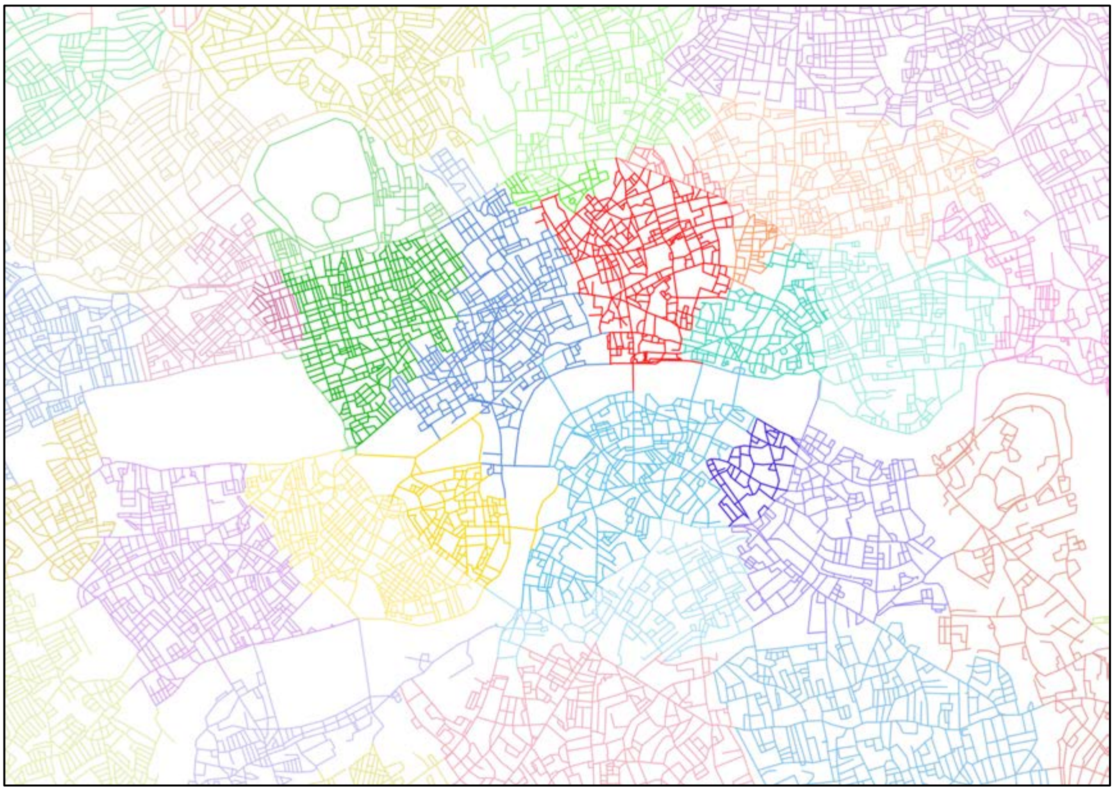

Figure 28: Street-based Local Area (SLA) – Topological partitions

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[3] The simplified *OS Meridian 2* was used for this analysis (Ordnance Survey 2016).

