Space layout affects search efficiency for agents with vision

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Abstract

Groups of mobile sighted individuals, whether insect, animal or human, behave in complex ways as they search their environment for the resources needed to live. Amongst urban human societies search behaviour is complex and emergent since it relates to settlement morphology and land use pattern, both of which themselves result from human activity. Recently, agent simulation experiments have been used to study patterns of emergent behaviour in the dynamics of crowd movement and in the construction of paths through open space. Here we report simulations in which agents are given long distance vision and direct their behaviour in response to information from the entire cone of vision afforded by the morphology of the local environment and their gaze direction. We show that the morphology of the environment and the location and aggregation patterns of resources within that environment affect the efficiency with which these agents can conduct their search. Linear streets and clustered aggregations afford efficient search for multi-target 'comparison' behaviour where agents search amongst a number of targets for a 'best match' to their requirements, whilst dispersed locations are most efficient for single target 'convenience' trips. We propose that urban space morphology and retail location patterns may have evolved to support efficient search. Finally, we argue that knowledge of distributed processes of decision taking such as that involved in search for resources and location selection on the part of resource providers, could lead to a new intellectual framework for land use planning.

Introduction

Urban systems are highly complex objects that emerge from the interactions between many different actors and agencies, each making decisions which are often contingent on those made by others, and which emerge from the interactions of different social, economic and physical systems, each with their own rules. Gaining a well founded understanding of urban growth and change processes over historical timescales will be vital if we are to secure sustainable pathways for urban development and development control. In particular, though, we need to understand how different interacting systems, composed largely of independent decision takers making numerous day to day decisions come together to influence this process, and how best to intervene in and guide what is essentially a ‘distributed’ decision taking process.

A concrete example will help make this clear. Charlotte Street in London’s West End is well known for its restaurants. Tottenham Court Road, running parallel and 100m to the east, is known for its electronics shops. Both streets vary from end to end in terms of densities of these functions as well as in density of pedestrian movement. It has been known for some time that urban spatial morphology exerts a powerful effect on pedestrian movement patterns (Hillier et al., 1993). It is not clear however to what degree specific land uses act as attractors of pedestrians, or the pedestrian footfall as an attractor of land uses. Still less is understood about the processes that lead to clustering and mixing of different land-use functions, or about the manner in which these patterns affect the way that people move through and use the urban landscape to support their living requirements. And yet, if we are to try and control urban development, to create cities that are both vital and viable, we need to understand how it is that distributed processes of decision taking can lead to apparently coherent outcomes.

Current research at the Space Syntax Laboratory and the Virtual Reality (VR) Centre for the Built Environment at the Bartlett, UCL is linking together space syntax analysis with multi agent simulation methods. In this way we are aiming to develop the experimental methods needed to investigate the dynamics of distributed decision taking in the built environment. In this paper we describe the early results of a series of experiments investigating the effects of spatial configuration, location of facilities and attraction in facilitating search for specific goods by a population of agents. The paper is in three parts: first we describe the current theoretical and research context surrounding our understanding of urban systems considered as an outcome of distributed decision making. We argue that three main strands of theoretical development are now maturing to the point at which they present a serious opportunity to gain an understanding of urban social, economic and morphological processes. Next we describe our experimental method and the results of a series of experiments in which we investigate the dynamics of aggregation of similar retail functions along street alignments in urban areas. These results are at the very earliest stage, however they are encouraging in that they show that with relatively simple mechanisms complex and unexpected results emerge. Finally, we discuss the possible implications of these techniques, and the knowledge they may give rise to, for urban planning processes. In particular we propose that the three strands of rational/utilitarian, incremental ‘trial and error’ and more recent participative planning, may be unified by new knowledge of the dynamics of distributed decision taking coupled to urban configuration.

Background: the research opportunity

Until recently a number of factors have barred progress in research into the dynamics of growth and change at the very fine spatial scale which is of such importance to our experience of the city and may well be of importance to its economic and social viability. A critical gap in knowledge surrounds the processes by which mixed development can be achieved and sustained. First, there have been few useful methods for representing and quantifying the phenomena of urban growth and change in such a way that historical changes in urban morphology and function can be quantified and put on a comparative basis. This has constrained research either to deal with relatively low-resolution data across a range of examples[1] - essentially ignoring the fine scale morphological variable, or to deal with single 'case study' examples at a higher resolution. Second, the complexity of the interactions involved has made it unclear what exactly to observe or measure, and particularly what factors might be considered to be prior to others. Since data gathering in real urban situations is very expensive, especially for longitudinal data, and existing datasets tend to be of relatively low spatial resolution or aggregated for data protection purposes, significant studies of these interactions are virtually nonexistent. Where detailed studies have been made they have tended to focus on single aspects of the domain rather than on the interactions between systems.[2] Third, it has been difficult to convert this area of investigation into an experimental science since intervention is both expensive and long term. Experimentation, where it takes place at all, has therefore largely been practice-based on live projects, with all the attendant risks.

