Space Syntax and Spatial Cognition

Or, why the axial line?

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Abstract

Space syntax research has found that spatial configuration alone, represented and measured in a specific manner, explains a substantial proportion of the variance between aggregate human movement rates in different locations in both urban and building interior space. Although it seems possible to explain 'how' people move on the basis of these analyses, the question of 'why' they move this way has always seemed problematic since the analysis contains no explicit representations of either motivations or individual cognition. One possible explanation for the predictive power of the method is that the way people understand their environment and decide on movement behaviours is somehow implicitly embedded in space syntax analysis. This paper explores the contribution made by space syntax theories and research to our understanding of environmental cognition, and addresses the question of why the axial representation is so empirically successful. On the basis of a review of some of the relevant findings of space syntax research, it proposes that 'cognitive space', defined as that space which supports our understanding of configurations more extensive than our current visual field, is not a metric space, but topological or pre-topological in nature. A hypothetical process for deriving a non-metric space from the metric visibility graph involving exploratory movement is developed. The resulting space is shown to closely resemble the axial graph. Recent research using simulation agents with vision confirms that axial movement patterns follow from a simple random movement rule combined with a forward facing visual field. It is argued that the social effects of spatial configuration in structuring communication and transaction between individuals is based on co-presence in space, and that co-presence is determined by the local visual field and the way that configuration brings movement routes through that field, are thus largely exosomatic in nature.

Keywords:
axial line, cognitive space, visibility graph, axial map, movement patterns, visual field, exosomatic effects

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Introduction

One of the favoured assumptions of those dealing with human action is that the 'prime mover' is individual motivation or goal directed behaviour. The evidence from space syntax research, however, is that one can get quite a long way in predicting movement behaviour without invoking goals and motivations, and in fact without explicitly assuming anything about individuals or their cognitive capacity. This empirical success is sometimes taken to suggest that individuals and their motivations are not considered important, or of interest in space syntax research. In this paper I argue the reverse. I propose that clues to the nature of individual motivation and cognition may be implicit in space syntax theory and analysis, and by making these explicit the field can contribute to a better understanding of individual level mechanisms.

It is important to note that space syntax research started out as research into societies as distinct to individuals, and it is perhaps this way of slicing the cake - taking a view on what is external and common to all individuals, and therefore potentially social - that has led us to take a quite fundamentally different approach to those commonly adopted by researchers who start through a consideration of the individual. I will suggest that the light syntax research can throw on issues of cognition stems from taking this social, and therefore broadly exosomatic, perspective.

I will start, however, with an apparently relatively minor outcome of this programme of social research, which was probably unforeseen at the outset, but which has become central to the broad social theory proposed by space syntax. Space syntax analysis (which represents and quantifies aspects of spatial pattern) has found that spatial configuration correlates powerfully with observed movement by both pedestrians (eg: Hillier et al, 1993, 1987, 1983; Peponis et al, 1989; Read, 1999) and drivers (Penn et al, 1998a; 1998b). This degree of correlation is surprising since the analysis appears not to incorporate many of the factors considered critical in previous efforts to model human movement patterns through the built environment. The analysis incorporates only certain aspects of the geometry of the environment, and makes no mention of the motivations or intentions of the 'movers', either explicitly through the use of 'origin-destination' (O-D) information or by inclusion of land use, development density or other factors that might act as a proxy for these. Even the geometric descriptions it uses are extremely parsimonious. No direct account is taken of the metric properties of space, and the analysis which to date has shown the most consistent empirical correlation, reduces the effects of metric distance to a minimum and places the most emphasis on the average number of changes of direction encountered on routes, not to specific destinations, but to all possible destinations. This appears to eliminate a key factor in most modelling approaches based on rational choice, in which the main 'cost' associated with travel - and which it is assumed the rational individual will seek to minimise whilst achieving their goals - is usually taken as travel time judged on the basis of metric distance[1].

It is, however, exactly the parsimony of the representation and the consistent strength of the empirical results that makes for the practical usefulness of syntax analysis as a design tool (see Stonor's paper in these proceedings). Few assumptions need to be made about future land use characteristics or individual travel motivations in order to assess the likely effects of different design geometries on movement patterns. Of course, during design it is exactly the effects of the geometry of the layout that one needs to assess, and any assumptions about future trip motivations for individuals are more likely to be wrong than right.

Perhaps it is also for this reason that syntax analysis has been found to be better able to explain observed pedestrian movement patterns through existing areas than traffic modelling techniques, which currently suffer from difficulty in obtaining individual level O-D data for pedestrian trips. The same cannot be said for driver behaviour however, where the O-D data are considered to be good. And yet here too syntax analysis appears better able to

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[1] It should be noted that all these aspects of the environment - land use, development density, metric properties etc. - are included as possible determining variables in our statistical analysis of observed movement patterns, alongside those that describe the spatial relational properties derived from space syntax analysis. The consistent finding from the statistical analysis is that they account for little, although they often provide useful explanations for outliers (individual spaces that lie well above or below the regression line) in the analysis.