[4] wikitravel.org/en/London

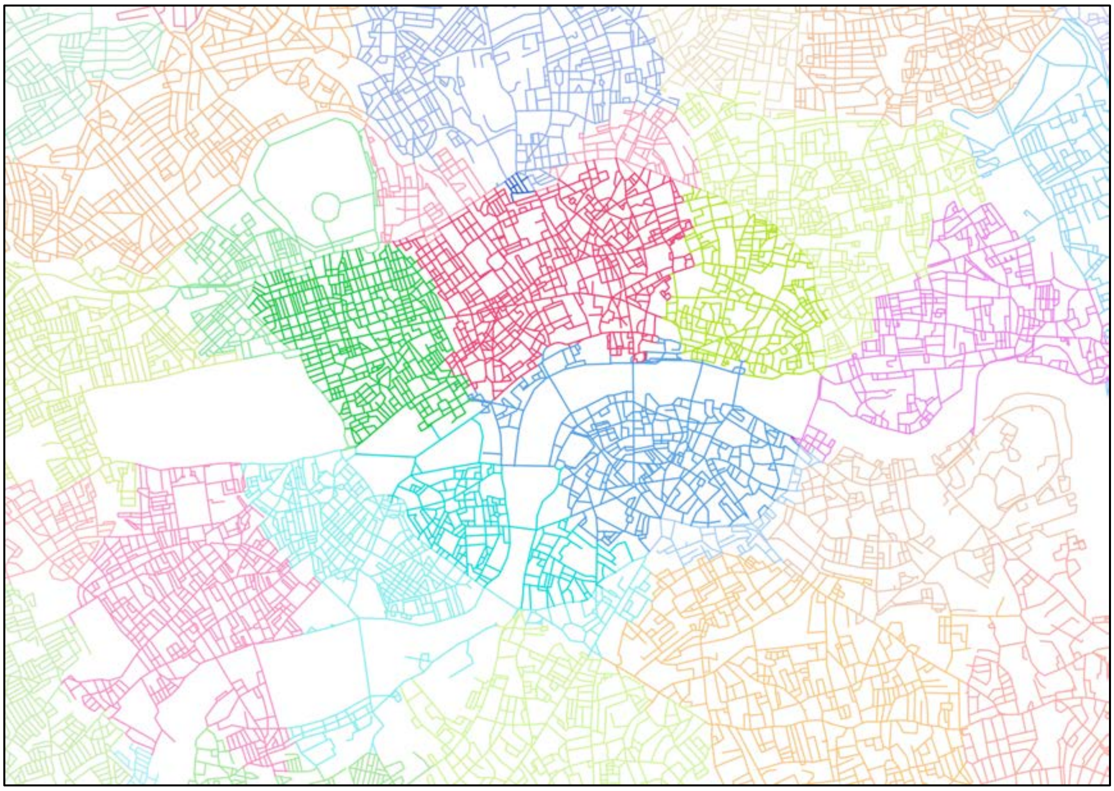

Figure 29: Street-based Local Area (SLA) – Euclidean distance partitions

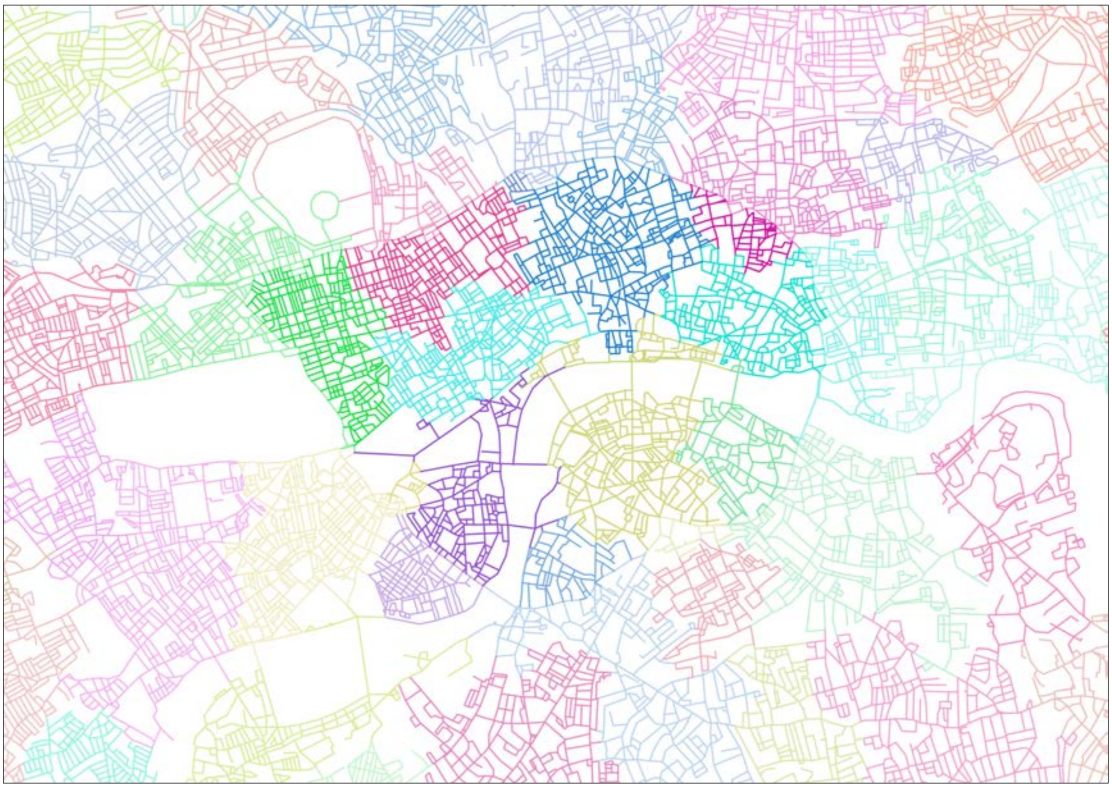

Figure 30: Street-based Local Area (SLA) – Angular weights partitions

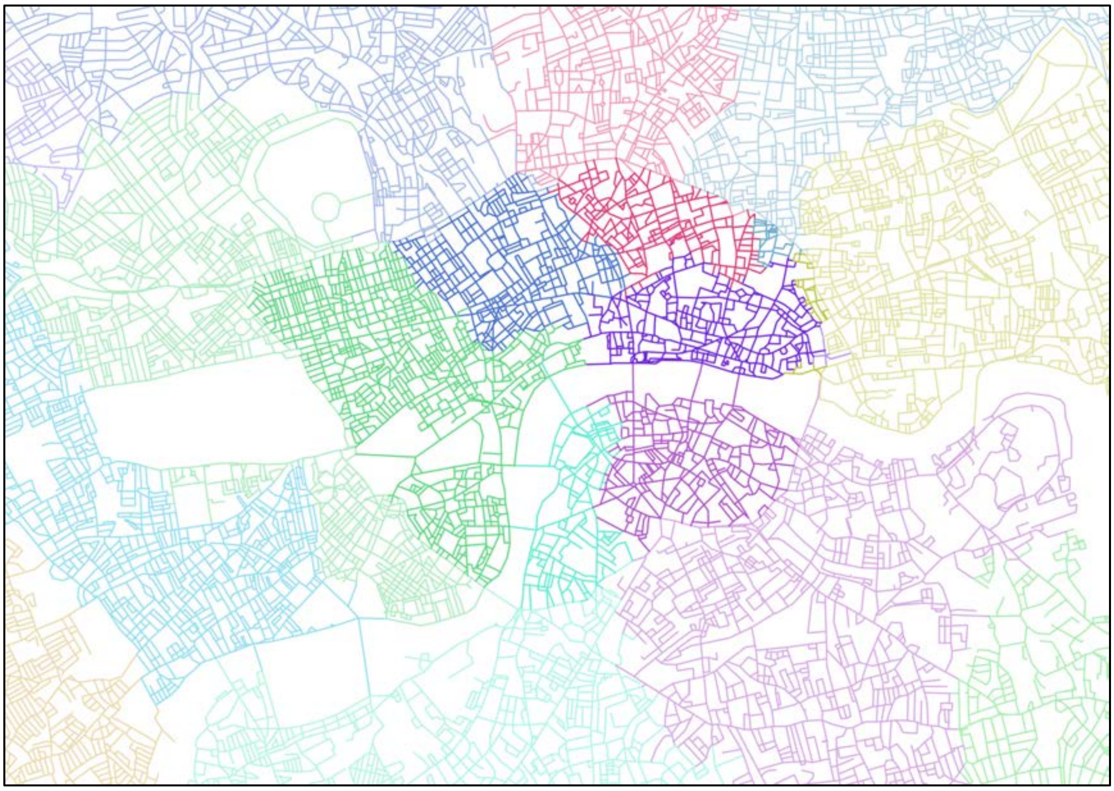

Figure 31: Street network coloured by borough membership

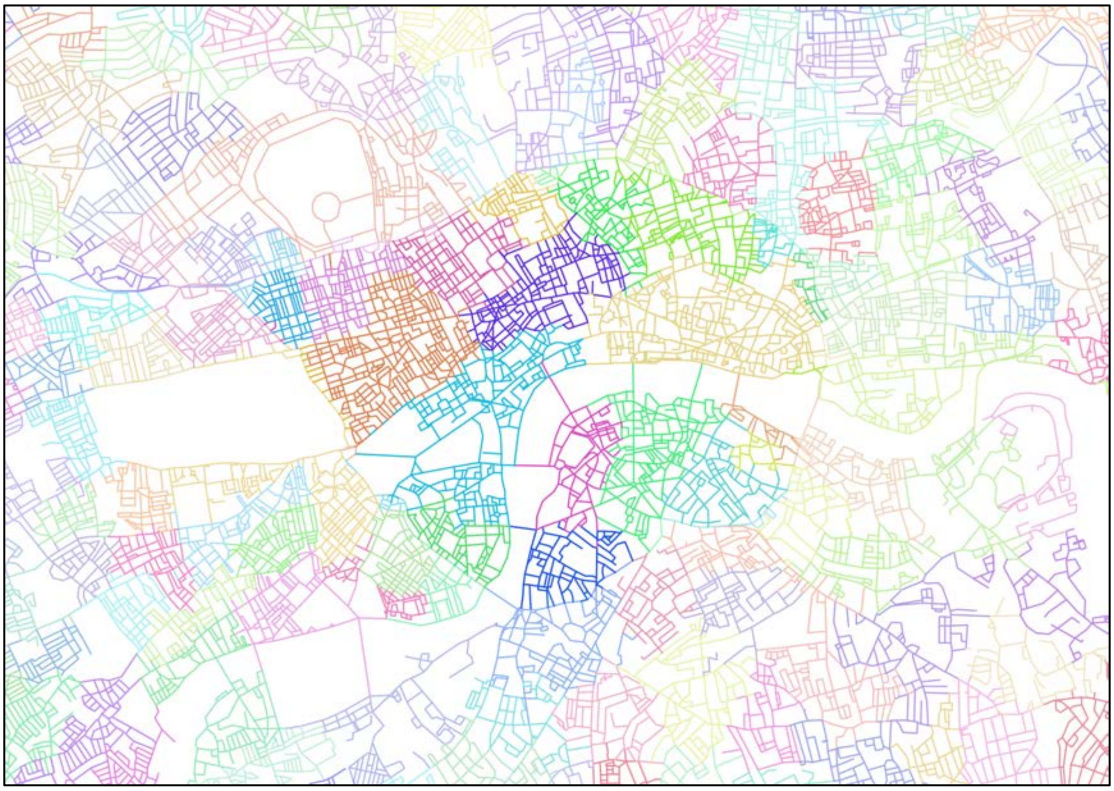

Figure 32: Street network coloured by ward membership

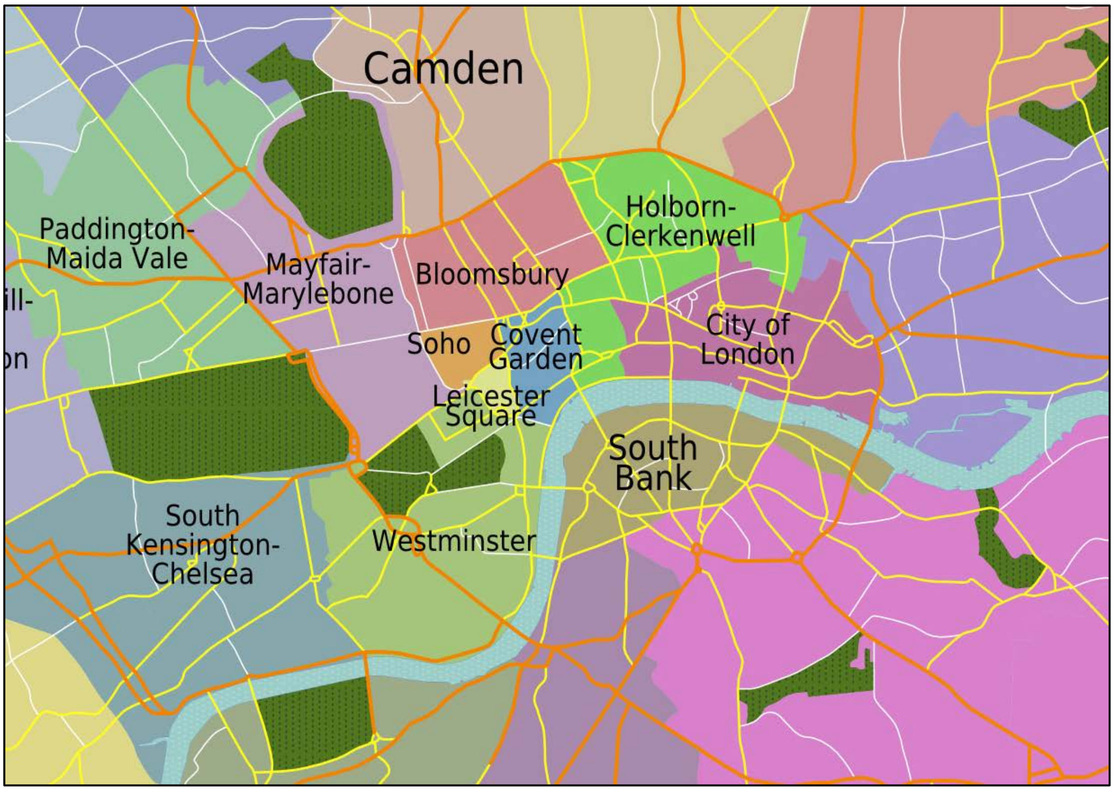

Figure 33: Functional districts in central London

Except for a few segments, the topological is the only representation that recognises the river as a natural border. Here, Westminster and Southbank are well distinguished while Soho, Covent Garden and Bloomsbury are generalised in a single partition. The differentiation of the City and Holborn is decent. When the Euclidean SLAs are examined, the area of Mayfair and Marylebone' is appropriately identified, even though the partition extends towards Paddington; Westminster region is nicely depicted as well, but the portion wrongly includes a part of Lambeth. Excluding the extensions towards the north, the most realistic partition is the one representing South Bank. The red portion includes districts such as Soho, Bloomsbury, Holborn and Covent Garden, where street morphologies are akin. The angles-weighted network produced more accurate partitions and a more intriguing subdivision. Soho, Covent Garden and Leicester Square are clustered in the same partition, Westminster, Lambeth and South-Bank are appropriately differentiated. South Bank is also divided into two regions, one ascribable to Newington and Tate area, the second to Southwark and London Bridge Area. Notwithstanding, the South Bank partition branches off to the other side of the river also in this context.

