Mental representation of space in Agent Based Models for pedestrian movement in urban environments: A conceptual model

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Abstract

Agent-based models have emerged as a powerful tool to simulate complex urban dynamics, in particular due to the capability of these models of representing the complex interaction between the environment and the city actors. However, most of the existing ABMs for pedestrian movement do not incorporate any cognitive representation of space, even though concepts as cognitive maps, mental images, spatial mental models and so forth, have proven to be essential constructs in guiding spatial behaviour. In this paper we propose a conceptual model aimed at the incorporation of explicit cognitive representations in ABM for pedestrian simulation in urban spaces. The model provides for the inclusion of relevant and meaningful geographic information, interpreted as cognitive salience, through the implementation of the computational image of the city in the simulation. We devise a geo-computational approach to Lynch's *The Image of the City* to automatically extract the five elements (nodes, paths, districts, landmarks, edges) that permit to represent spatial knowledge and mental images in ABM. It is speculated that the so portrayed cognitive representation may guide the individual spatial behaviour of the agents in the simulation, that, in turn, contributes to the emergence of general patterns as movement flows and crowd behaviour.

Keywords: Agent-based models, pedestrian movement, cognitive maps, image of the city, simulation, urban spaces

1 Introduction

Cities are complex realities, far from equilibrium, traversed by flows of people, activities, and dynamic phenomena (Batty, 2013) where low-scale interactions amongst urban agents, their mental representations and social and urban artefacts, mould the global structures. One of the main components of cities are pedestrians, the actors of the sidewalk. After decades dominated by a traffic approach, pedestrian navigation in urban spaces has been recently studied in psychology, geography, computational architecture, engineering and computer science. According to Torrens (2016), the street now has a computational component that facilitates analysis, prediction and understanding of pedestrian flows. Today, 'our understanding of how people behave on streetscapes is open to investigation in ways that have never presented as paths for inquiry before' (Torrens, 2016, p. 1).

Agent-based models (ABMs) have emerged as a suitable tool for comprehending interactions, simulating actions of different agents at a micro level, and measuring the resulting systems at the macro level (Wooldridge, 1999; Crooks and Heppenstall, 2012). Agents are modelled to perceive the environment and produce a series of actions that, in turn, restructure the environment itself. Translating this to the pedestrian context: 'Agent-based simulations can be used to uncover the mechanisms of human movement patterns' (Jiang and Jia, 2011, p. 61), they allow to examine individual autonomous choices of pedestrians and how these bring about the consequent crowd flows.

Despite the growing interest in cities and spatial behaviour, and the potentialities of ABM representations, the development of authentic pedestrian simulations in the city is circumscribed. Existing literature reveals a surprising carelessness in representing cognizing agents. Spatial cognition is at best reduced to distance minimisation algorithms (e.g.: Haklay *et al.*, 2001; Torrens, 2012) and the agents' mental representations of the environment are rarely implemented: while in Penn and Turner (2001) agents are enriched with a coarse cognitive map, pre-computed by means of the *visibility graph analysis* (Turner *et al.*, 2001), in Moulin's et al. (2003) and Torrens' works (Torrens, 2012, 2014) agents' cognitive maps just include forthcoming obstacles or way-points along the route.

While, on the one hand, the tendency to simplify human cognition may be due to a form of reductionism inherited from the classical cognitive science theories, on the other hand, modellers seem to devote themselves exclusively to fine-scale details as movement, collision avoidance and realism of the gait. The underlying principles of movement are explained resorting to simple physical or social forces, or, in Space Syntax research, mostly to the street configuration: 'Higher cognitive abilities are not required in the formation of movement patterns at a collective level' (Jiang and Jia, 2011, p. 61). However, overlooking cognitive aspects is not justifiable when interactions and movement are analysed in complex environments, being cities, stations, airports, hospitals. Mental representations of space do not only guide people's behaviour, supporting orientation, movement and spatial inferences (Tversky, 1993), but also mediate the interactions between humans and their environment (Kitchin, 1994).

In this work, a conceptual model of an ABM for pedestrian movements in cities, that allows for the intertwined relationship between human cognition and an environment endowed with information, is advanced. The model is aimed to incorporate behavioural geography theories in the model, to realistically predict crowd flows in the city. Assuming that the cognitive salience of a few environmental elements in the city guide pedestrians and their actions, it is argued that a geo-computational framework to *The Image of the City* (Lynch, 1960) may support the development of an ABM with more realistic cognitive representations of space than in recent models.