Recently, however, a number of methodological and theoretical advances may have begun to make it possible to gain the understanding that is required. First, the development of a theoretical framework for understanding of the emergent effects of distributed processes through multi agent systems and the mathematics of complexity. Although much of the effort in applying this mathematics has concentrated on developing a framework for understanding evolution and self-organisation in biological processes (Waddington, 1966; Kaufmann, 1993), or in the economics of markets (Epstein and Axtell, 1996), many of the underlying methods may be applicable to other discrete and distributed information systems. This offers hope that systems as apparently complex and chaotic as urban growth and change, and the distributed decision making and markets that underlie them, may become tractable to theory. Early work by Allen, Sanglier and Prigogine (Allen and Sanglier, 1978, 1981; Prigogine and Stengers, 1984: 196-203) has suggested that certain phenomena in urban growth display chaotic behaviour patterns. In particular, using computational models they have demonstrated that small variations in initial conditions can lead to widely divergent end results in terms of development density and land use patterns, however, once set, the development pathway can demonstrate a high degree of inertia. It might even be suggested that policy measures can be considered as perturbations on an evolutionary landscape. More often than not planning policy measures may fail to overcome the inertia and nudge the system development from its path, or they may nudge it onto a new but undesired trajectory. An understanding of the shape of the evolutionary landscape is of vital importance if policy is to be targeted to achieve desired outcomes. Although this work is highly suggestive, the spatial scale at which it has proven possible to apply urban models of this sort is too gross to deal with the finer scale issues of land use mix and street configuration which appear to be so important to our everyday experience of the urban landscape.

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The second is in the development of space syntax techniques of analysis of urban and built space, coupled to theories of society in which the spatial morphology of the built environment plays an active rather than a passive role (Hillier and Hanson, 1984; Hillier, 1996; Hanson, 1998). Their methods represent and quantify the pattern properties of built space in order to control for morphological variations in studies of other aspects of urban function. Research using these techniques has found that spatial configuration has a pervasive effect on many aspects of social function. The main finding is that up to 80% of the variance in pedestrian (Hillier et al., 1993; Peponis, 1994; Read, 1996) and vehicular movement (Penn et al., 1998) from space to space in urban areas can be explained by simple measures of the degree of 'integration' of the street segment (a measure of the mean depth of the whole network away from the street alignment, where steps of depth are measured by changes of direction in the street grid). The density of development of land indexed by mean building height, and the predominant ground level property use were found to be important secondary factors for pedestrian flows, and roadway width important for vehicular traffic. Both local and global configurational factors were therefore implicated in both modes of movement behaviour. However, since movement flows in turn appear to be the driver for a number of other urban phenomena, including retail land use locations which are critically dependent on 'passing trade', it seems clear that the dynamics of urban land use and its relationship to configuration is characterised by feedback, and may well exhibit non-linear behaviour both in time and in space. The research suggests that markets in retail property and therefore markets in other property types (especially commercial) may be affected by the spatial configuration of the city more directly and at a finer scale than central place and gravitational theories of location have indicated. Support for this has been found recently in a study of commercial property transactions in Berlin. Using space syntax methods to quantify the configurational variables, direct evidence has been found for fine scale configurational drivers for commercial property market values as these have shifted and stabilised following reunification of the city and the establishment of a market for property in the east (Desyllas, 1996; 1998). More recently Hossain (2001) has studied the detailed location of different retail types as these have evolved in large unplanned and unregulated market buildings in Dhaka. She found clear evidence for different locational strategies emerging for prime market attractor functions and suscipient functions. Prime attractors appeared to aggregate (and so facilitate comparison shopping) and be able to survive some degree of spatial segregation within the building complex, where suscipient functions, which are dependent on 'passing trade', sought out more spatially strategic locations (e.g. adjacent to entrances or stairways) and invariably dispersed from one another.

Other urban phenomena have also been found to be dependent on movement and so on configuration: variations in property crime vulnerability appear to be negatively related to both vehicular and pedestrian movement rates (Hillier, 1998); spatial segregation and a lack of 'intelligibility' (indexed by the correlation between local and global configurational variables) in inner city housing estates has been found to be related to the degree of separation between adult and child/teenager space use patterns (Penn et al., 1995; Hillier, 1996: 183-214); and fine scale variations in atmospheric pollution at head height have been found to vary according to vehicular flows, and hence to vary systematically with urban morphology (Penn and Croxford, 1998). The research shows that these methods for quantifying spatial configuration can shed light on both 'normal' and 'pathological' states of urban function. Since many aspects of social, economic and environmental life are lived out within the space pattern defined by the built environment, methods of analysis which are sensitive to the configuration of space through which we move can form a useful unifying framework to allow research to address the interactions between the different independent but interactive systems that seem to characterise urban function. The problem is that whilst these methods can usefully help us to 'explain' empirical case data, the do not currently deal with the dynamic and emergent aspects of urban systems at the level of individuals. To do this we believe that an experimental methodology needs to be added to the explanatory analysis based methods developed to date.