Overall, the choice of the method depends on the desired level of detail. The angular weights tend to create smaller SLAs, producing a representation that is difficult to compare with the ward boundaries (sometimes arbitrary), or the larger boroughs. Probably angular regions place themselves in a halfway position. Although the unweighted and the Euclidean networks showed an excessive generalisation, the latter performs even worse. Other community detection techniques may be more appropriate, depending on the city studied. However, some urban areas could be completely insensitive to this kind of methods. One may think of several American cities characterised by regularity and continuity in the street network. In this case, it is extremely complicated to distinguish the junctions or the paths; the city is organised in regions only based on ethnic or socio-economic factors.

4.4 Landmarks

> *Landmarks are point references considered to be external to the observer. They are more easily identifiable, more likely to be chosen as significant, 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). Spatial prominence can establish elements as landmarks in either of two ways: by making the element visible from many locations or by setting up a local contrast with nearby elements (Lynch 1960, 80).*

5200 buildings were extracted by *OS OpenMap Local*. Elements with an area lower of 200 m^2 of were excluded from the analysis; the remaining buildings were 4219.

Visual properties

Reading Lynch’s words about landmarks, it quickly becomes clear that visibility is a key aspect in landmark identification. One only need think about the relevance assumed by a skyscraper in a district developed vertically or in an old European historic centre. Height properties should be contextualised and relativised, to take into consideration the background of a building and its surroundings. In other words, height and façade area are not enough in landmark extraction. ‘Distant landmarks, prominent points visible from many positions’ (Lynch 1960, 81) are shown in the figure below.

Figure 34: Buildings coloured by visual component scores

Except for Waterloo Station, the Shard, the Guy's Hospital with its tower and the residential complex at St George Wharf, buildings in the south are less visible. Along the south bank of the Thames, buildings show a slightly higher visibility creating a contrast with the rest of the region. Such a natural edge reinforces the image of the nearby edifices, whose views are not obstructed. To the west, the only remarkable buildings are the BT and the Euston towers. On the other side, the east is characterised by a complex of visible skyscrapers, as the Cromwell and Shakespeare towers in the Barbican estate[5], up to the more recent Broadgate Tower, Tower 42, The Gherkin, Heron and Willis towers. These buildings form an interrelated system of visual landmarks, a 'cluster' of local points (Lynch 1960, 83), that orientate people's movement in several parts of the city. Figure 35 demonstrates further that positions nearby the parks or along the Thames, with their openness and fewer obstructions, are ideal observer points, especially towards the financial district and London Bridge area.

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[5] The Lauderdale Tower is digitalised in the main Barbican Centre's polygon.