‘explain’ observed traffic flow data[2]. How is this possible? A form of analysis, which explicitly excludes the individual, appears to be able powerfully to predict the behaviour of a population of individuals. An analysis based on a mapping of the environment, which excludes metric distance,[3] appears to predict the outcome of movement decisions based presumably on some kind of rational choices on the part of countless individuals. These are the facts of the case, however, and as such are sufficient to support a general ‘predictive’ theory proposed by Hillier and colleagues (1993). They tell us ‘how’ movement depends on spatial morphology, and the degree to which this is the case, and therefore the maximum degree to which other factors, such as individual goals and motivations, specific attractors and generators or land uses and development densities, can be involved. However, if we wish to turn this into an ‘explanatory’ theory, one that gives an account of ‘why’ behaviours of this sort take place, I believe that we need to generate a reasonable account of cognition that is compatible not only with what we know about how the human brain works, but also with the empirical evidence that comes from our own research about how it affects observable behaviour.

A number of studies have started to tackle this issue, often not directly, but as an aspect of work aimed at other problems, and some progress has been made in understanding observed movement behaviour. Other research has been experimental in nature, and by tracking subjects in real or virtual environments and observing their behaviour, has started to focus on the circumstances surrounding individual route choice decisions. More recently we have begun to approach the problem by developing computer simulations that aim directly to model possible decision making processes at the level of the individual in order to see whether these reproduce observed population level behaviours. The main aim of this paper is to marshal the evidence we have to hand so far and to begin to make some propositions about what it might mean for human cognition. In this paper I will not review the vast field of research into human cognition and cognitive mapping in particular, which is already well covered in the literature (see for example Kitchin, R. & Freundschuh, S., 2000, review volume on the psychological and geographical literature, or Burgess et al’s excellent compendium of current neuroscience in this field)[4], although I will refer to some of the main ideas that seem to have a bearing on what we are finding. The aim here is rather to give pointers to those pieces of space syntax research (some of which lie hidden in Doctoral theses on library shelves) that would be difficult especially for anyone outside our field to find out about and which seem to me to constitute pieces in a jigsaw puzzle where most of the pieces remain yet to be found, but where perhaps, an outline of the picture is just beginning to emerge[5]. Finally, I try to draw some tentative conclusions on what a ‘spatially plausible’ theory of cognition might look like.

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[2] This is no criticism of traffic modelling. Where science uses data to test hypotheses which are assumed to be false, and thus to increase our understanding, modelling uses data to calibrate models based on theories that are assumed to be correct. The aims of syntax are exactly to understand and explain certain aspects of human behaviour and their relation to the environments that people build. Traffic modelling has never had that aim and has been explicitly developed as an approach to modelling the effects of policy change and design intervention, in a world in which we lack a good explanatory theoretical framework, but in which we must continue to intervene.

[3] It should be noted that certain aspects of metric distance remain in the analysis due to their effects on the geometric relationships that are possible between lines on a plane surface.

[4] It is notable how the two fields seem to pursue their studies in relative isolation.

[5] I have tried to structure this evidence into some kind of a logical order rather than a chronological one, where the logic is informed with the benefit of hindsight. This is partly because later work often helps one to understand the importance of earlier findings, and partly because it is easier

Syntax and movement

Space syntax analysis has been fully described elsewhere (Hillier & Hanson, 1984; Hillier et al 1997; Penn et al 1998) so in this paper I will only outline a few key aspects of the analysis that relate to the matter at hand. The procedure used by space syntax analysis is one of representing and quantifying aspects of the built environment and then using these as the independent variables in a statistical analysis of observed behaviour patterns. In the cases I am considering here the main aspect of behaviour of interest is movement and our main dependent variable is the average flow of people (or cars) per unit of time past some observation point. The question we ask is what aspects of the environment appear to be correlated with observed flows across a sample of different locations in the area under study. We quantify a number of aspects of the built environment (see Footnote 1 above), but those that seem consistently to correlate best with observed flows are measures of spatial integration in the axial map of the area. Spatial integration is a measure of the mean depth in a graph where each node is an axial line and each intersection between lines is represented as an edge linking those nodes.

Conventionally, the graphs are undirected and unweighted and so both long and short lines are reduced to dimensionless nodes, thus effectively eliminating metric distance from the analysis.[6] Clearly however, longer lines in an axial map tend to have a greater number of intersections with other lines, are more highly connected in the graph and so tend to be shallower or more integrated. However, the effect of the axial map in which the fewest and longest lines of sight and access are passed through the open space of a study area, is to reduce each line to a dimensionless node in the graph, in such a way that a single line that passes from one side to the other of a city would constitute only a single additional step of depth irrespective of how many city blocks one were to traverse along it (see Footnote 3 above). At first this seems to be a somewhat baffling aspect of the form of analysis, however the difficulty is strictly one of our comprehension. The measure of spatial integration for each line is of the mean depth of that line from all other lines within some defined number of steps (or radius). Thus the measure is not one of the role of that line on a single specific route, but of its role on all routes from all lines to all other lines in the system. In this way the measures that are found to correlate best with movement are not defined in terms of individual routes, but in terms of a particular line's place in a whole configuration or map of all possible routes. In this sense the space syntax measures that have been found thus far to correlate best with observed movement behaviour are not egocentric, but fundamentally allocentric[7].