Lastly, the development of powerful computing makes it possible to develop simulation experiments to allow the investigation of the dynamic interactions between different systems which we think might govern the processes of urban function and urban growth and change. Simulation methods have shown considerable success in other complex social and economic domains and have a number of attributes which make them suitable for experimenting with urban processes. In particular, the socio-economic function of the built environment can be viewed in terms

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of the interactions between various actors and agencies. As physical goods, buildings are designed, financed, constructed and occupied by people and organisations, and each of these processes is characterised by negotiation. Changes in property ownership and use, and its eventual refurbishment or redevelopment are achieved through similar processes. As a commodity, property is traded in markets which again may be considered in terms of agent negotiation. Agent based computational paradigms using BDI architectures (beliefs, desires, intentions; Shoham, 1993; Eiser et al., 1998) lend themselves to building simplified experimental simulations of these processes (see for instance with respect to the emergence of market phenomena: Epstein and Axtell, 1996; Moss, 1999). There are however, two other areas in which simulation methods have been implemented. The first is in the use of restricted random aggregation processes to generate ‘urban form’. Hillier’s ‘beady ring’ settlement simulations (Hillier, 1984: 55-61) and more recently White and Engelen (1993), Batty and Longley (1994) and Erickson and Lloyd Jones (1998), have all explored the use of different random, Lindenmeyer system and fractal growth processes. The second is in the simulation of patterns of movement and wayfinding through complex environments. Here there are a number of approaches, ranging from those used for robotic navigation (Kuipers and Byun, 1991) to the swarming and flocking algorithms used to simulate animal behaviour for animation and graphics applications in film (Terzopoulos, 1999). Research by Penn & Dalton (in Gilbert and Doran, 1994) developed simulated automata and tested various rule sets governing wayfinding decisions to see which most closely matched observed pedestrian flows through urban areas. Recently more sophisticated agents have been developed under an EPSRC Platform Grant at UCL (GR/N21376) which have ‘vision’ and so can perceive their environment and other agents and can act in response (Penn and Turner, 2002; Turner and Penn, 2002). These agents use an exosomatic visual architecture (EVA) to allow large numbers ($\sim10^3$) to inhabit the same environment at the same time and to move in real time on current PC computers. We are currently investigating the kind of perception/action rules needed to allow these agents to reproduce observed pedestrian flow behaviours in real environments.

Taken together, these three strands of research present a clear opportunity. Where urban planning has in theory depended on the ability to predict the outcome of specific policy measures, the realisation that has emerged over the last fifty years is that the tools and methods at the disposal of the planner are woefully inadequate to deal with situations in which we have relatively sparse information. In the early 1970’s Lee voiced the concerns of many planners with his critique of largescale urban models as practical planning tools when he showed that these models depended ultimately on knowledge and data that were at that time unavailable. More recently, with the increasing availability of digital data in GIS there has been a resurgence of interest in these approaches to modelling. However, now the critique of the rational planning approach has shifted and is based on the difficulty of ever knowing enough about individual preferences to be able to construct predictive models. This critique of centralised planning has evolved through the participatory paradigm (Healy, 1997) and is now represented in the extreme libertarian view that it is only through the adoption of market based planning that distributed information and knowledge can be used efficiently (Pennington, 2002). There appears now to be broad agreement across the ideological spectrum that rational utilitarian approaches to human systems, in which complex multi-dimensional and subjective valuations and meanings must play a defining role, are likely to fail. Against this background the study of urban systems as examples of complex interactive systems in which decision taking is distributed amongst many decision takers, but in which patterns emerge, holds considerable attractions. In order to do this we have developed a new experimental approach to the analysis of urban morphology.

An agent based approach to land use mix

Our approach to this subject has grown out of the space syntax research described above. Syntax research has found that the morphology of the urban grid itself has a powerful effect on a wide range of social behaviours and pathologies. This morphology is defined by the relative placement of buildings and other bounding features in the urban landscape. In order to investigate this space syntax methodology first represents the pattern of space using a geometrically defined map composed of elements such as the locally 'fattest' convex areas or the locally 'longest' line of sight, before constructing a graph of the relationships of connections between these local elements. Properties of these graphs are then measured. We are now investigating a different approach by developing software agents which have vision of their environment – that is they have a visual field which at any moment is defined by the boundary features of the environment, and the agent's angle of vision and direction of gaze. The agents are given movement rules that depend on what they can see from where they are currently in the environment. Our initial research using these agents found that a very simple rule, 'select a location at random from the entire plan area visible to you, turn and move in that direction, and repeat the process every three steps', led to remarkably high correlations between aggregate agent movement flows and observed pedestrian movement in buildings (Penn and Turner, 2002). This correlation was maximised when agents were given an angle of vision of 170∞, approximately that of normal human vision (Turner and Penn, 2002). Turner (2003) has found that in a central London study area this agent rule correlates with observed pedestrian movement at least as well as space syntax 'axial integration' and significantly better than visibility graph analysis.