2 The conceptual model

Although *The Image of the City* was written 60 years ago, Lynch has influenced research in spatial cognition, behavioural geography, computer science and AI since then. His theory states that nodes, paths, districts, landmarks and edges shape people's mental representation of the city, guiding their spatial behaviour and adjusting the interactions within and with the city spaces.

2.1 The model

We argue that a geo-computational approach to the five elements makes the inclusion of mental representation of the city in ABM more attainable. In this direction, we advance a conceptual model for the development of an ABM for pedestrian simulations in urban spaces (see Figure 1).

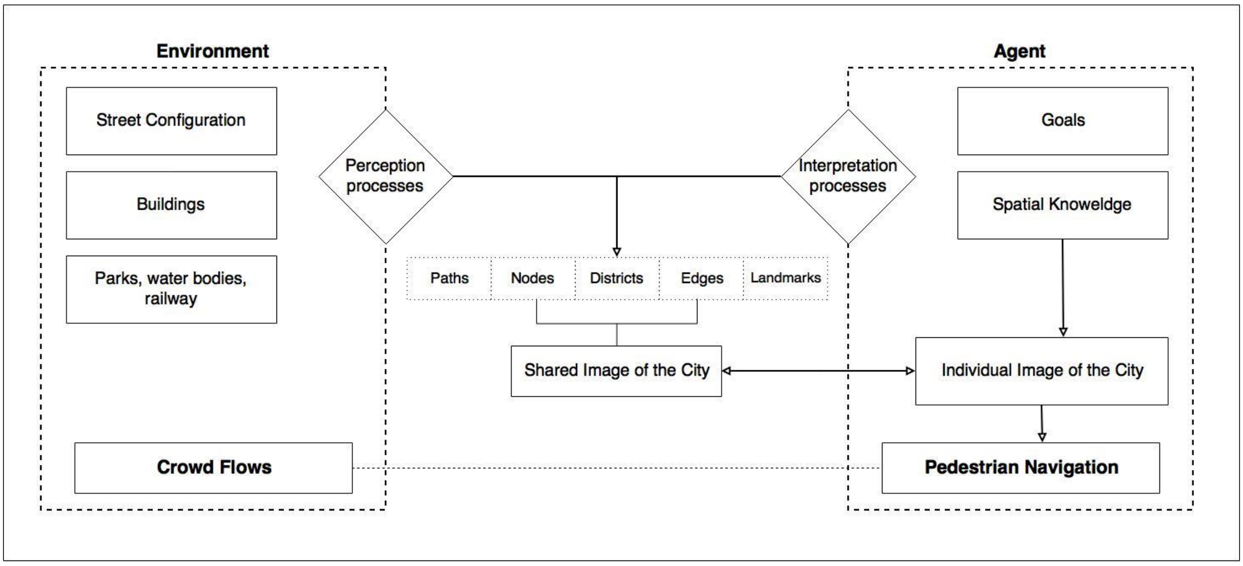
The model is represented by two components: agents and their environment, whose interaction gives shape to the mental representations of that environment and course of actions of the agents. Physically, the environment is composed of pure geographical information, as the location of the streets and the footprints of the buildings, but cognitively, the environment and its attributes (street configuration, morphology, buildings architectural properties, use, age, etc.) are perceived and elaborated by the agents through meaning-attribution and interpretation processes. The environment becomes rich of information, and therefore, of cognitive salience. In this way, a general and shared image of the city originates from the overlapping of the mental maps of the users of the city.

What really guides pedestrians in their navigation here is their imperfect mental representation, result of their knowledge, their experience, their goals, their activities and habits. It is, for example, hypothesized that experienced agents, representing people living or working in a certain city, have a solid and well-defined cognitive map of that city. They may rely more on cognitive landmarks (for example semantic and pragmatic component), rather than visual ones (see: Sorrows and Hirtle, 1999); since they have a deep knowledge of the environment, they are likely to minimize travel time. Conversely, unexperienced users, such as tourists, may owe a more blurred representation, tending to minimize cognitive fatigue or stress, choosing paths to their destination that minimise angular deviation; they make mistakes because of their representational distortions, and hence rely on visual landmarks.