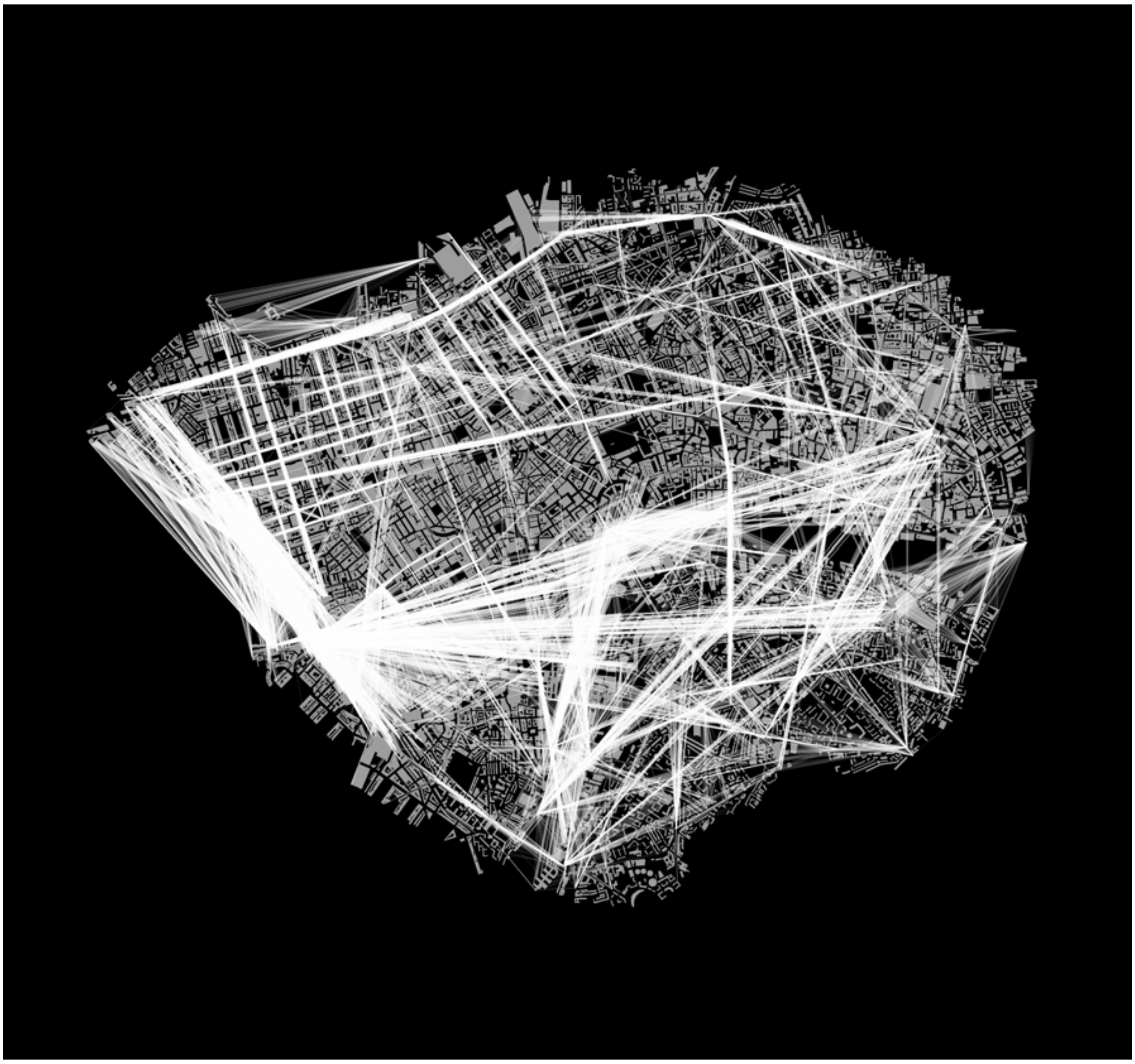

Figure 35: Sight lines without obstructions

Structural and topological properties

The concepts of contrast and prominence encourage to explore features that may determine the cognitive salience of a building from a structural point of view. Buildings with a vast space around them, distant from the road and with a little number of adjacent buildings are easily noticeable and memorable.

Figure 36: Buildings coloured by structural component scores

Similarly to the previous component, buildings in the south obtain low values. In this case, a more homogenous distribution transpires: to the west, buildings have similar shapes (squares or regular polygons) and extension, while in the south buildings are rectangular and narrow. Moreover, the density of the buildings in these areas is rather steady. On the contrary, shape and topological relations appear more irregular and varied in the east. In a sense, this component, more than differentiating buildings, originates macro areas characterised by a moderate within-variation of structural properties and a high homogeneity in topological relations. Different historical, architectural and urban planning trends may explain the emergence of these regions. Nonetheless, Somerset House, the Barbican, King’s Cross, 10 Downing Street, the Imperial War Museum, the Palace of Westminster and the Barbican Centre are distinguishable and noticeable when structural properties are examined.

Historical, cultural and pragmatic meanings

Besides structural and visual aspects, Lynch himself stated that ‘the activity associated with an element may also make it a landmark’ and ‘historical associations or other meanings are powerful reinforcement’ (Lynch 1960, 81). While the visual and structural attributes alone influence the movement of people unfamiliar with an environment, citizens and experienced users are more sensitive to cultural, historic and pragmatic meanings. These traits relate to the activities that individuals undertake across the city, to social and cultural constructs, public and private evaluations (Nasar 1998). From this perspective, a long-standing pub placed in a secondary street may play a decisive function in the cognitive maps of its customer and, at the same time, be completely unnoticed by commuters or tourists.