The degree of correlation with observed movement as well as the precise form of the analysis varies. A number of choices exist: first, in the size and boundary of the area that is mapped; second, in the precise measures of the graph that are found to best correlate; third, in the secondary factors which regression analysis shows also to play a significant role, and;

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that way to maintain a thread through a series of pieces of research that were not originally conceived of as a whole. The structure of the paper is to start with the findings of syntax research which now appear relevant to cognition but aimed originally at other issues, and then move on to those pieces of research directed at understanding more about cognition itself.

[6] But see Nick Dalton's Meanda software which has introduced a weighting on the edge dependent on angle of intersection, and by this introduces a new range of measures more sensitive to angular deviation of routes.

[7] This is a position that is intimately connected to the foundations of space syntax as a social theory. Specifically, space syntax tends to look at how an individual is constituted by all others in a group or society, and thus how a space is constituted by other spaces in a configuration.

fourth, in the interpretation one places on the meaning of these results. In statistical terms somewhere between 60% and 80% of the variance in movement rates from location to location, in areas where land uses and development densities are relatively homogeneously distributed, can be accounted for by measures of spatial configuration alone. Usually only one or two such measures play a significant role in the multiple regression. Pedestrian movement patterns show greater variation while driver behaviour in studies carried out to date shows greater consistency and is more highly correlated. The strength of these correlations and their repetition from case to case in different cities throughout the world leaves little doubt that at the population level spatial configuration is the primary factor in determining the average movement choices of a population.

Named local areas

There are, however, also general principles to be derived from the way that analysis varies for specific case studies. One of the most important of these for the purposes of this paper is the effect of choice of boundary on the resulting correlation. In an early series of findings Hillier et al (1992) suggested that one could define a specific contiguous area within which correlations between observed movement and spatial integration were maximised. In these studies Hillier suggested that this could be used to give a rigorous definition to a local urban area by defining the boundary to be that which maximised the correlation. The definition of the Barnsbury area in London provided a case in point. As one expands the area being analysed correlations increase, reach a peak and then began to reduce. The boundary of the maximal correlation, Hillier suggested, could be considered as the 'natural' boundary of the area. This boundary seemed, at least for areas of London, to coincide well with named areas. Similar results were found, if instead of expanding the boundary, one merely moved it over the surface of the map. When observations were chosen from parts of two adjacent 'natural' urban neighbourhoods the correlation was poorer than when a well-defined neighbourhood was chosen alone. Effectively, the regression equation for different neighbourhoods was different, and the steepness of the regression could vary markedly between different adjacent areas. These findings suggest that aspects of the relatively intangible concept of 'sense of place' might be open to a more formal definition based on the predictability of patterns of pedestrian movement behaviour from urban morphology.

Hillier expands this argument through his definition of the 'local area effect'. In this he defines the correlation between local and more global radius measures of integration, and notes how for certain 'well working' neighbourhoods within urban areas there is a strong and substantially steeper correlation between local and global measures for the neighbourhood compared to the regression for the city as a whole. This 'steeper than average' correlation suggests that relatively large changes in local conditions are reflected in smaller changes in global conditions, and so that changes one perceives locally as one moves about the area give a magnified indication of one's global position, thus making ones reading from local to global a more sensitive instrument.

The notion that correlations between local and global configurational variables constitute a measure of the inherent intelligibility of a spatial configuration is a recurrent one in space syntax, and, as I have proposed elsewhere (Penn & Dalton, 1994), suggest that human cognitive capacity may be partly in the form of a 'correlation detector', in which consistent variations in one perceived dimension (a local spatial property, land use, development density, or the presence or absence of people, for instance) can give clues to other more global properties. In this way spatial learning may be more a matter of internalising the principles linking one dimension, which can be directly apprehended, to another which cannot.

Route hierarchies

Findings with regard route hierarchies for vehicular traffic add to this picture (Penn et al, 1998a; 1998b). In a series of studies of traffic in London I found very little variation between regression equations across a range of study areas in different parts of town. Vehicular traffic is remarkably consistent and highly correlated with spatial configuration. However, I did find that larger radius measures of integration were better related to primary routes (radius 5-7) whereas secondary and local streets correlated more highly with a more localised radius 3 measure. There seem to be at least two plausible explanations for this finding. First, that driver behaviour varies significantly for those that are relative strangers to an area. Where the proportion of relative strangers might be expected to increase on primary routes this could be reflected in larger radius measures reflecting their more global role in the city's movement structure. The second explanation is simply that the primary routes are used for longer length trips, and so the more global correlation merely reflects the distribution of trip lengths in different levels of the route hierarchy.

The notion that a fundamental aspect of urban structure lies in the way that local and global patterns are related is clearly not only of interest in cognitive terms. It also forms an important plank of the social theory at the basis of space syntax. If cities act as mechanisms for generating contact between locals and those from elsewhere (as the needs for transaction and communication would dictate), then a spatial mechanism at the basis of this would be likely to include correlations between local and global movement structures.