Therefore, the individual Image of the City is seen as a dynamic construct, in constant evolution. This also implicates that agents are equipped with a general representation of the whole city, and a dynamic map around the agent itself. The dynamic cognitive map is linked to the global representation: news paths could be memorized, meaningful buildings encountered along the path may assume relevance and become crucial, new districts become attractive and so forth.

Even though most of the existing literature supports a solid definition of the Lynchian elements in terms of pedestrian

Figure 1: A conceptual representation of the agent-based model, its components and its interactions



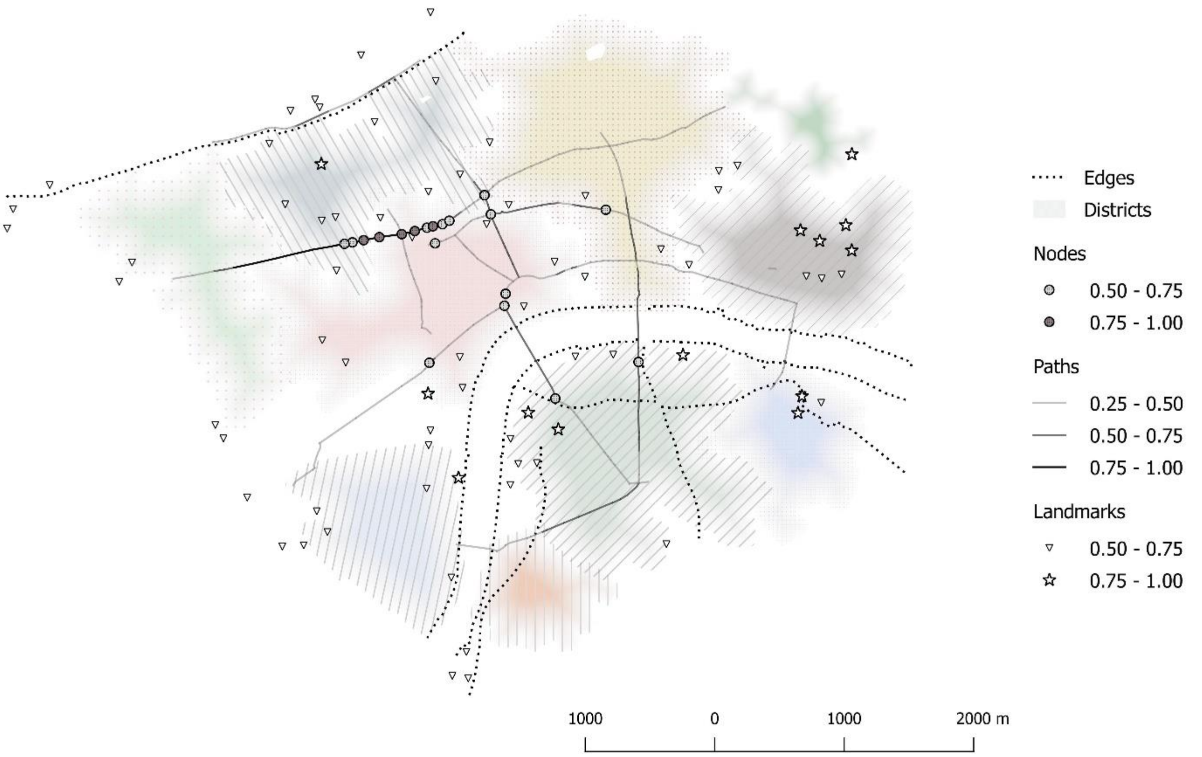
navigation, an accurate formalisation of their role and functions will be required in such a simulation. Synthetically, we intend to design and model the five elements as follows:

- *Nodes:* besides being gateways to the city or its areas, they represent destinations (as centres of activities) or intermediate decision-points where people must choose amongst several alternatives.
- *Paths*: road segments will offer different levels of attractiveness, affording to be traversed or not, accordingly to the route-choice criteria used by the agents and their goals. We speculate that in some cases nodes may have priority in determining the destinations, while in other cases (for instance: explorative or unpurposed behaviour) the paths and its attributes guide movement.
- *Districts:* at the higher level of the spatial hierarchy, agents may select the functional regions of their origin and destination within which the origin- and destination-nodes lie; waypoint nodes that belong to these and other intermediate regions are then identified and connected with the appropriate street segments (paths) (Manley, Orr and Cheng, 2015). Furthermore, districts may guide agents in identifying possible final-destinations, coherently with their purposes.
- *Landmarks*: they constitute anchor-points, features that help people to remember their route, to take the right turn at a fork. Besides being relevant features at the street level, it is supposed that unexperienced people need to see some of the most prominent landmarks while walking, for example every two junctions, to orientate themselves.
- *Edges*: they attract people to walk along them (as rivers) or they indicate people not to walk beyond them, when they separate part of the city or delimitate the city centre from the suburbs or less walkable areas.