Although these results make a lot of intuitive sense, and are pleasingly simple, it is clear that the methods can be taken much further. Agents with 'vision' allow two types of interaction to be dealt with directly. The first is that agents can see and respond to each other. At present we use this to allow individual agents to pass each other in the street without bumping into each other. The second is that agents can see information on the boundary (or in any other part) of the visual field. Thus a building surface, which forms a visual boundary to the agent's field of view, can also be tagged with information describing its 'function'. It is this part of the simulation we have experimented with in the study reported here. By giving selected parts of the boundary a 'taste', encoded as a random two dimensional vector, and then giving each agent a 'hunger' also encoded as a random vector, we have set up a series of experiments in which the agents are used to explore an environment, and we can study how effective they are in finding a 'taste' that suits their 'hunger'.
09.8 We can go on to study how the morphology of the environment and spatial factors such as location, aggregation or dispersion of the 'shops' affects the agents' search efficiency.

The experiments are set up first with a simplified grid like environment, in which we have varied the location and degree of aggregation of the 'shops'. Then we repeat this process using a version of the grid in which blocks are partially misaligned to give an apparently less ordered overall pattern. This gives us a model with which to investigate a kind of simplified shopping behaviour, and in particular to begin to ask questions about the relationship between spatial configuration, location of 'attractors' and the efficiency with which agents with long distance vision can search in a complex environment. Within the different environments we have chosen to either aggregate the location of the shops or to randomly distribute them. Aggregations take one of two forms, either as two dimensional clusters, or aggregations along the length of streets. We have tested a number of different versions of aggregations in which their location within the overall grid varies. Similarly, we have experimented with a single centrally located cluster and with splitting this into three peripheral sub-clusters.

For each of these experimental set-ups a typical experiment entails releasing agents randomly throughout the area, and then tracking where they go. First we use agents which have no 'hunger', and which ignore the location of shops. This generates a pattern of movement on the basis of the simple rule described above as this is affected by the pattern of visibility afforded by the environment. Next, we set the agents to find a shop. The first shop they see they go to, and when they reach it they leave the system. In this experiment the shops act as the ultimate attractors in the system. While this is happening we record various pieces of information describing the agents' behaviour, the number of steps it takes to reach the first shop, and in particular we look at the match between each agent's 'hunger' vector and the 'taste' vector of the shop it reaches. Two vectors can be compared for their degree of similarity by taking their dot product. The average dot product for the agent population is recorded. The next stage is to repeat the process asking the agents to visit two (then three and four shops, and so on), and then to return to the one whose taste vector best agrees with their hunger vector. This generates a form of browsing behaviour in which agents search the shops they can see for a 'taste' that best matches their 'hunger'.

Our interest here is primarily methodological. Can agent based simulations show any substantive differences between agent search in different morphologies? However, we are also interested in the answer to a number of specific questions. Are spatial agglomerations of shops more or less efficient than random dispersion from the agents' point of view in terms of time taken to search, and in terms of the outcome of the search in terms of the match between hunger and taste vectors? How do linear 'along a single street' agglomerations compare to clustered agglomerations from this point of view? How do search time and the match of taste to hunger vary as the agent visits increasing numbers of shops? How does this shopping behaviour affect patterns of agent movement in the environment as a whole? The results of our experiments are described below before these questions are revisited in the discussion.

The simple grid

A simple 12x12 grid was used for a series of simulations. The movement pattern of agents without any form of attractors shows movement rates increase towards the geometric centre of the grid (Figure 1.). We next locate 24 shop frontages on single sides of individual blocks. Figure 2 shows a maximally dispersed random allocation of frontages, and the result of asking agents to select the shop with the best match 'taste' for their 'hunger', either as Hobson's choice (the first shop you come to), or given increasing lengths of search ranging from 2 to 24 shops. Under the Hobson's choice scenario the shops act as pure attractors or sinks in the system, and agents who enter do not re-emerge into the environment. However, the pattern for two shops and for all 24 is remarkably similar in structure, and is clearly different, but related to the purely centralised pattern shown in Figure 1. The differences, which appear to be related to shop location and routes between shops, increase with number of shops visited, as the trips between shops outweigh the natural tendency towards the geometric centre.

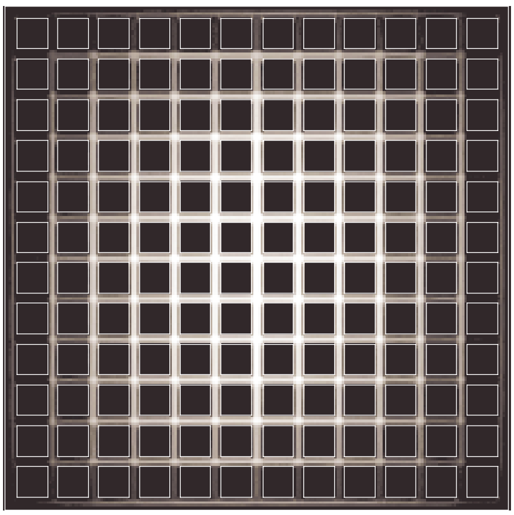


Figure 1: The pattern of agent movement in a 12x12 grid using agents with long distance vision and the simple rule to move towards a destination selected at random from the visual field, re-evaluated every 3 steps (red represents high movement rates)