Effects of intelligibility on movement

This thesis gains strong support from detailed studies of common 'pathologies' of urban design. There are two specific findings of importance. First, that the correlation between spatial integration and movement (an area's 'predictability') is itself correlated to the degree of 'intelligibility' of the area (that is the correlation between local and global spatial measures) (Hillier et al, 1987). Thus as areas become less intelligible, they also appear to lose the relationship between spatial integration and movement. Second, that the precise way in which intelligibility tends to break down in a number of our modern housing estates follows a formula in which the local area effect scattergram is characterised not by a steep and tight correlation, but one in which vertical layers of points show a hierarchical set of spaces, one step, two steps, three steps and more from the surrounding streets, but with spaces at each level varying in local conditions in such a way that global relations cannot be predicted on the basis of local perceptions (Hillier et al 1992).

Dongkuk Chang's doctoral research (Chang, 1998) brings a great deal to our understanding of movement behaviour in highly complex and unintelligible urban areas. Chang investigated pedestrian movement behaviour in two multi-level urban complexes, the Barbican and the South Bank Centre in London. His findings bear directly on the issue of cognition since both areas are said to be maze-like and confusing. A conventional space syntax analysis found both also to be relatively unpredictable - there was a low overall correlation between axial integration and observed movement. Chang's concern was to develop an understanding of the way that people move through and behave in high-density multi-level complexes embedded in downtown areas. In order to do this he had to develop a series of new methods of observation and analysis. Perhaps his main contribution was to develop a method of disaggregating the various variables that might contribute to the way that people move through these complexes, in such a way that they could be combined into a single predictive model. He was then able, by removing one variable at a time, to evaluate its effect on observed movement. In this way he determined the relative importance of vertical level changes, changes of direction, visibility of stairs, major attractors and generators of movement and a range of other factors in determining movement patterns. His recombined model was able to account satisfactorily for over 80% of variance in movement rates between different locations in each complex (Chang, 1998; Chang & Penn, 1998).

The key findings of Chang's research were that even in highly unintelligible areas movement was largely predictable from aspects of the environment. However, whereas in relatively intelligible 'traditional' urban areas the single variable of axial integration accounted for the substantial proportion of variance in movement flows, in his multi-level complexes a much wider range of variables needed to be taken into account. These included axial integration, but also steps of depth from attractors, visibility of stairs and ramps, and steps of depth created by level changes. His analysis of the relative significance of these variables found consistently that the way the internal route structure related major sources and sinks for movement - both complexes had major arts venues at their centre and major transport interchanges on their periphery - to be the most significant factor. Horizontal change of direction was a more significant factor than either the number of intervening junctions passed on a straight line of movement, or vertical level changes.

Chang also used methods of observation by 'stalking' individual pedestrians as they moved through each area. By observing aspects of their micro-behaviour he was able to classify them as being familiar or unfamiliar with the area, and to draw conclusions on the kinds of routing decisions they must be making. The preference for minimising horizontal changes of direction was found to override that of vertical level changes, and this seemed a significant factor in the overall movement pattern observed in both areas. A key observation was that maintaining a straight line appeared to be preferred to maintaining a correctly oriented trajectory towards the final destination, with deviations along shorter lines taking place later in the trip to bring one to the destination (Chang, 1998, p227).

Exploratory behaviour

The method of observation of individual route choices was developed some years earlier by Peponis et al (1990) in the first direct investigation of cognition and wayfinding to use space syntax techniques. In this study they propose the concept of a 'search structure', which links the inherent intelligibility of a building to wayfinding performance. The concept is useful, particularly since it distinguishes two aspects of cognition, which are often conflated in the literature. These are the path - which must be used to find a specific destination, and is therefore presumably of importance in wayfinding performance - and the understanding of what the overall configuration of a building is like.[8] Peponis' study focussed on wayfinding behaviour in two phases, first, during an initial exploratory phase, and second, during a task performance phase. During the first exploratory phase 15 subjects were followed as they explored a hospital building. During the second phase the subjects were asked to find specific locations in the building where each of the buildings four main departmental areas acted as

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[8] This distinction bears a close resemblance to O'Keefe and Nadel's distinction between a route and a map (O'Keefe and Nadel, 1978. p80-89).

origins and destinations. During exploratory search a significant correlation was found between the degree of axial integration of a line and the frequency with which it was visited. During the second phase of the study an equally strong relation was found between integration and frequency of visit for nodes defined as 'redundant' - that is, which do not lie on shortest paths between origin and destination. Peponis proposes that 'the implied rule seems to be "when in doubt go to an integrated space"' (Peponis et al, 1990, p573), however he stresses that the research was not designed to show, nor did it show, that integration features in peoples cognitive representation of environments, merely in their overt behaviour.

This research did appear to question, however, the common hypothesis that 'the progression of spatial learning from knowledge of a limited area to knowledge of "routes" and eventually to "survey" knowledge of whole configurations.' Peponis proposed that this sequence may be incorrect or oversimplified. 'Our subjects appeared to exhibit an inherently configurational regularity in search performances with no knowledge of routes whatsoever. Furthermore, this regularity can act like the background against which routes linking known origins to specified destinations are sought.' (ibid, pp575-576). This proposition was reinforced by a detailed analysis of the routes individuals took, which allowed a conjectural set of rules governing wayfinding behaviour to be identified: 1. avoid backtracking; 2. if all else is equal continue on the same line; 3. divert from the line where a new view allows you to see more space and activity, or a longer view and lets you see further ahead; 4. confirm the unexplored parts of the building before the already explored parts.[9] A key aspect of this work lies in the understanding that cognition depends in part on local information, in part on memory of those areas of a building already explored, and partly on the ability to 'project' or develop hypotheses about those parts of a building that have yet to be explored so that exploration could maximise new information. The latter depends on some conception of the overall configuration of a building, parts of which are relatively certain, and other parts of which need confirmation.