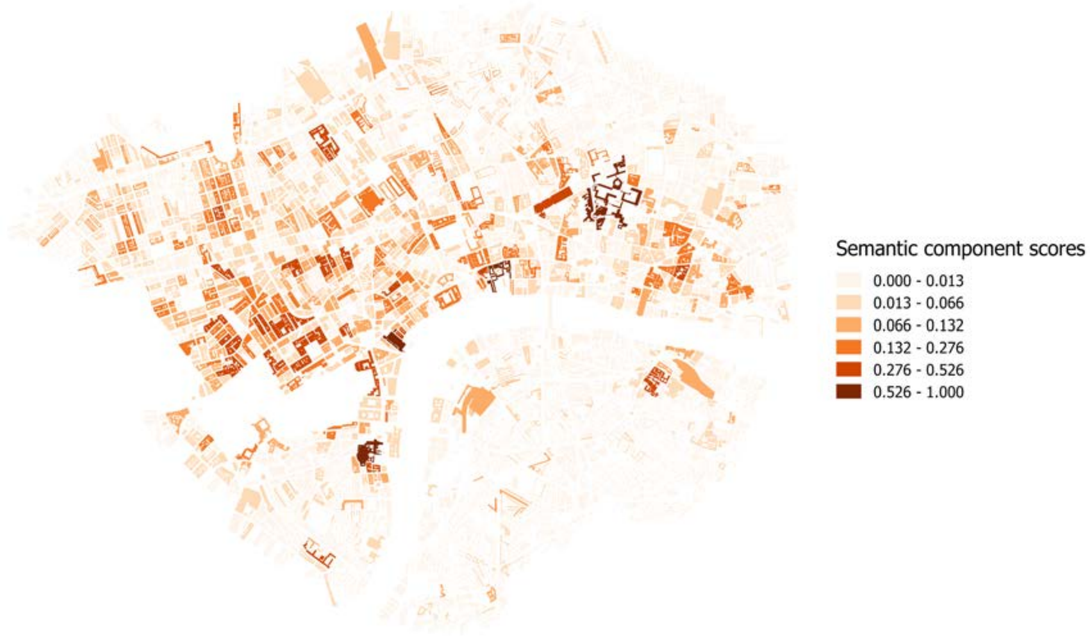

Figure 37: Buildings coloured by semantic component scores

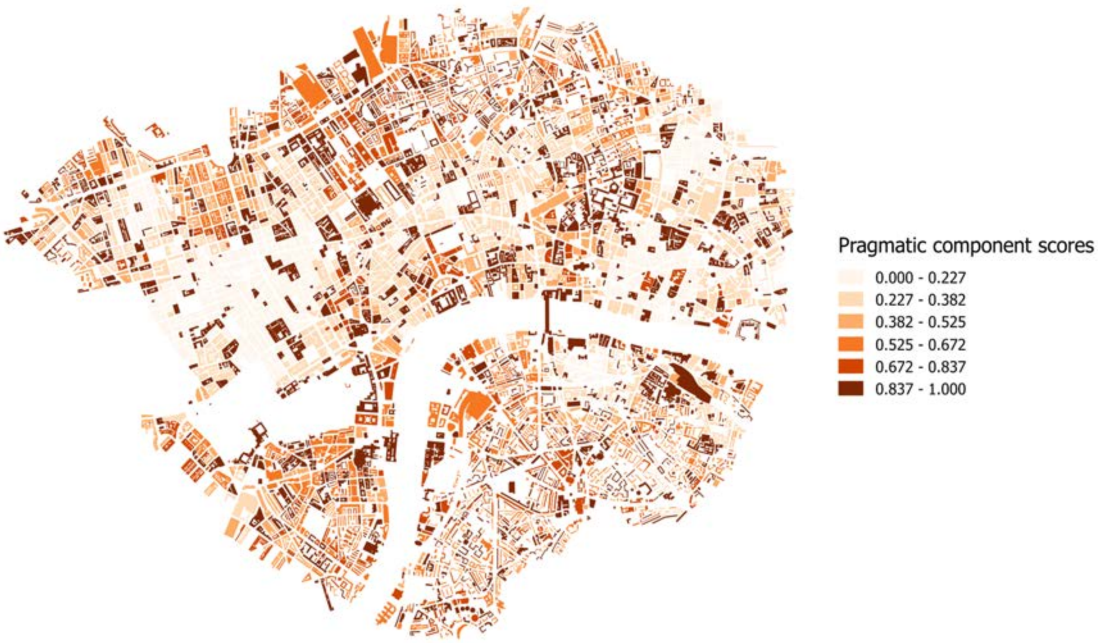

Figure 38: Buildings coloured by pragmatic component scores

Figure 37 shows once more time the low legibility of the south. Conversely, high scores are obtained by elements in the western areas, presumably richer in terms of attraction and historic references. Westminster Abbey, Charing Cross station, the Ashley Building and the Barbican Centre are the most prominent landmarks in this sense. However, this measure could be subject to validity biases; the score may depend more on the number of historic elements present in a building, rather than on their actual cultural relevance, a sort of quantity vs quality issues. In fact, some buildings notoriously acknowledged as representative of London, as the National Gallery, Buckingham and Westminster palaces obtained low scores. This drawback is partially compensated by the pragmatic index, which should award rare buildings like museums or abbeys. For instance, Tate Modern and Britain, along with the buildings listed above, eventually appear on the second map (figure 38). Here, it is worth considering the strong homogeneity in the land use classification (probably retail and commercial) in Marylebone and Mayfair districts, broken up by isolated and distinctive buildings. This trend follows Oxford Street and its branches towards the east, where, nevertheless, the pragmatic legibility is much higher. The same could be said walking along the Thames, up to Westminster: in these parts of the city, the function of buildings is probably more varied and stimulating.

Global scores

An overall score was obtained, after the application of the assigned weights, to combine the significance of these components. The relative map is shown below.

Figure 39: Buildings coloured by overall scores

As emerged from the sub-components analysis, the southern region is characterised by a low imageability; only the bank flows along a series of more significant buildings. The northern region, instead, has overall higher values, apart from Clerkenwell. Here there are almost no references. Mayfair, Marylebone and Bloomsbury arouse a more vivid cognitive map, but the prominence of the buildings is rather homogeneous. The positions of the railway stations, of Euston and BT towers, are probably used as the first point of references; successively the major directrices, with their natural and gentle evolution, might guide flows and activities. Westminster is brightly legible nearby its monuments and along the river, with irrelevant buildings in the southern area. This region is evidence of the role of structural, pragmatic and cultural aspects in landmarking. In fact, except for The Palace of Westminster, these buildings are not particularly meaningful from a visual point of view. On the contrary, The City, the region with the major number of landmarks, displays a general scarcity of cultural meanings: here, the salience of the landmarks is mostly visual. In a way, the idea that landmarks are the result of complex interactions amongst different components has been corroborated; when visual properties are irrelevant, buildings are remembered in relation to other subtle traits. Figure 40 shows the distribution of the 24 main landmarks across central London, while figure 41 illustrates the selectivity of the measures implemented: about 95% of the buildings achieve a landmark overall score lower than 0.4.

Figure 40: Most important landmarks in central London (highest overall landmark scores)

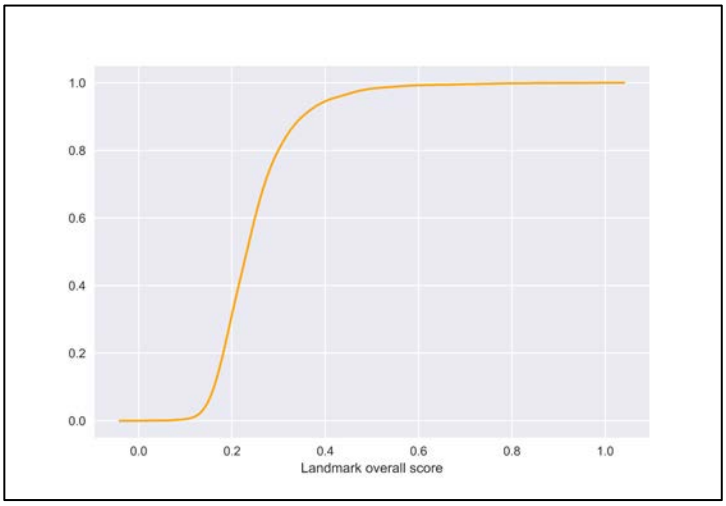

Figure 41: Cumulative probability distribution: Landmark overall score

Figure 42: Barbican Towers, Tate Modern, the financial district and its skyscrapers

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

For their nature, edges are fundamental organising features: they regulate people's flows, affecting the entrance to specific areas, forcing people to use one path instead of another one. Their continuity makes them spatially prominent but, in some cases, they are not impenetrable: 'Many edges are uniting seams, rather than isolating barriers' (Lynch 1960, 65).