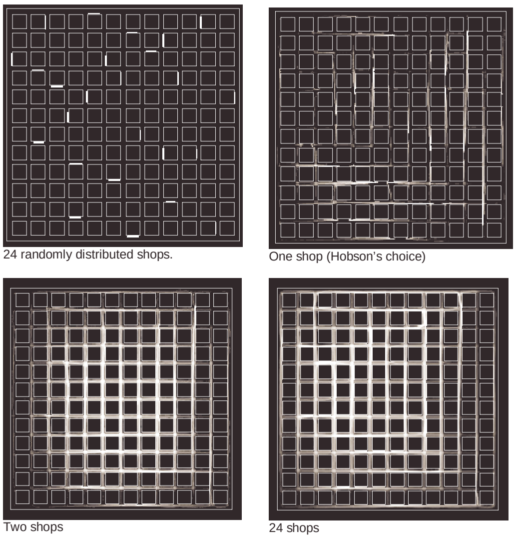


Figure 2: Twenty four randomly dispersed shop frontages

The second experiment consists of locating all 24 frontages as close as possible to the geometric centre of the grid. Figure 3. shows that, when only one or two shops are visited the higher rates of movement are actually outside the core, and agent movements reduce in the centre, however, a highly concentrated pattern of agent movement emerges as the number of shops visited increases. Again this is a characteristic of shop to shop movement outweighing other forms of movement behaviour.

The single central cluster shown in Figure 3 was closely aligned with the natural central tendency for agent movement without specific destinations. We therefore tried an experiment with three peripherally located clusters each of eight frontages, located so that none shared a direct alignment on the grid, but each consisted of a crossroad on differently located pairs of street alignments (Figure 4).

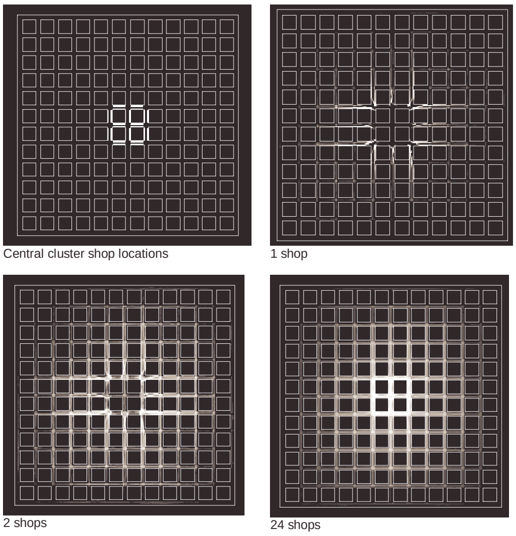
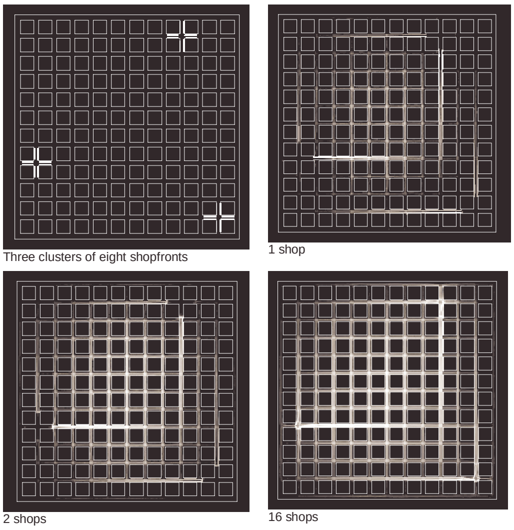


Figure 3: Central cluster of 24 shop frontages

The three clusters show a clear deficit of movement under the Hobson's choice pure attraction experiment, with the main alignments leading to the crossroads gaining use in proportion to how centrally located they are on the grid. The more shops that are included in the agents' itinerary, the clearer becomes this central tendency, but also a masking effect of close, but parallel routes. Note, for instance, at the difference between the movement rates on the vertical and horizontal alignments leading to the lower right cluster. It is also notable that the centre vertical alignment gains high movement rates despite not being directly aligned with any of the clusters. This appears to be an effect of its centrality in the configuration as a whole, coupled to being reasonably distant from the nearest vertical alignment towards the topmost cluster.

The fourth experiment placed a single street of shop frontages along both sides and the full length of the central vertical alignment (Figure 5). It is clear in this experiment that the street of shops acts as a sink or 'black hole' under the Hobson's choice scenario. It clearly divides the central tendency movement into two blocks, each of which now display a central tendency within the east and western halves of the grid. The street in pure attractor mode appears to behave effectively as a boundary separating the two sides of the grid. As numbers of visits increase the central tendency reasserts itself, and rapidly the single street is established as the only major movement space for the majority of its length.