2.2 The computational image of the city

In order to be able to implement the above-described conceptual model, a computational extraction of *The Image of the City* from spatial data of the physical urban environment is required. Regardless of the multi-disciplinary implications of *The Image of the City*, a complete integration of the five elements in GIScience has never been advanced. Haken and Portugali (2003) propose an information approach to *The Image of the City* to connect the external artefacts with the mental representations: the cognitive salience of the urban elements may depend on the amount of quantitative and qualitative information that they convey to individuals. At the same time, Space Syntax scholars have explored *The Image of the City* by means of the concepts of axial lines and isovists (Dalton and Bafna, 2003), suggesting the employment of network techniques for detection of nodes, paths and districts. Moreover, the work of Sorrow and Hirtle (1999) has influenced the development of landmark extraction procedure

Figure 2: The computational image of the city, London (UK) city centre. Different colours indicate different districts.



in GIScience (e.g.: Winter *et al.*, 2008).

These researches have inspired the formulation of a complete geo-computational approach to *The Image of the City*. We propose to compute a series of measures to identify the five elements of Lynch from simple geospatial sources as street network, building and other urban structures (railways, water bodies, parks, etc.) datasets:

- *Nodes:* street junctions are considered vertexes in an undirected primal graph where *betweenness centrality* is computed and used to rank them. Pass-through, crucial intersections may be considered Lynchian nodes.
- *Paths: edge betweenness*, based on Euclidean distance or angular deviation, is used to rank links representing street segments in an undirected network. The most important paths are formed by the segments that minimise distance or angular change along routes across a city.
- *Districts:* community-detection techniques are employed to subdivide the street network in functional regions. The *modularity optimisation* algorithm is used to detect functional districts from the street morphology (Blondel *et al.*, 2008; Law, 2017).
- *Landmarks:* visual, structural, pragmatic and semantic (cultural/historical) components contribute to the definition of a landmark and derive from attributes such as: height, façade area, visibility (sight lines analysis), extension, openness (space around the building), number of adjacent buildings, distance from the road, historical importance (binary or continuous values), and distinctiveness of the land use type.
- *Edges:* continuous sections of motorways, surface-railway structures and waterfronts are identified as edges.

Nodes, landmarks and paths are ranked by the relative index and by means of the percentile ranges used by Lynch. This methodology has been presented more extensively and tested on the area of Boston studied by Lynch, so as to compare the computational Image of the City with Lynch's (Filomena, Verstegen and Manley, 2018). For the current study, the methods are applied to the central area of London delimited by the Congestion Charge Zone.

2.3 Preliminary results

Figure 2 displays the result of the methods in section 2.2, Main nodes, paths and landmarks are depicted along with the districts extracted from the street morphology and the major edges of the region. The next step in our research is to connect this map to an ABM as conceptualized in Figure 1.

3 Conclusion

Agent-based models represent one of the most relevant tools to simulate pedestrian patterns in urban spaces. Nevertheless, while ABM for pedestrian movement favours the exploration of emergent, non-linear macro-scale-behaviours, the cognitive component has been often neglected in such simulations.

In this paper, we claimed the necessity of reconsidering the role of mental representations and, thus, of spatial cognition processes in ABM for pedestrian movement in cities. In particular, we proposed to employ *The Image of the City* and further advancements of the theory, to extract a computational image of the city. Network science techniques, landmark extraction methods and edge detection criteria are used for this purpose. Thereby, we argued that the implementation of the computational Image of the City might permit to devise a simulation where agents are placed in an environment endowed with salient information; from the interaction of those two systems a mental representation of the city takes shape and guides individual spatial behaviour, allowing for individual differences, scopes and spatial experience. In this context, the individual, cognitively-grounded behaviour contributes to the emergence of crowd flows.

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