In this sense, linear features that break the perceptual continuity of the city were selected through a process that entailed a series of subjective decisions. Surface or elevated railways track were extracted along with parks and the river. Only wide parks and uninterrupted railway structures were kept, to abide by the principle of continuity illustrated by Lynch. Secondly, the dual carriageway portion of Euston Road[6] was selected. The choice of including extended parks could be questionable but is due to the intention of depicting an overall image of the city: whereas pedestrians may take advantage of parks and natural scenes, their presence may defragment the more abstract, or configurational, representation of the city. Moreover, they certainly represent an edge in the case of vehicular traffic.

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[6] Euston road is the only continuous dual carriageway street with a traffic divider detected in the area. Other roads will probably play a similar role in the CCZ but it is necessary a more thorough dataset, endowed with a width field.

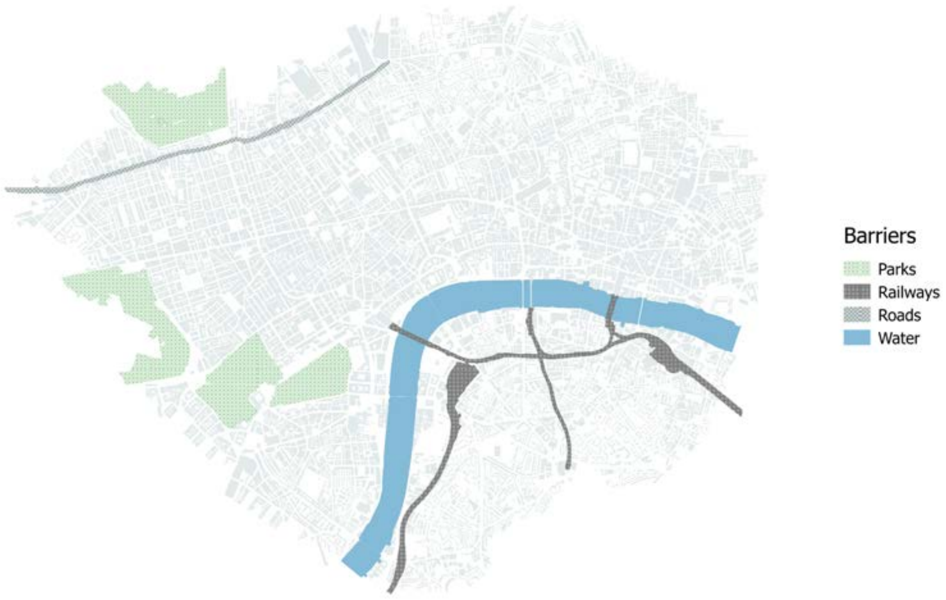

Figure 43: Visualisation of primary edges in central London

The number of crucial edges, following the discussed criteria, is rather limited and characterises the south of central London and, with different implications, the west and the north-west. The Thames caused a clear interruption between the south and the north, furtherly emphasised by the railway. Indeed, the network of bypasses and bridges regionalises the legibility of the south: the south river bank is marked by a legibility and an intensity similar to the opposite side, but the rest of the southern region is fragmented, without point of references. In the north, Euston Road probably delimitates the central area of London, separating it from Camden, supported by Regent Park. Finally, while Green Park and St James parks seem internal boundaries, Hyde Park may separate the centre from more residential areas.

4.6 The city image

‘These elements are merely the raw material of the environment image at the city scale. They must be patterned together to provide a satisfying form’ (Lynch 1960, 83). Interactions between elements come into play in shaping the mental image of the city: citizens create associations and interconnections amongst the different elements, directly experiencing the environment. Edges readjust the overall perception, setting limits on urban travels or making paths and districts more distinctive. But, as stated by Lynch, conflicts and ambiguity may emerge in this process. Euston Road is emblematic: whilst being one of the preeminent traffic directrices of the city, it also keeps away people from it, or that force them to walk along it. More, edges reinforce nearby landmark, making them more visible and decisive in wayfinding choices; this is the case of the Thames.

In figure 44, all the districts[7] (angular weights) and edges are displayed along with nodes[8] (betweenness centrality), paths (angular betweenness), and main landmarks (highest scores cluster). Figure 45 represents the image of London, without districts and with buildings coloured by landmark score.