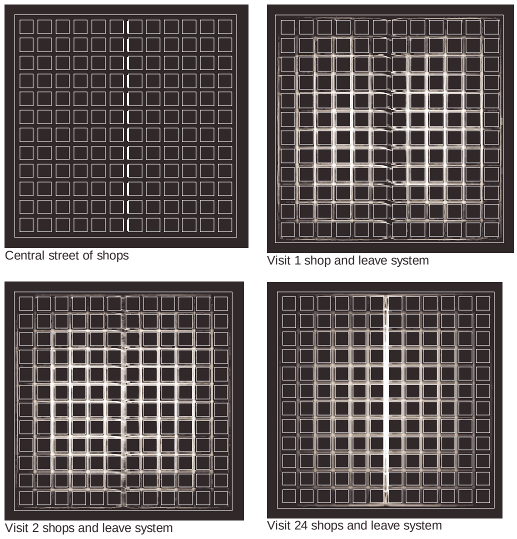


Figure 4: Three clusters located peripherally in the grid

Figure 5: A single central street

The deformed grid

The second series of experiments investigated the effect of minor deformations to the alignment of the blocks in the grid. Our aim here was to change the local visibility conditions while maintaining effectively the same network structure. The procedure was fairly haphazard, in that blocks were moved vertically, horizontally or both, but without any particular system in mind, until the configuration while still recognisably a 12 by 12 grid containing street like spaces, now also contained a number of small ‘squares’, and most street alignments were broken somewhere along their length. The agent movement pattern resulting from agents without shopping destinations is shown in Figure 6. This shows that the deformations completely eliminate the geometric and metric central tendency found in the uniform grid (Figure 1). A number of other features of the movement patterns are noticeable. The small open ‘squares’ feature as turning points in the movement pattern, and often appear to be crossed diagonally. A number of relatively short linear spaces in different areas of the plan gain relatively high movement rates. This appears mainly to be related their position in the configuration.

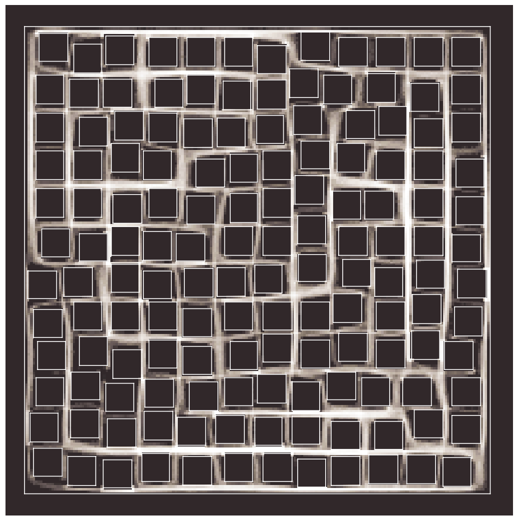


Figure 6: Agent movement in the deformed grid without shopping destinations

In view of the effects of geometric centrality on the results of the uniform grid experiments the diffusion of movement throughout the plan area of the deformed grid would clearly provide a contrasting set of conditions for the visual agents in making a search for shops. We therefore replicated as exactly as possible the locations of the various shop frontages in the different experimental