Yoon Kyung Choi extended this research in his doctoral thesis on exploration and encounter in museum buildings (Choi, Y.K., 1991; Choi Y.K., 1999). Museums are a particularly interesting building type in this regard since they are predominantly used in an exploratory mode, and their functional programme is as much to do with categorisation of their content as with defining the mode of encounter between users and that content. Thus, 'Museums become subdivided to accommodate the number of objects that they house and to express the categorical distinctions between objects. The way in which the are experienced and explored, however, depends upon the overall pattern of integration and intelligibility of their layout and the way in which the arrangement of objects responds to these patterns.' (Choi, Y.K., 1991, p.xxi). Layout was also found to modulate the pattern of co-awareness and the pattern of encounter between visitors as they moved through the museum. Choi goes on to describe two possible models for this interaction: 'the deterministic model, which dictates viewing sequences and channels encounters in limited ways; and the probabilistic model, which modulates exploration and encounter statistically according to the syntactic properties of the layout.' (Choi, 1999, p241). Thus spatial layout becomes a key method not only of expressing classifications, but also of reproducing those classifications through the

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[9] Rule 1 would seem to be a direct result of rule 4, but I take the distinction Peponis makes to mean that there is a particularly strong disincentive for backtracking, whilst there is a general incentive for exploring unexplored regions of the building.

associations we internalise as we explore. It is the relationship between the way we explore, influenced as that must be by spatial configuration, and the way we internalise or store in memory the edited results of that exploration which are the subject of the next piece of research I review.

Learning, behaviour and cognition

Understanding the relationship between configuration, cognition and behaviour was the subject of Young Ook Kim's doctoral research (Kim, Y.O., 1999). Kim conducted a study of the Hampstead Garden Suburb area of North London in which he combined observations of spatial behaviour, questionnaire interviews, including a sketch mapping exercise with a sample of 76 local residents, and space syntax analysis of the spatial configuration of the area embedded in its surroundings as well as of the sketch maps. The Suburb is divided into two halves. The older half is relatively intelligible, the newer half is significantly less so. By examining the responses of those living in each half separately, Kim was able to draw some significant conclusions on the effects of spatial configuration on the way that residents understood their neighbourhood, and the role played by intelligibility in that.

His analysis found that spatial integration was correlated with observed movement, with the more intelligible area showing stronger correlations. This area was also found to be more 'legible' by the residents who perceived their 'neighbourhood' to be of a greater size. There is, however, a considerable problem posed by the analysis of sketch map data. Sketch maps are notoriously variable in accuracy and it appears impossible to distinguish between the competence of the respondent as a cartographer and their cognitive competence. In order to address this Kim adopted two main strategies, the first based on syntax analysis applied to sketch maps, the second based simply on counts of the frequency with which features occurred in all sketch maps amongst the sample population

Since space syntax analysis can be used to compare different morphologies on the same quantitative basis, he simply mapped the sketch maps axially. The assumption underlying this was that only features that were considered important by the respondent would have been drawn, and these would generally be expressed in a map as features that would also be represented in an axial mapping. Strong correlations were found between axial integration in residents sketch maps and axial integration of the real map, confirming that although the sketch maps were often distorted and partial, that in syntactic terms they represented global features of the real world (Kim & Penn, 2001). Correlations were also found between sketch map integration and observed movement. Again correlations were more powerful in the more intelligible area than the less intelligible one.

The frequency with which individual streets were represented on all respondent's sketch maps was also informative. The main finding was that more integrated streets were drawn more frequently. Using this method Kim found three key associations that were consistently reproduced. These were between integration - both in the real world and in the respondent's sketch map, observed movement behaviour and frequency of representation of a street on residents sketch maps. The problem posed by these findings is one of logical sequence of cause and effect. Does configuration lead to repeated patterns of behaviour and therefore reinforce learning and a cognitive representation, or does the cognitive representation direct behaviour with the observed correlations between configuration and movement behaviour simply arising as a by-product? Kim's resolution of this question is elegant. Drawing on the differential effects of intelligibility - which is certainly (and at least) a property of the external world - he concludes that all three domains interact, but are essentially independent of each other (Kim, 1999, p255) in intelligible systems. This, he argues, is not a question of logical priority, but of a mapping between the three domains.

The role of intelligibility and experience

Ruth Conroy's doctoral research throws further light on this issue (Conroy, 2001). Conroy used a head mounted display to immerse experimental subjects in a series of virtual models of real and experimental urban areas. One advantage of the use of 'virtual environments' is that the subject's location and gaze direction can be tracked precisely, with data on speed, location and orientation being logged for later analysis. In addition, the same environments can be rendered with varying degrees of surface detail, and new 'experimental' environments can be constructed to test specific questions. Conroy first shows that movement in virtual environments is closely correlated to that observed in the real environment. This is important in that it gives greater confidence that other findings are of relevance. Next she investigates two aspects of micro-behaviour: linear analysis in which she examines the way that routes are formed and the degree to which linearity of paths is conserved (see also Conroy-Dalton, 2001, in these proceedings); and positional analysis in which she concentrates on pausing behaviour, the choices made at junctions and the local spatial properties of pause points within the environment.