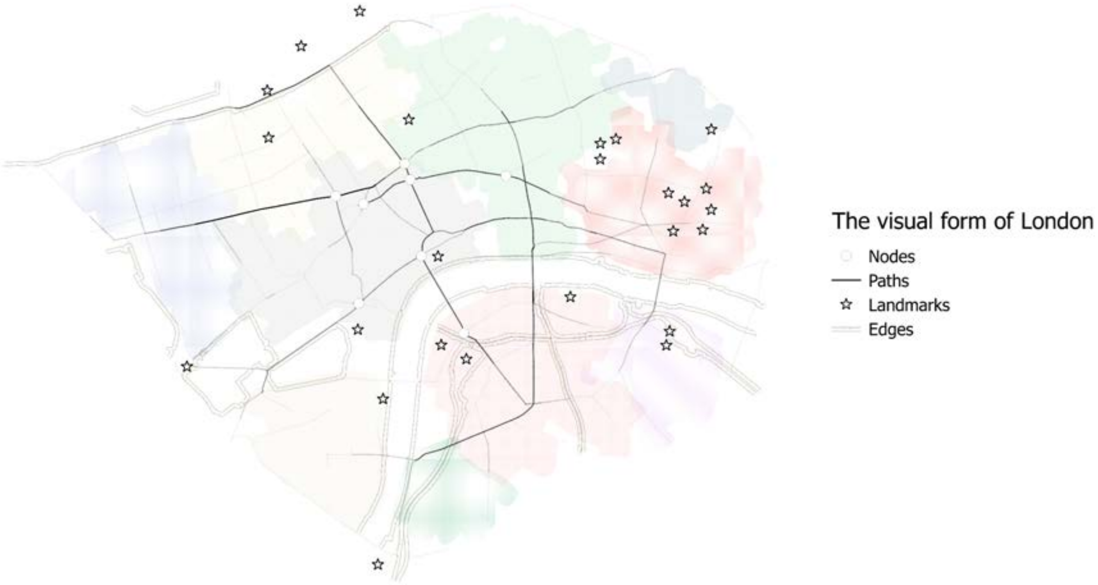

Figure 44: The image of the city of London

Central London is characterised by a well-structured skeleton map of paths. Although the nodes are mostly located in the central area, the primary paths branch off towards the other parts of the city, sometimes accompanied by the presence of landmarks, as along the river, sometimes in striking regions where there is an absence of point of references. This is the case of Mayfair and Holborn, and, surprisingly, Soho and Covent

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[7] For what concerns districts, the misattributions were manually corrected for visualisation purposes.

[8] Some nodes in Oxford street were excluded

Garden districts. While in the first case, people rely on distant landmarks or just exploit the openness of the paths, Soho, Covent Garden and Leicester Square may be perceived as a complex of activities, uses and stimuli. There, orientation could be difficult especially for beginners, but the distinctiveness of the district is undisputed. An opposite argument could be made for the financial centre, where the legibility of the area is evidently moulded by a group of visible and distinguishable skyscrapers. The south is probably the less imageable region: edges break the continuity and are probably used as references; the landmarks are distributed along the river and may act as attractors, moving people and flows towards the north, more engaging for what concerns services and cultural references. In the northern region, Finsbury is probably the least vivid part of the region. Besides from the scarcity of landmarks, this area does not seem to integrate with the path skeleton that almost circumnavigates it.

Figure 45: The computational image of London

Conclusion

Final remarks and further developments

Lynch provided a complex framework that has fostered the understanding of spatial cognition behaviour and urban dynamics. His approach, although qualitative, aspires to obtain a shared cognitive map from a set of significant elements; indeed, these geographic artefacts guide the genuine human-environment interaction giving shape to the individual images. Moved by a motivation to integrate GIS and cognitive sciences, as Lynch has blended urban geography and environmental psychology, a geo-computational approach to the image of the city was here proposed.

The study presented is not definitive and does not purport to be. Some techniques may be enriched and perfected, to respect the multifaceted nature of the elements. Nodes may be extracted with a complex combination of centrality indexes, including in the analysis, as indicated by Lynch, also transit networks. Likewise, in path identification, a more accurate distinction between the users and a combination of angular and Euclidean metric could provide a better picture. While the limit of a unique methodology for districts has already been discussed, the work has the merit of having offered a thorough model for landmark detection. Measures often neglected or just recommended (e.g. visibility, land use) in previous research, were here tested in a large dataset. Nevertheless, it was shown that the landmark extraction could be better calibrated, manipulating the weights of the different components. The method should be validated comparing the results with qualitative sources of information – as sketches, functional maps or questionnaires – or with traffic and pedestrian origin-destination datasets. A critical and explorative perspective is essential when it comes to considering vague mental concepts.

The computational visual map of London drew in this work did not differentiate amongst pedestrian, cyclists and drivers. Even though Lynch especially talks about the pedestrian perceptual experience, Mondschein and colleagues (Mondschein, Blumenberg & Taylor 2010) stress that there are systematic differences in people's mental representations in relation to the mean of transport. Following this remarks, Tomko and Winter (2013) proposes an approach for modelling the city representation, from accessibility factors. Delving into this direction may expand the sets of measures suggested, and conciliate the image of the city with transport accessibility analysis.

In conclusion, the transition from *The Image of the City* to the computational image of the city does not want to be a simplification or a new form of reductionism. Throughout the 20th century, the understanding of the human cognition had been already limited by rigid metaphors (the mind as a *black-box* in the behaviourist paradigm, and as an *information processor* in classic cognitive sciences). Rather, the present work aims to inspire a new debate and to address cognitive mapping research from a multidisciplinary perspective, joining the study of the internal and the external representations.

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Appendix

1. Land use classification

In the absence of a complete land-use data-set, this field was obtained as follow:

- Functional Buildings (*OS Local Map*) maintained their main classification.
- For the remaining buildings, the POIs inside the respective boundaries were selected.
- The most frequent categorisation of the POIs contained in each building was extracted (for instance: with 4 commercial activities, 1 tourist attraction and 1
- The others buildings were classified based on Open Street Map generic classification.
- The last few unclassified edifices were categorised as residential.

Possible land-use categories:

- Residential.
- Commercial services.
- Attractions.
- Manufacturing and production.
- Accommodation, eating and drinking.
- Public infrastructure.
- Sport and entertainment.
- Education.
- Religious Buildings.
- Emergency Service.
- Transport.
- Medical Care.
- Construction.
- Industrial.
- Cultural Facility.

2. Network simplification workflow

Street network analysis required an accurate prior phase of preparation to correct topology errors and simplify the network. In this sense, several procedures were performed:

1. Roundabouts were detected and simplified with the tool Collapse Road Detail in *ArcMap*. This procedure avoids that each junction in a roundabout is considered a node. A roundabout is instead treated as a single node.
2. In *QGis* the road network was corrected with *v.clean*[1]. The tool simplifies and removes small angles between lines, small regions, and corrects topological errors.
3. The last step included a manual, and therefore subjective, cleaning operation supported by the *QGis Topology Checker*[2] tool. Loop, duplicated and multipart geometries, pseudo-nodes were corrected.

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[1] grass.osgeo.org/grass73/manuals/v.clean.html

[2] docs.qgis.org/2.0/en/docs/user_manual/plugins/plugins_topology_checker.html