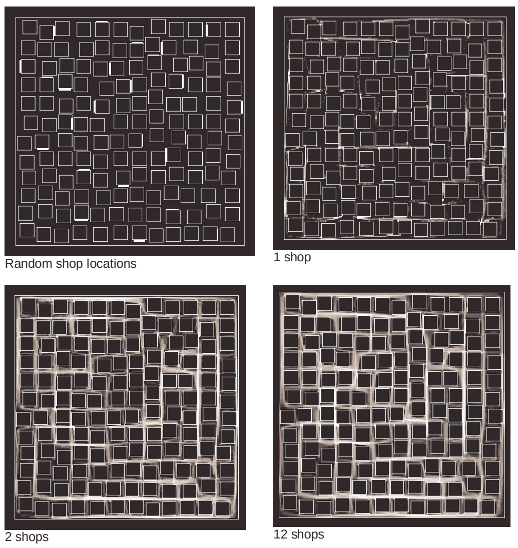


Figure 7: Randomly dispersed shop frontages in the deformed grid

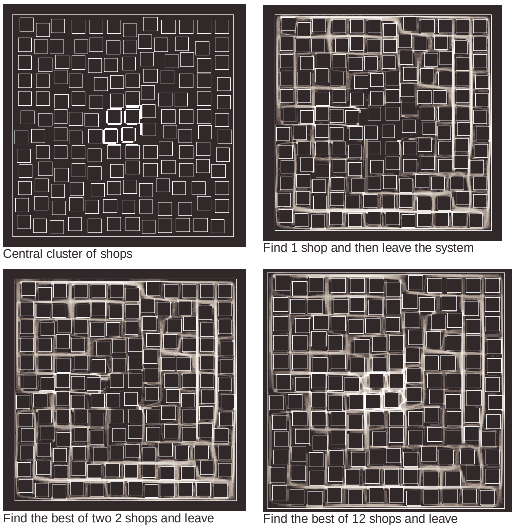


Figure 8: The central cluster of 24 frontages in the deformed grid

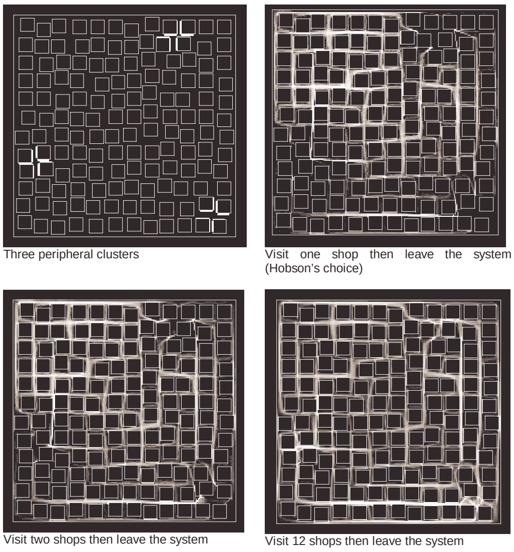


Figure 9: The three peripheral clusters in the deformed grid

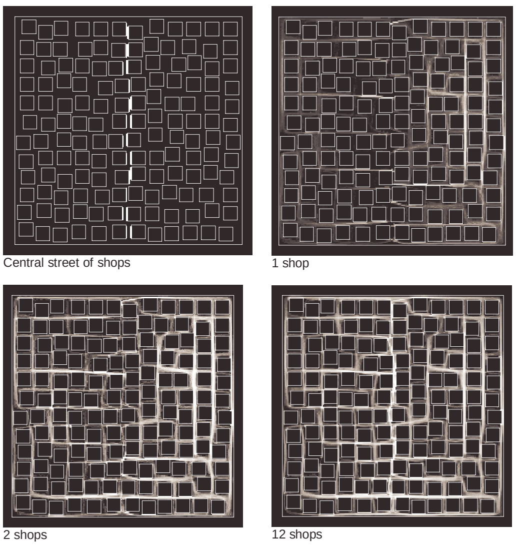


Figure 10. The single central street in the deformed grid

set-ups. These are described briefly below.

The randomly distributed shop frontages in Figure 7, coupled to the deformations in the grid lead to an almost complete dispersion of movement with some tendency to higher rates in the more linear spaces near the periphery. There is very little difference in movement patterns as the number of shops visited rises with the 2 and 12 shop versions giving almost exactly the same pattern.

In contrast, the centrally placed cluster (Figure 8) shows a strong central drop in movement under the Hobson's choice variant, with peripheral movement in the same alignments favoured by the system without shops (Figure 6). As numbers of shops visited increase, the central shopping core gains movement, but still in a relatively restricted manner, whilst the peripheral movement spaces, which are visually isolated from the core, maintain their movement rates. This contrasts directly with the equivalent uniform grid experiment where all movement was eventually located in the central shopping cluster (Figure 3).

The effect of visual isolation from the shopping clusters in maintaining movement is repeated in the 3 cluster experiment, where it is most visible in the north west corner for the Hobson's choice variant. However, as the number of shops visited increases, this area loses its importance in favour of alignments that point directly at the clusters, in particular, the peripheral longer alignments on the south and east sides of the grid (Figure 9).

The single central street system again divides the system in two for the Hobson's choice scenario, but this time with radically different effects on the east (where strong vertical alignments capture the movement) and the west, where most alignments are horizontal and so appear to drain movement towards the street attractor and deplete the western half of the plan. As the length of shopping itineraries increases the central street and its horizontal feeders gain movement and form the main movement space (Figure 10), however the eastern vertical alignments still keep the high movement levels through this process, perhaps because of their visual isolation from the shopping street.

The visual environment as a search interface

The series of experiments described above was used to capture information on the agents' behaviour and the degree to which their 'hunger' was met by the 'tastes' of the shops they found. These data are summarised in the series of graphs in Figure 11 below.

Graphs 11a and 11b plot the average dot product of the taste and hunger vectors for agents final choice of shop as the number of shops visited increases. The regular curve for all systems is exactly what one would expect for randomly assigned vectors. It shows that there is a decreasing payoff the greater the numbers of shops visited. This applies to all the different systems regardless of configuration or location of shops.