Her results are highly suggestive of the way that aggregate regularities in behaviour noted above are produced. She shows that linearity is strongly conserved, with subjects usually following long lines of sight with pauses in configurationally 'integrated' locations offering strategic visual properties, long lines of sight and large isovist areas. However, she also finds striking differences between intelligible and unintelligible environments. In one experiment subjects were asked to navigate to a specific central destination from the edge of the area in two very similar environments. In the first, the environment is designed to be relatively intelligible, with a strong central integration core and relatively linear arrangement of major spaces. In the second environment all the buildings blocks are the same, and their general locations are maintained, however they are slightly shuffled so that precise block-to-block alignments no longer coincide, linear spaces are broken and the overall intelligibility is markedly reduced. The results of subjects' navigation in the two systems could not be more different. In the intelligible system, the majority of all movement is relatively direct between origin and destination; there is no redundancy in the route, and a great degree of similarity between the routes chosen by different subjects. Pause points are located at major decision points on the map, and these tend to be at locations where a fair amount of additional information is presented to the subject. Few pauses occur anywhere else. In the unintelligible system, however, routes are far more distributed over the area, routes are indirect and many show a high degree of inefficiency in wayfinding. Pause points are now apparently more randomly located, though still predominantly at junctions. The result is a far lower degree of consistency between the behaviour of subjects faced with the same wayfinding task in the less intelligible system compared to the same subjects faced with the same task in the more intelligible system.

Conroy's findings pose an interesting problem. How does conservation of linear movement relate at a fundamental level to intelligibility? It is clear that in less intelligible systems the paths chosen are themselves less linear, and yet in intelligible systems and unintelligible ones alike there appears to be a strong incentive to maintain linearity. Saif-ul-Haq's findings are relevant in this context (Saif-ul-Haq, 1999). He reports a study of wayfinding in a hospital building that adds two pieces to the jigsaw puzzle. First, the depth of the building entrance (from the remainder of the interior) is found to be a key factor; and second, the effect of experience on the part of the subjects is to increase the correlation between routes and global measures over time. Ul-Haq concludes, "when relational and Euclidean understanding of space develops, it may not be 'map-like' but may consist of topological relationships that consider larger and larger systems." (ibid, 40.1). These, ul-Haq stresses are early conclusions, however, if they hold up would be significant.

The shape of cognitive space

Let me review the story. The external world of configured space has been found to affect movement behaviour at the aggregate level. Puzzlingly, it is a specific representation and set of measures that appear to best correlate with movement. These are based on the axial map, and comprise some variant of mean depth in the axial graph. The puzzle is why? Why the axial map? And why mean depth? One hypothesis is that these observations tell us something fundamental about the way that people understand and think about external spatial configuration, in effect, the way they learn, represent and retrieve spatial configuration such that they can act intentionally in directing their behaviour. It is possible that these findings also indicate something fundamental about the geometry and topology of space itself, or about the processes of growth and construction of urban form.

There are powerful reasons why our cognitive capacity would evolve to represent the underlying structural constraints imposed by the shape of space, however, there is also an anomaly here that needs to be investigated. If, as Nerlich has argued, the geometry and topology of the space we inhabit is Euclidian 3-dimensional (Nerlich, G., 1994),[10] then this is a metric space (a space that supports the notion of distance) with some very basic mathematical properties. A distance measure or metric is formally a mapping d from pairs of elements of a set X to the positive real numbers, d:X (X®(+ satisfying four axioms for all x,y,z (X:

[1] d(x, x) = 0.
[2] d(x, z) (d(x, y) + d(y, z).
[3] If d(x, y) = d(y, x) = 0 then x = y.
[4] d(x, y) = d(y, x).

These axioms are: [1] that points are not extended in space; [2] that the distance between points x and z must be less than or equal to the sum of distances between x and a third point y, and y and z; [3] if two points are zero distance apart then they are the same point; and, [4] the distance from x to y is the same as from y to x. It is seems self evident that space at least as we experience it on the local scale is metric in this sense. And yet, when we consider the way that we 'know or understand' configurations of space - let us call this 'cognitive space' - we seem to be faced with a conundrum. Cognitive space appears not to be metric since on occasion axiom 4 does not hold[11] - the distance of a route in one direction appears (cognitively) different to the distance in the opposite direction. This expresses itself in both the findings about conservation of linearity, first noted by Peponis et al. (1991) above, and in Conroy's

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[10] This field has given considerable meat for discussion since the ancients, and continues to do so. However, Nerlich's (1994) arguments from metaphysics, and those of O'Keefe & Nadel (1978) from the neuroanatomical perspective seem conclusive on two points. First, the independent reality of space, and second its Euclidean 3 dimensional shape.

[11] I will go on to argue that axioms 1 and 3 also do not hold for cognitive space.

paper in these proceedings (Conroy Dalton, 2001), which poses the 'British Library problem'. It is easy to show examples where the conservation of linearity leads one to adopt one route from A to B, and quite a different route back from B to A. Conroy shows that this asymmetry also holds if one chooses one's next step on the basis of heading as directly as the local configuration will allow towards one's eventual destination (given that one has a good sense of direction and can compute the minimum angle move from amongst those on offer). If this is the case then it is possible that cognitive space is not a metric space at all, but something more fundamental and rather simpler such as a topological or pre-topological space.

The idea that cognitive space may not be a metric space requires further investigation. Here I need to develop what I mean by 'cognitive space' - taking this to be the space within which the representation that will allow one to decide on movement behaviour is inscribed. Given a current location and a desired destination there must exist a system in the brain that allows one to direct one's next move. It has been argued that this system involves some mapping of the real world (O'Keefe & Nadel, 1978). Alternatives to mapping, such as memory for explicit routes, or procedural memory of sequences of moves (such as "turn left, go two blocks, turn right"), seem unable to account for many of the competences we see in human behaviour, such as the ability to plot and follow a new route once lost, or the ability to explore new territory. O'Keefe and his colleagues have proposed that the physical implementation of the cognitive mapping system in the brain involves the hippocampus, and have demonstrated that this contains neural units that fire when an individual is in a specific location within an environment, but do not fire when they are elsewhere. They have shown that these cells fire largely on the basis of local information derived from the environment, such as distance from walls, or proportional distance between two walls. However, more recent work from the same group (Hartley et al, 2000) has found that if one changes the morphology of a space, say by subdividing it with a wall across the middle to create two parts that locally appear similar, a place cell which originally fired when the subject was in, say, the south east corner now fires in both the original location and in the new 'south east corner' type location created by the placement of the wall. However after some time, firing in the original 'correct location' is reinforced and firing at the new 'incorrect' location is reduced. This suggests that the instantaneous 'place cell' firing based on local perceptions is moderated in some way by a more global understanding of the configuration of the environment derived through learning. What I mean by 'cognitive space' is the space required to support the representation of this more global understanding of configuration based on some form of learning from experience, and it is this space that I believe may not be a metric space.

How is cognitive space constructed? The process must involve two components. During the exploratory component a cognitive map is filled in. During the wayfinding component it is used to direct behaviour. Of course, both components can occur at the same time.

Exploratory component:
real world+cognitive map+exploratory>learning operator>cognitive map
(partial) behaviour (improved)

Wayfinding component:
cognitive map+real world +wayfinding intent>retrieval operator>next
move

Hartley's finding that firing at the correct location is reinforced over time (while the incorrect location fires more weakly) suggests that learning involves a process of integration of individual point locations that is accomplished through repeated exploration over time. One possibility is that the integration process is in two stages. The first involves the grouping together of discrete points into higher-level aggregates (clusters of points that are all directly inter-visible). The second involves the identification of relations between these aggregates. Both aggregations and relations between aggregates could be developed through experience of the locations that are directly accessible to each other during exploratory behaviour.

One way to imagine this process of integration is by considering the visibility graph (Turner & Penn, 1999; Turner et al, 2001). The visibility graph places a node on every grid point in open space within an environment, and connects those nodes that are visible to each other.[12] In this case the process of integration would amount to finding the maximal cliques in the graph, and then representing these as single nodes and their connectivity relations through a process of clique reduction.[13] Clique reduction is not a simple locally defined process, however it is possible that through a process exploratory movement one might arrive at reinforcement of common sets of visible points, as well as the definition of the transitions between these. In this way the process of integration, although it would lose information on metric distance, would retain information on the structure of permeability in space.

It is worth considering the way that movement affects the points in space represented by nodes in a visibility graph that are visible at any moment in time. First, we must distinguish between the different kinds of movement that are possible. Since our visual field is not a full 360° there are obvious differences between forward movement, side-to-side movement and head turning movement. The most obvious effect is for head turning. As we turn our heads we lose sight of certain portions of the environment and see other portions. The nodes in the visibility graph that are visible to us therefore vary greatly. If we consider side-to-side movement whilst maintaining a forward direction of gaze, the environment appears to change far less, but we do lose sight and gain sight of portions of space behind objects in the foreground. In fact sensing differential flows in surface textures and features during side-to-side motion seems to be a component in depth perception, however, sensing these kind of flows is limited mainly to the central foveal area of the visual field, and it is difficult to make sense of changes in the periphery of vision during side to side motion. During forward motion, the effects are different again. Since the central portion of the visual field is now moving approximately along the line towards the edges separating foreground objects from their background, little change is perceived as nothing much comes into or goes out of view. Of course, in peripheral vision we are constantly losing sight of the points in the environment that fall behind us.

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[12] Visibility Graph Analysis (VGA) has been found to correlate strongly with observed movement patterns especially in building interiors, and often more strongly than conventional axial analysis.

[13] A clique is any set of nodes in a graph that are all connected to each other. A maximal clique is the largest such set following a process in which smaller cliques are subsumed into larger ones (but note that a node can be a member of a large number of different maximal cliques). Clique reduction takes each clique and replaces it with a node, and, where a node in the original graph is a member of more than one clique, the nodes representing those cliques are connected in the reduced graph.