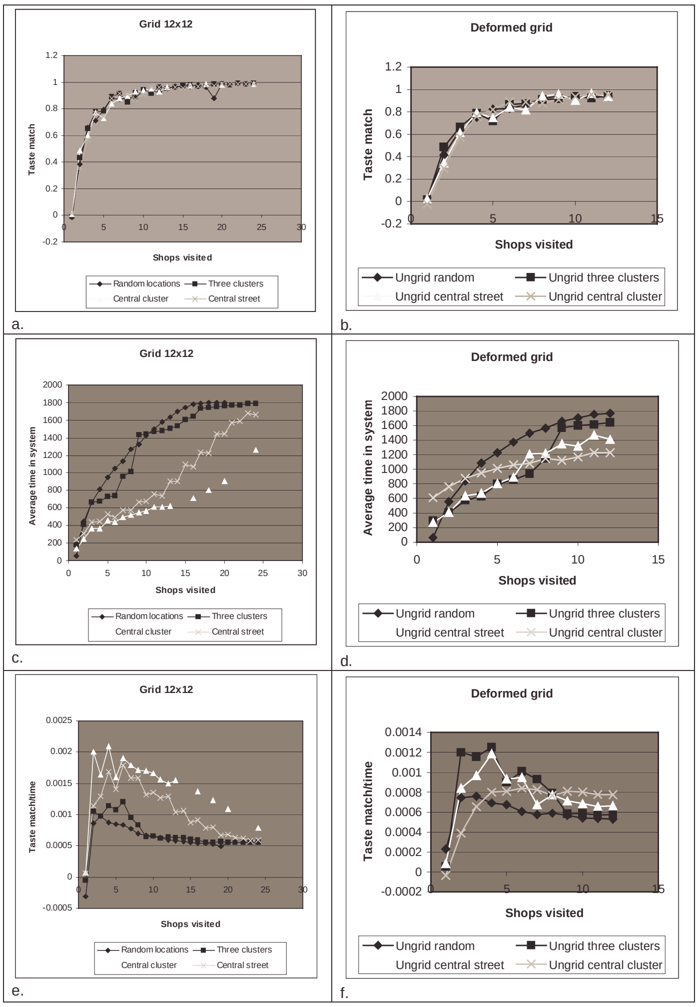


Figure 11: Graphs of agent search performance

There is, however, a marked difference in performance of the different systems with regard the time taken for the agent to find and visit different numbers of shops. The data for this are given in 11c. and 11d. The smooth curve for the randomly dispersed frontages is apparent in both deformed and uniform grid systems. In terms of time taken to find shops, this is generally the poorest performer in the regular grid, closely followed by the three cluster system. The latter shows step changes in performance related to the need to locate a second cluster when there are 9 or more shops to be visited, and a third when there are 17 or more. The central street system shows an almost linear increase in time for increased numbers of shops visited for both uniform and deformed grids, with a regular pairwise step, possibly as a result of the proximity of opposite sides of the street – thus finding one new frontage brings a second with little additional effort. The central cluster provides for the fastest search in the uniform grid showing an S shaped curve where only for the higher numbers of shops does the overall time reach the same point as the other systems. In the deformed grid, however, the result is quite different. The central cluster takes the longest to find of all systems for small numbers of shops, crossing the random line at 3 shops the street and 3 clusters at between 5 and 7 shops. For higher numbers, the central cluster provides the shortest search time.

These results make a lot of sense. In a strongly globalised system – the regular grid – a single central cluster is easy to find and once found affords a highly efficient means of searching a large number of shops. However, when the environment is deformed in such a way that it affords less global visibility, the single central cluster will take some time to find in the first place. Once the first shop has been found, the subsequent ones will be found with little additional effort. In this more localised system there are clear benefits to some forms of dispersion such as the 3 clusters and the linear street. These make initial finding easier, and then afford savings in finding the next shop, however when the number of shops on the itinerary is large the central cluster affords the most efficient search.

Graphs 11e and 11f show the payoff in terms of a better taste match for time spent shopping as the number of shops visited increases. All graphs rise to a peak and then fall off more slowly. In the uniform grid the single central cluster gives the best payoff, however in the deformed grid the multi cluster and linear street versions are the most effective except for at high numbers of shops.

The problem of planning with distributed information

The attraction of these results is that they make intuitive sense – at least with hindsight. It is only with hindsight that the effect of attractors as effective boundaries or sinks in an urban system seems obvious. The point is that what matters in urban space is not shops as 'attractors', but 'shopping' as a human activity. It is only when a series of shops are strung together into a shopping trip that people are produced on the street. Similarly, the effect of an attractor on patterns of movement is not in its own immediate vicinity, but in the spaces and alignments that lead to and away from it. The city has evolved, perhaps, to optimise these relationships between retail location and the spatial configuration, and it is worth taking some time to follow the consequences of this through. Cities show a number of key features in the way that they locate retail land uses. The first is that both clusters and linear streets are common, in fact the central shopping district in most cities forms a cluster, but this is linked to outlying smaller clusters by linear shopping streets. In the light of the simulation experiments we have conducted, this seems possibly to be an outcome of a simple mechanism in which search by agents with vision (viz, human shoppers) leads to certain locations and forms of aggregation affording greater efficiency. Efficiency of search in this sense is directly related to spatial configuration on the one hand, and to the transmission and exchange of information between agents on the other. In the case of shopping, the transmission of information is precisely the mechanism through which the market operates to set prices for goods. A market provides an extremely simple mechanism to allow individual preferences to be evaluated and re-evaluated so that what a retailer has on offer and the price he charges can be brought into some form of accord with what a consumer is prepared to pay. In this way, urban spatial configuration becomes a key aspect of the market mechanism and works 'rationally' albeit in a distributed fashion.

We can see this in our immediate area of London. Tottenham Court Road is well known for its computer shops, and just around the corner in Charlotte Street there is a wealth of restaurants. Both are connected to Oxford Street with its department stores, and form a part of the core retail district of London's west end. As we live our lives every day, we make use of a range of these different facilities in sequences that are determined in part by their spatial disposition and by the way the configuration of space acts to afford us access. These sequences for any individual at any time may well be different, and are undoubtedly complex, however, if our simulations have any bearing on reality, there appear to be some simple underlying principles to the effects of configuration of search by agents that have long distance vision.

Notes

[1] See the debates (e.g. Hall, 1991) surrounding Newman and Kenworthy's (1989) review of city density and transport energy use.

[2] There is a long tradition of detailed case studies in human geography, e.g. Wise's (1949) study of Birmingham, Peter Hall's (1962) study of inter-industry linkages in London and Max Hall's (1959) study of New York manufacturing.

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