In view of this, we might expect that the different kinds of movement would appear at different locations in the environment during exploration, and would lead to the definition of aggregations of locations that would be considered to be 'the same' as each other during the process of integration. Conroy (2001) has shown that different behaviours occur in different locations with her studies of intelligible and unintelligible environments. She found a characteristic dispersion of head turning and direction changing behaviours in the unintelligible system, and more directed linear forward motion with head turning limited to strategic decision locations in the intelligible one. This suggests that during forward motion, while the information is relatively stable in the environment, discrete locations are aggregated. However, when substantial new information is revealed, say at a street intersection, a different kind of behaviour comes into play that aims to maximise information capture - we pause and turn our heads - and this may then lead us to change direction onto another heading. The effect of this process is that aggregations of locations acquired deemed to be 'similar' during forward motion (the cliques in the visibility graph) will be predominantly linear in shape, and the resulting clique reduction will substantially reproduce the axial graph.[14]

This form of reinforcement of sets of locations, commonly associated in experience of movement, might form the basis of an anatomically plausible representation of configuration. It is easy to demonstrate, however, that even though the underlying visibility graph is a metric space, the configuration space resulting from integration of locations through forward movement is not metric. Points in this space are extended in contradiction with axiom [1], two points may be in the same location since cliques can overlap in contradiction with axiom [3] and relations are not necessarily symmetric in contradiction with axiom [4]. Further consideration shows that this form of aggregation of information on the basis of informational similarity between locations provides a highly efficient means of compression. Detail is retained where it is vital for a decision, that is where information changes rapidly as a consequence of movement, but local information need not be stored since that is already present in the environment and can be directly retrieved.

Exosomatic vision architectures

It is the idea that information may be stored in the environment that forms the basis for some of the more recent space syntax research in this field. In early work on wayfinding Sheep and I developed a series of experiments using stochastic computer agents to wander around axial maps (Penn & Dalton, 1994). The aim was to investigate the rules that were needed to guide individual action in order to reproduce observed aggregate behaviour patterns. More recently agent simulation techniques have been developed using agents with vision in virtual models of the environment (Mottram et al, 1999; Mottram & Penn, 1999). These agents used relatively sophisticated but computationally expensive methods to give agents vision of their environment and each other.

In the latest generation of agent simulations Turner and I have developed an 'exosomatic vision architecture' (Eva) for agent simulations (Penn & Turner, 2000). This architecture is based on a visibility graph of the environment, and allows the simulation agents a degree of 'vision' based on access to the visibility graph. The area of space that can be seen directly from an agent's current location is given by the neighbourhood of its current node in the graph.

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[14] The notion of informational stability during movement relates clearly to Gibson's optical flows, and also to Conroy's measure of 'drift', a measure of the eccentricity of an isovist field from its viewing location.

Since this can be pre-computed there is no additional computational cost entailed in populating the environment with many agents. However, it is also possible to give the agents access to the range of syntax global graph measures associated with not only their current location, but all visible nodes in their neighbourhood.[15] The graph information can also be stored in a look-up table based on a series of 'buckets' arrayed in polar coordinates around the current location. By limiting the buckets to which an agent has access it is possible to give agents different visual fields. In our current implementation there are 32 buckets giving the agents a possible range of visual fields anywhere from 11° to 360°. Currently the movement rule is based on random selection (repeated every three steps) of a destination from any point within the visual field.

The research for which the Evas are being developed aims at investigating the way that attractors and spatial configuration act together to influence movement behaviour. We are modelling a retail interior in which there are clear attractors - almost everyone buys bread for example - but in which spatial configuration also plays a clear role. The Evas are being used to investigate the degree to which purely configurational information must be supplemented by goals and motivations in order to account for observed behavioural patterns.

This research is at an early stage, however our findings to date indicate that the angle of vision given to agents is a critical factor in their performance. Strong correlations have been found between agents and observed patterns of real movement behaviour, but these correlations are at a maximum ($r^2 = 0.75$, $p<.0001$) when the angle of the visual field lies between 150° and 200°. This is close to a normal person's field of vision at around 170°. It is striking then that repeated random selection of an immediate goal from within the forward facing visual field, leads to aggregate movement rates so close to those observed in reality. It is possible that this is close to the maximum proportion of movement behaviour that can be explained on the basis of configuration alone, leaving the remaining 25% of the variance to be explained by other factors such as goals and motivations, or attractors and generators.

There are two immediate consequences of this finding. The first is that the number of people that come into ones visual field is structured by the configuration of that environment (all other things being equal). Since co-presence is a prerequisite for both communication and transaction (or has been until the very recent past) it seems clear that both social and economic structures depend ultimately on the same factors. The second is that the structuring factor that leads to differential rates of human movement in the environment may be largely exosomatic. Human cognition of this exosomatic structure would therefore appear to be central, not only to our ability to navigate around the world, but ultimately to our ability to live a social and economic life. It is perhaps for this reason that unintelligible environments are so personally as well as socially depriving in their effects.

If the part of our cognitive apparatus that allows us to predict others whereabouts, to act socially, and locate ourselves with respect to others in an intentional way is exosomatic - located in an environment constructed largely by others - we are disabled if that apparatus is poorly structured. This is the effect of unintelligible space. By making it impossible for individuals to act intentionally, we remove autonomy as surely as if we tampered directly with the brain.

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15 See Tecchia et al (2001) for a similar approach using syntax measures to inform agent movement.

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